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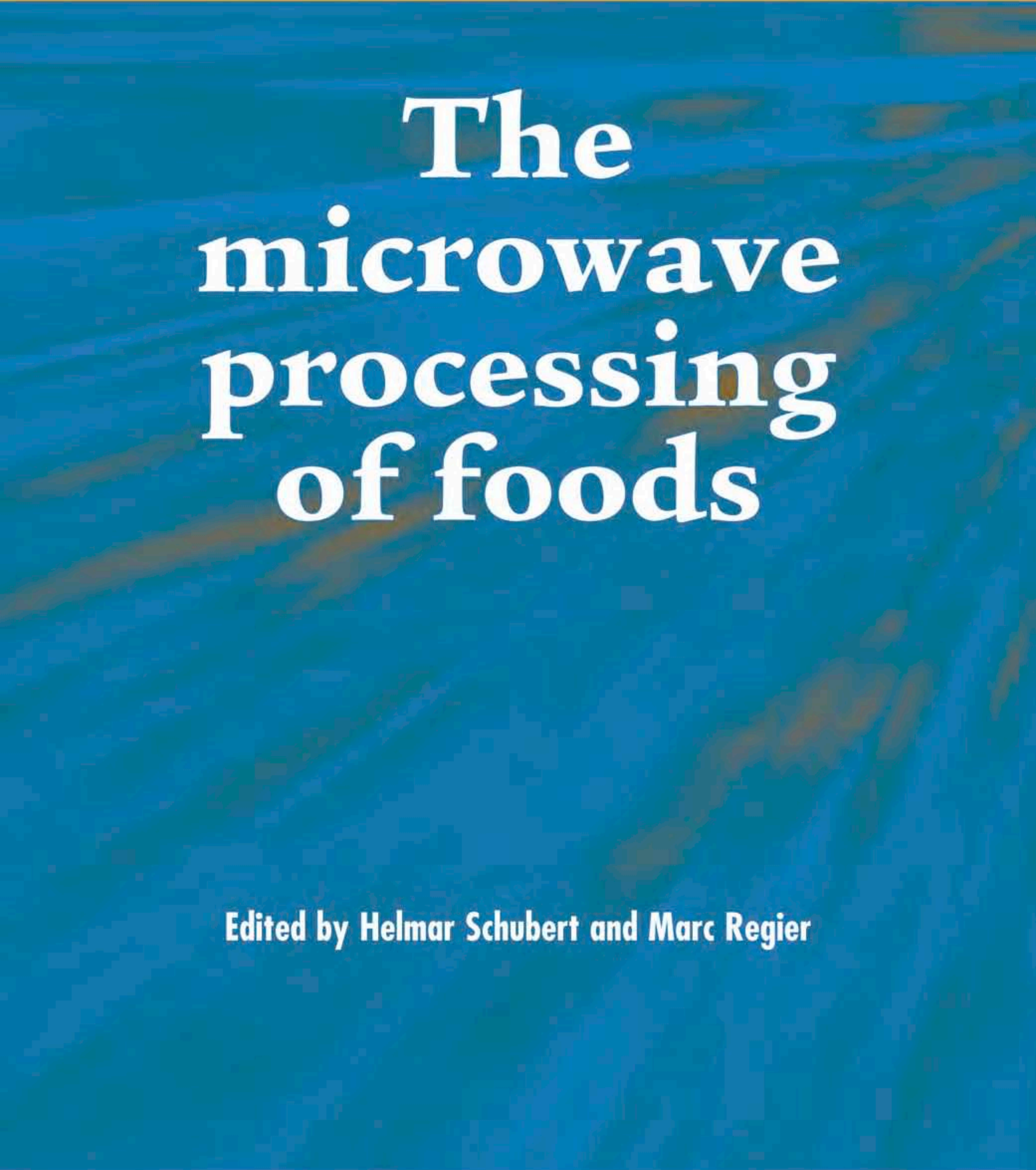

# The microwave processing of foods

Edited by Helmar Schubert and Marc Regier

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Helmar Schubert and Marc Regier

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# Part I

# Principles

# 1

# Introducing microwave processing of food: principles and technologies

**M. Regier and H. Schubert, University of Karlsruhe, Germany**

## 1.1 Introduction

This chapter treats the physical background of microwaves and the corresponding physical theory but also makes some general remarks on the setup of microwave applications. It starts with the definition of the frequency covered and the corresponding wavelength range and legislative regulations, before introducing the basic equations: Maxwell's equations and those that cover the interaction between electromagnetism and matter. Starting with these basics, the wave equation and some example solutions are derived, so that the important concepts of penetration depth and power absorption, which are useful for the estimation of thermal interaction between microwaves and matter can be introduced. After covering the general setup of microwave applications including microwave sources, waveguides and applicators, the chapter is completed by useful links to further literature.

## 1.2 Definitions and regulatory framework

Microwaves are electromagnetic waves within a frequency band of 300 MHz to 300 GHz. In the electromagnetic spectrum (Fig. 1.1) they are embedded between the radio frequency range at lower frequencies and infrared and visible light at higher frequencies. Thus, microwaves belong to the non-ionising radiations.

The frequency $f$ is linked by the velocity of light $c$ to a corresponding wavelength $\lambda$ by eqn 1.1:

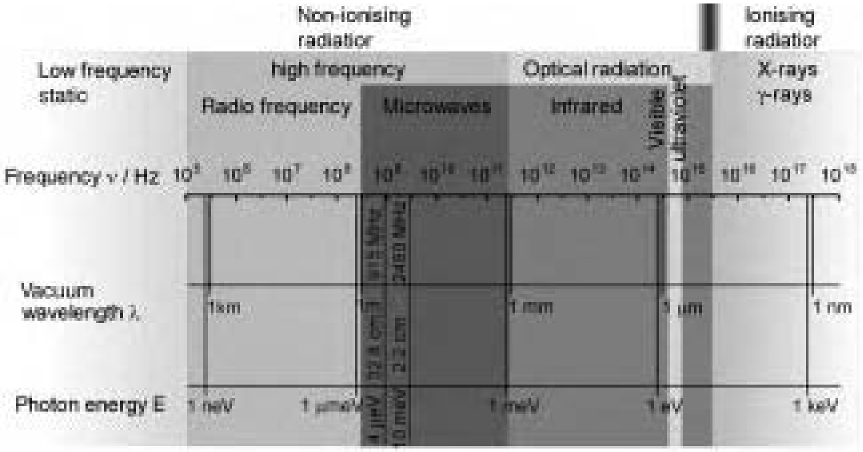

**Fig. 1.1** Electromagnetic spectrum. Additionally, the two most commonly used microwave frequency bands (at 915 MHz and 2450 MHz) are sketched.

$$c = \lambda \cdot f \qquad [1.1]$$

In this case the velocity of light as well as its wavelength within matter are dependent on the material. For the speed of light in a vacuum ($c_0 \approx 3 * 10^8$ m/s) the corresponding wavelength of microwaves is between 1 m and 1 mm, so that the term 'microwave' is a little misleading. The name rather points to their wavelength within the matter, where it can indeed be in the micrometre range.

### 1.2.1 Regulations

As already shown in Fig. 1.1 the frequency range of microwaves adjoins the range of radio frequencies used for broadcasting. But the microwave frequency range is also used for telecommunications such as mobile phones and radar transmissions. In order to prevent interference problems, special frequency bands are reserved for industrial, scientific and medical (so-called ISM) applications, where a certain radiation level has to be tolerated by other applications such as communication devices. In the range of microwaves the ISM bands are located at 433 MHz, 915 MHz and 2450 MHz; the first is not commonly used and the second is not generally permitted in continental Europe. Outside the permitted frequency range, leakage is very restricted. Whereas 915 MHz has some considerable advantages for industrial applications, for microwave ovens at home the only frequency used is 2450 MHz.

Apart from the regulations concerning interference, there exist two types of safety regulations:

(a) the regulation concerning the maximum exposure or absorption of a human, working in a microwave environment,
(b) the regulation concerning the maximum emission or leakage of the microwave equipment.

The exposure limits for humans are based on the estimation of thermal effects that microwaves can cause in the human body. Especially sensitive organs like the eye, with a reduced thermal balancing possibility and/or geometric focusing effects, are taken into account. Thus, the limit for human exposure that is generally considered safe in most countries is 1 mW/cm$^2$ body surface. Concerning ionising radiation, for microwaves it is common to express the exposure or absorption by humans in terms of the specific absorption rate (SAR), which is defined as the quotient of incident power to body weight. For microwaves the International Commission on Non-Ionizing Radiation Protection (ICNIRP, 1998; IRPA, 1988) recommends a maximum value for the SAR to be set to 0.4 W/kg.

The maximum emission of microwave equipment is limited to a value of 5 mW/cm$^2$ measured at a distance of 5 cm from the point where the leakage has the maximum level. Thus the permissible leakage level is higher than the maximum exposure limit. But the power density of non-focused radiation, which is normally the case for leakage, decreases in proportion to the inverse square of the distance from the source. So a leakage that just manages to stay within the limit of 5 mW/cm$^2$ at a distance of 5 cm is already below the maximum exposure limit of 1 mW/cm$^2$ at a distance of 11.2 cm.

## 1.3 Electromagnetic theory

As already mentioned, microwaves are electromagnetic waves, which can basically be described by Maxwell's equations (1.2–1.5):

$$\nabla \cdot \vec{D} = \rho \tag{1.2}$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \tag{1.3}$$

$$\nabla \cdot \vec{B} = 0 \tag{1.4}$$

$$\nabla \cdot \vec{H} = \vec{j} + \frac{\partial \vec{D}}{\partial t} \tag{1.5}$$

Equations 1.2 and 1.4 describe the source of an electric field ($\rho$) without a magnetic monopole as source for the magnetic field. On the other hand, eqns 1.3 and 1.5 show the coupling between electric and magnetic fields.

The interaction of electromagnetism with matter is expressed by the material equations or constitutive relations 1.6–1.8, where the permittivity or dielectric constant $\epsilon$ (the interaction of non-conducting matter with an electric field $\vec{E}$), the conductivity $\sigma$ and the permeability $\mu$ (the interaction with a magnetic field $\vec{H}$) appear to model their behaviour (see also Chapter 2). The zero-indexed values describe the behaviour of vacuum, so that $\epsilon$ and $\mu$ are relative values.

$$\vec{D} = \epsilon_0 \epsilon \cdot \vec{E} \qquad [1.6]$$

$$\vec{B} = \mu_0 \mu \cdot \vec{H} \qquad [1.7]$$

$$\vec{j} = \sigma \cdot \vec{E} \qquad [1.8]$$

In general, all these material parameters can be complex tensors (with directional-dependent behaviour). In the case of food substances, some simplifications are possible for most practical uses: since food behaves non-magnetically, the relative permeability can be set to $\mu = 1$ and the permittivity tensor can be reduced to a complex constant with real ($\epsilon'$) and imaginary part ($\epsilon''$), which may include the conductivity $\sigma$ (see Chapter 2).

### 1.3.1 Wave equations and boundary conditions

Maxwell's equations cover all aspects of electromagnetism. In order to describe the more specific theme of electromagnetic waves, the corresponding wave equations (for the electric or the magnetic field) can be easily derived, starting from Maxwell's equations, with the simplifications of no charge ($\rho = 0$) and no current density ($\vec{j} = 0$). The derivation is shown here only for the electric field; it can be transferred simply to the magnetic field. Applying the curl-operator ($\nabla\times$) on eqn 1.3 yields eqn 1.9:

$$\nabla \times \left(\nabla \times \vec{E}\right) = -\nabla \times \frac{\partial \vec{B}}{\partial t} = -\frac{\partial}{\partial t}\left(\nabla \times \vec{B}\right) \qquad [1.9]$$

Using the constitutive equation for the magnetic field (1.7), this can be transformed to eqn 1.10, supposing the permeability $\mu$ to be constant and introducing eqn 1.5:

$$\nabla \times \left(\nabla \times \vec{E}\right) = -\mu_0 \mu \frac{\partial}{\partial t}\left(\frac{\partial \vec{D}}{\partial t}\right) \qquad [1.10]$$

Utilising the material equation for the electric field (1.6), the first of Maxwell's equations (1.2) and the vector identity $\nabla \times \left(\nabla \times \vec{X}\right) = \nabla\left(\nabla \cdot \vec{X}\right) - \Delta\vec{X}$, one gets the following well-known wave equation:

$$\Delta\vec{E} - \mu_0 \mu \epsilon_0 \epsilon \frac{\partial^2 \vec{E}}{\partial t^2} = 0 \qquad [1.11]$$

The corresponding wave equation for the magnetic component $\vec{B}$ can be derived in a similar way, yielding the same equation, by replacing $\vec{E}$ by $\vec{B}$. Comparing this wave equation (1.11) with the standard one, one can infer that in this case the wave velocity is defined by eqn 1.12:

$$c = \frac{1}{\sqrt{\mu_0 \epsilon_0 \mu \epsilon}} = \frac{c_0}{\sqrt{\mu \epsilon}} \qquad [1.12]$$

The nature of possible solutions of eqn 1.11 can be illustrated by considering the case of a so-called linearly polarised plane wave. Linearly polarised means that, for example, the electric field consists of only one component, e.g. in the $z$-direction $E_z$. If this component depends only on the one local coordinate, e.g. $x$ (and the time), the wave is called a plane wave. If the material parameters are additionally frequency independent, eqn 1.11 then reduces to

$$\frac{\partial^2 E_z}{\partial x^2} - \frac{1}{c^2}\frac{\partial^2 E_z}{\partial t^2} = 0 \qquad [1.13]$$

It can be shown that all functions of the form $f(kx \pm \omega t)$ solve this equation. Often used as solutions also for the more complex case (1.11) are time-harmonic functions (eqns 1.14):

$$\begin{aligned} \vec{E} &= \vec{E}_0 \cos(\vec{k}\vec{x} - \omega t) \\ \vec{E} &= \vec{E}_0 \sin(\vec{k}\vec{x} - \omega t) \\ \vec{E} &= \Re\left[\vec{E}_0 \exp\left\{i\left(\vec{k}\vec{x} - \omega t\right)\right\}\right] \end{aligned} \qquad [1.14]$$

Here $\vec{k}$ is the wave vector pointing to the direction of propagation with its absolute value defined by

$$\vec{k}^2 = \frac{\omega^2}{c^2} \qquad [1.15]$$

and $\omega = 2\pi f$ is the circular frequency of the wave.

It should be noted that the separate wave equations for the electric and magnetic fields cannot completely replace Maxwell's equations. Instead, further conditions, listed in Table 1.1, show the dependency between the magnetic and electric fields. In this theory, the dispersion (the dependence of the velocity of light on the frequency $\omega$ in materials) is included. For including absorption within matter, a complex permittivity and with this a complex wave vector have to be introduced. When additionally a finite conductivity $\sigma$ in eqn 1.10 is allowed, so that a current $\vec{j} = \sigma\vec{E}$ occurs, instead of the simple wave equation (1.11) the expanded eqn 1.11a has to be used:

$$\Delta\vec{E} - \mu_0\mu\sigma\frac{\partial\vec{E}}{\partial t} - \mu_0\mu\epsilon_0\epsilon\frac{\partial^2\vec{E}}{\partial t^2} = 0 \qquad [1.11a]$$

Taking time-harmonic functions for the electric field as solutions as above, eqn 1.11a reduces to:

$$\Delta\vec{E} + \omega^2\mu_0\mu\epsilon_0\left(\epsilon - i\frac{\sigma}{\epsilon_0\omega}\right)\vec{E} = 0 \qquad [1.11b]$$

**Table 1.1** Correlations between electric and magnetic fields

| Transversality | Correlation of electric and magnetic field |
|---|---|
| $\vec{k}\cdot\vec{E}_0 = 0$ | $\vec{k}\times\vec{E}_0 = \omega\cdot\vec{B}_0$ |
| $\vec{k}\cdot\vec{B}_0 = 0$ | $\vec{k}\times\vec{B}_0 = -\omega\cdot\mu_0\mu\cdot\epsilon_0\epsilon\cdot\vec{E}_0$ |

This equation shows that a finite conductivity $\sigma$ is equivalent to an imaginary term in the permittivity $\epsilon$.

### 1.3.2 Example solutions, the exponentially damped plane wave

Coming back to an example solution in the case of an absorbing material, where the permittivity $\epsilon$ has an imaginary part $\epsilon = \epsilon' - i\epsilon''_{\text{total}}$, we have:

$$\epsilon''_{\text{total}} = \epsilon'' + \frac{\sigma}{\epsilon_0 \omega} \qquad [1.16]$$

Then the time-harmonic plane wave has to be a solution of eqn 1.11c:

$$\frac{\partial^2 E_z}{\partial x^2} + \omega^2 \mu_0 \mu \epsilon_0 \left(\epsilon' - i\epsilon''_{\text{total}}\right) E_z = 0 \qquad [1.11c]$$

For the magnetic component of the plane wave $H_y$ (which has to be orthogonal to the electric field $E_z$) a similar equation can be derived, leading to a general solution with $g$, $h$, $m$ and $n$ constants to satisfy the boundary conditions (see Table 1.2):

$$\begin{aligned} E_z &= g \cdot \exp\{(ik + \kappa)x\} + h \cdot \exp\{-(ik + \kappa)x\} \\ H_y &= m \cdot \exp\{(ik + \kappa)x\} + n \cdot \exp\{-(ik + \kappa)x\} \end{aligned} \qquad [1.17]$$

The continuity of $E_{\|}$ (which is one boundary condition of Table 1.2) should be emphasised, since it can explain the often observed effect of edge or corner overheating. Later it will be shown that the power dissipation in a sample volume is proportional to the squared electric field (eqn 1.23). At edges and especially at corners, not only can the microwaves intrude from two or three directions, respectively, but also at these volumes electric fields of two or three polarisations have a parallel surface to intrude continuously without any loss of amplitude. Therefore the heat generation there will be very large.

The solution approach of eqn 1.17 describes an exponentially damped wave, with wave number $k$ and damping constant $\kappa$, both dependent on the permittivity $\epsilon$. Comparison of coefficients yields eqn 1.18:

$$\omega^2 \mu_0 \mu \epsilon_0 (\epsilon' - i\epsilon''^{*}) = (\kappa + ik)^2 \qquad [1.18]$$

**Table 1.2** Boundary conditions in different circumstances

| Prerequisite | Boundary condition |
|---|---|
| No surface charge | Continuity of $D_\perp$ |
| – | Continuity of $B_\perp$ |
| No surface content | Continuity of $H_{\|}$ |
| – | Continuity of $E_{\|}$ |
| Ideally conducting wall (metallic) | $E_{\|} = 0$ |
| Ideally conducting wall (metallic) | $B_\perp = 0$ |

leading to

$$k = \omega\sqrt{\frac{\mu_0\mu\epsilon_0\epsilon'}{2}} \cdot \left(\sqrt{\sqrt{1 + \frac{\epsilon''^{*2}}{\epsilon'^2}} + 1}\right) \qquad [1.19]$$

and

$$\kappa = \omega\sqrt{\frac{\mu_0\mu\epsilon_0\epsilon'}{2}} \cdot \left(\sqrt{\sqrt{1 + \frac{\epsilon''^{*2}}{\epsilon'^2}} - 1}\right) \qquad [1.20]$$

The corresponding electric field penetration depth (shown in Fig. 1.1), the distance in which the electric field is reduced to 1/*e*, is defined by eqn 1.21:

$$\delta_E = \frac{1}{\kappa} = \frac{1}{\omega} \cdot \sqrt{\frac{2}{\mu_0\mu\epsilon_0\epsilon'\left(\sqrt{\sqrt{1 + \frac{\epsilon''^{*2}}{\epsilon'^2}} - 1}\right)}} \qquad [1.21]$$

An important consequence of the frequency dependence of $\kappa$ is that microwaves of 915 MHz penetrate approximately 2.5 times further than waves of 2450 MHz, when similar permittivities at both frequencies are assumed. This greater penetration depth helps to heat larger (industrial) pieces more homogeneously.

With the assumption of the excitation and the propagation of a plane wave that satisfies the boundary conditions, first estimations of the field configurations are possible. This yields, for example, the laws of geometric optics, which are also valid for microwaves, when a typical object is much larger than the wavelength.

### 1.3.3 Geometric optics: reflection and refraction

*Angles*

Consider a plane wave, as shown in Fig. 1.2, travelling from a semi-infinite non-absorbing medium I ($n_1 = \sqrt{\epsilon_1}$) into a semi-infinite absorbing medium II ($n_2 = \sqrt{\epsilon_2} = n_{2r} + in_{2i}$). Both permeabilities should be $\mu = 1$ and the boundary plane between the two media should be the *x-y* plane at $z = 0$. The electric field of the plane wave (neglecting the explicit writing of the real part) can be written as:

$$\vec{E} = \vec{E}_0 \exp\left[i\left(\vec{k}\vec{x} - \omega t\right)\right] \qquad [1.22a]$$

Using Table 1.1 the corresponding magnetic field is defined by:

$$\vec{B} = \frac{1}{\omega} \cdot \vec{k} \times \vec{E} \qquad [1.22b]$$

This wave transports energy in the direction of the wave vector $\vec{k}$, which is depicted in Fig. 1.2 as a ray. Also in this case, the boundary conditions (with no surface charge and current) of Table 1.2 are valid, so that a reflected (eqn 1.23)

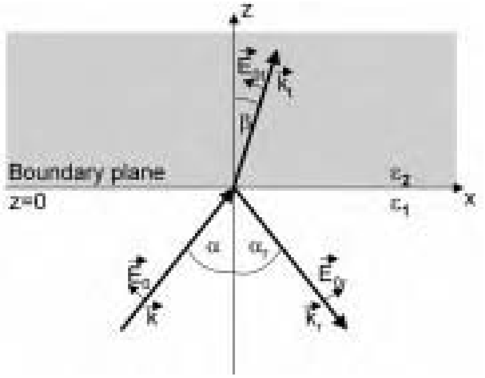

**Fig. 1.2** Reflection and refraction of a plane wave incident on a plane dielectric boundary.

and a refracted (transmitted) wave (eqn 1.24) with the same time dependency have to be present:

$$\left.\begin{aligned} \vec{E}_r &= \vec{E}_{0r}\exp\left[i\left(\vec{k}_r\vec{x}-\omega t\right)\right] \\ \vec{B}_r &= \frac{1}{\omega}\cdot\vec{k}_r\times\vec{E}_r \end{aligned}\right\}\quad (z<0) \qquad [1.23]$$

$$\left.\begin{aligned} \vec{E}_t &= \vec{E}_{0t}\exp\left[i\left(\vec{k}_t\vec{x}-\omega t\right)\right] \\ \vec{B}_t &= \frac{1}{\omega}\cdot\vec{k}_t\times\vec{E}_t \end{aligned}\right\}\quad (z>0) \qquad [1.24]$$

The wave vectors obey eqn 1.25, so that $\vec{k}$ and $\vec{k}_r$ are real but $\vec{k}_t$ is generally complex:

$$\frac{\vec{k}^2}{n_1^2}=\frac{\vec{k}_r^2}{n_1^2}=\frac{\vec{k}_t^2}{n_2^2}=\frac{\omega^2}{c^2} \qquad [1.25]$$

Recapitulating, for $z>0$ $\vec{E}_t$ is the solution, whereas for $z<0$ the solution consists of the sum $\vec{E}+\vec{E}_r$. By taking the incident wave with $\vec{E}$ and $\vec{k}$ as starting points, the remaining variables $\vec{E}_r$, $\vec{E}_t$, $\vec{k}_r$ and $\vec{k}_t$ can be determined by the boundary conditions of Table 1.2.

At the plane $z=0$ the local dependencies of all waves $\vec{E}$, $\vec{E}_r$ and $\vec{E}_t$ have to coincide, so that

$$k_x x + k_y y = k_{r,x}x + k_{r,y}y = k_{t,x}x + k_{t,y} \qquad [1.26]$$

Without constraining universality, the $y$-component can be chosen to vanish, $k_y=0$, yielding:

$$k_y = k_{r,y} = k_{t,y} = 0 \qquad [1.27]$$

$$k_x = k_{r,x} = k_{t,x} \qquad [1.28]$$

Equation 1.27 shows that the incident, the reflected and the diffracted wave vectors are in the same plane (this is the plane depicted in Fig. 1.2). The angles shown in Fig. 1.2 are defined by the following equations which are even more general, since $\vec{k}_t$ and with it $\beta$ may be complex:

$$\begin{aligned} k_x &= k \sin\alpha \\ k_{t,x} &= k_t \sin\beta \\ k_{r,x} &= k_r \sin\alpha_{\mathrm{r}} \end{aligned} \qquad [1.29]$$

Equations 1.25, 1.28 and 1.29 directly yield the law of reflection (eqn 1.30):

$$\alpha = \alpha_{\mathrm{r}} \qquad [1.30]$$

and the law of refraction (eqn 1.31), taking weak damping $(n_{2i} \ll n_{2r})$ into account:

$$\frac{\sin\beta}{\sin\alpha} = \frac{n_1}{n_2} \overset{n_{2i} \ll n_{2r}}{\approx} \frac{n_1}{n_{2r}} \qquad [1.31]$$

*Intensities*

In order to determine the intensities of the reflected and the transmitted waves, the boundary conditions of Table 1.2 have to be used. Again all permeabilities are set to $\mu = 1$, so that the following equations are derived:

$$\left[\epsilon_1\left(\vec{E}_0 + \vec{E}_{0r}\right) - \epsilon_2 \vec{E}_{0t}\right] \cdot \hat{e}_z = 0 \qquad [1.32]$$

$$\left[\vec{k} \times \vec{E}_0 + \vec{k}_r \times \vec{E}_{0r} - \vec{k}_t \times \vec{E}_{0t}\right] \cdot \hat{e}_z = 0 \qquad [1.33]$$

$$\left[\vec{E}_0 + \vec{E}_{0r} - \vec{E}_{0t}\right] \times \hat{e}_z = 0 \qquad [1.34]$$

$$\left[\vec{k} \times \vec{E}_0 + \vec{k}_r \times \vec{E}_{0r} - \vec{k}_t \times \vec{E}_{0t}\right] \times \hat{e}_z = 0 \qquad [1.35]$$

Two orthogonal cases of linear polarisations have to be distinguished, with which any kind of polarisation can be formed. The first case, where $\vec{E}_0$ (and with it also the fields of the transmitted and reflected wave) is parallel to the incident plane, $\vec{E}_0 \cdot \hat{e}_y = 0$, is covered here in detail, whereas for the second polarisation orthogonal to the incident plane $\vec{E}_0 = E_0 \cdot \hat{e}_y$ only the results are presented.

Owing to the fact that all wave vectors as well as all electric field vectors are in the incident plane, which is parallel to the $z$-axis, eqn 1.33 is trivially fulfilled. With the angles defined in eqn 1.29, the remaining equations yield:

$$\epsilon_1(E_0 + E_{0r})\sin\alpha - \epsilon_2 E_{0t} \sin\beta = 0 \qquad [1.36]$$

$$(E_0 - E_{0r})\cos\alpha - E_{0t}\cos\beta = 0 \qquad [1.37]$$

$$\sqrt{\epsilon_1} \cdot (E_0 + E_{0r}) - \sqrt{\epsilon_2} \cdot E_{0t} = 0 \qquad [1.38]$$

Equations 1.38 and 1.36 are equivalent, if the law of refraction (1.31) and $n = \sqrt{\epsilon}$ are taken into account, so that one of them can be neglected. The remaining equations can be solved for $E_{0r}$ and $E_{0t}$, yielding Fresnel's formulas:

$$\frac{E_{0t}}{E_0} = \frac{2\sqrt{\epsilon_1\epsilon_2}\cdot\cos\alpha}{\epsilon_2\cos\alpha + \sqrt{\epsilon_1(\epsilon_2 - \epsilon_1\sin^2\alpha)}} \qquad [1.39a]$$

$$\frac{E_{0r}}{E_0} = -\frac{\epsilon_2\cos\alpha - \sqrt{\epsilon_1(\epsilon_2 - \epsilon_1\sin^2\alpha)}}{\epsilon_2\cos\alpha + \sqrt{\epsilon_1(\epsilon_2 - \epsilon_1\sin^2\alpha)}} \qquad [1.40a]$$

The squared field ratios correspond to the reflection and transmission coefficient, respectively, so that the sum of both equals 1.

If the electric field is orthogonal to the incident plane, a very similar derivation yields the corresponding Fresnel's formulas 1.39b and 1.40b:

$$\frac{E_{0t}}{E_0} = \frac{2\cos\alpha}{\cos\alpha + \sqrt{\frac{\epsilon_2}{\epsilon_1} - \sin^2\alpha}} \qquad [1.39b]$$

$$\frac{E_{0r}}{E_0} = \frac{\cos\alpha - \sqrt{\frac{\epsilon_2}{\epsilon_1} - \sin^2\alpha}}{\cos\alpha + \sqrt{\frac{\epsilon_2}{\epsilon_1} - \sin^2\alpha}} \qquad [1.40b]$$

Both cases are depicted in Fig. 1.3 for the transition from air to a non-absorbing dielectric ($\epsilon_2 = 80$). The case where the electric field is parallel to the incident plane is interesting, since there an angle (the so-called Brewster's angle) exists where $E_{0r} = 0$, so that nothing is reflected.

With this approach, especially that of eqn 1.31, the particular heating of the centre of objects with centimetre dimensions and convex surfaces, like eggs, can

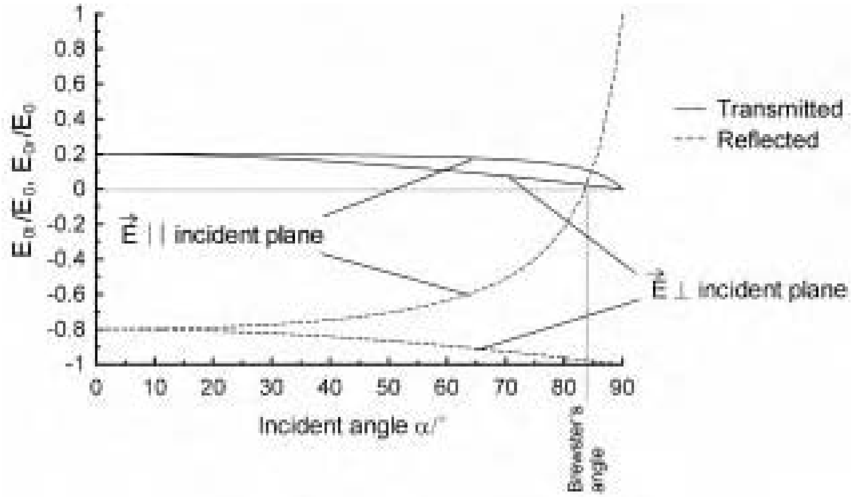

**Fig. 1.3** Reflected and transmitted parts of the electric field of a plane electromagnetic wave hitting a half space of a dielectric ($\epsilon = 80$) with incident angle $\alpha$.

be easily understood, since at the convex surface the microwave 'rays' are refracted and focused to the centre.

For objects that are of the same size as the wavelength or smaller, historically the theory of Mie has been used to determine the microwave absorption, but nowadays direct field modelling by numerical solutions of Maxwell's equations (see Chapter 16) has become more and more important.

In order to calculate temperature changes within an object by microwave heating, it is important to determine the power density, starting from the electromagnetic field configuration. Since normal food substances are not significantly magnetically different from a vacuum ($\mu = 1$), in most cases knowledge of the electric field is enough to calculate the heat production by power dissipation. This power dissipation (per unit volume) $p_V$ is determined by ohmic losses which are calculable by

$$p_V = \frac{1}{2}\Re\left(\vec{E} \cdot \vec{j}^*\right) \qquad [1.41]$$

The current density $\vec{j}$ is determined by the conductivity, and the electric field by eqn 1.8. The equivalence of the imaginary part of the permittivity and the conductivity (eqn 1.16) can also be described as

$$\sigma_{\text{total}} = \sigma + \omega\epsilon_0\epsilon'' \qquad [1.42]$$

The resulting power dissipation can be written in terms of the total conductivity or the total imaginary part of the permittivity, the so-called loss factor:

$$p_V = \frac{1}{2}\sigma_{\text{total}} \cdot |\vec{E}|^2 = \frac{1}{2}\omega\epsilon_0\epsilon_{\text{total}} \cdot |\vec{E}|^2 \qquad [1.43]$$

The dependence on the squared electric field magnitude yields the result that the power dissipation penetration depth $\delta_p$ is only half the value of the electric field penetration depth $\delta_E$ (eqn 1.25):

$$\delta_p = \frac{1}{\omega} \cdot \sqrt{\frac{1}{2\mu_0\mu\epsilon_0\epsilon'\left(\sqrt{\sqrt{1 + \frac{\epsilon''^{*2}}{\epsilon'^2}} - 1}\right)}} \qquad [1.44]$$

## 1.4 Microwave technology

Each microwave system consists normally of three basic parts: the microwave source, the waveguide and the actual applicator. In the following, these parts are described in more detail.

### 1.4.1 Microwave sources: magnetrons

The magnetron tube is by far the most commonly used microwave source for industrial and domestic applications; Metaxas (1996) puts the proportion at 98

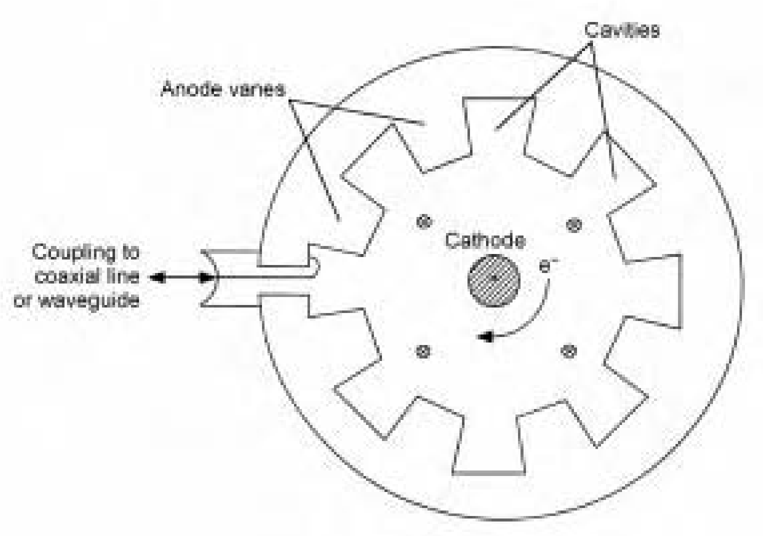

**Fig. 1.4** Schematic view of a magnetron tube (adapted from Regier and Schubert, 2001).

per cent. Therefore, this section is to be limited to the description of a magnetron and only from a phenomenological point of view. More detailed descriptions can be found, for example, in Metaxas and Meredith (1983) and Püschner (1966).

A magnetron consists of a vacuum tube with a central electron-emitting cathode of highly negative potential (see Fig. 1.4). This cathode is surrounded by a structured anode that forms cavities, which are coupled by the fringing fields and have the intended microwave resonant frequency. Owing to the high electric dc field, the emitted electrons are accelerated radially. But since an orthogonal magnetic dc field is applied, they are deflected, yielding a spiral motion. The electric and the magnetic field strength are chosen appropriately, so that the resonant cavities take energy from the electrons. This phenomenon can be compared to the excitation of the resonance by whistling over a bottle. The stored electromagnetic energy can be coupled out by a circular loop antenna in of one of the cavities into a waveguide or a coaxial line.

The power output of a magnetron can be controlled by the tube current or the magnetic field strength. Its maximum power is generally limited by the temperature of the anode, which has to be prevented from melting. Practical limits at 2.45 GHz are approximately 1.5 kW and 25 kW for air- or water-cooled anodes, respectively (Roussy and Pearce, 1995). The 915 MHz magnetrons have larger cavities (lower resonant frequency means larger wavelength) and thus can achieve higher powers per unit. The efficiencies of modern 2.45 GHz magnetrons range around 70 per cent, most being limited by the magnetic flux of the economic ferrite magnets used (Yokoyama and Yamada, 1996), whereas the total efficiency of microwave heating applications is often lower due to unmatched loads.

### 1.4.2 Waveguides

For guiding an electromagnetic wave, transmission lines (e.g. coaxial lines) and waveguides can be used. Owing to lower losses of waveguides at higher frequencies such as those of microwaves, these parts are used for microwave power applications. Principally, waveguides are hollow conductors of normally constant cross-section, rectangular and circular forms being of most practical use. The internal size defines a minimum frequency $f_c$ (the so-called cut-off frequency) by the solution of the wave equations (eqn 1.11 and the corresponding equation for the magnetic field) and appropriate boundary conditions (Table 1.2) below which waves do not propagate. For rectangular waveguides with width $a$ and height $b$ the following equation can be derived for the cut-off frequency $f_c$:

$$f \geq \frac{\sqrt{\left(\frac{m}{a}\right)^2+\left(\frac{n}{b}\right)^2}}{2\sqrt{\mu\mu_0\epsilon\epsilon_0}} \overset{\min}{=} \left\{ \begin{array}{l} \dfrac{1}{2a\sqrt{\mu\mu_0\epsilon\epsilon_0}}, a \geq b \\ \dfrac{1}{2b\sqrt{\mu\mu_0\epsilon\epsilon_0}}, a \leq b \end{array} \right\} = f_c \qquad [1.45]$$

Within the waveguide the wave may spread out in so-called modes, which define the electromagnetic field distribution within the waveguide. These modes can be split into transversal electric (TE) and transversal magnetic (TM) ones, describing the direction of the electric and the magnetic field, respectively, towards the propagation direction. The most common waveguide is of rectangular cross-section with a width $a$ equal to double the height $b$ and is used in TE10 mode, which is depicted in Fig. 1.5.

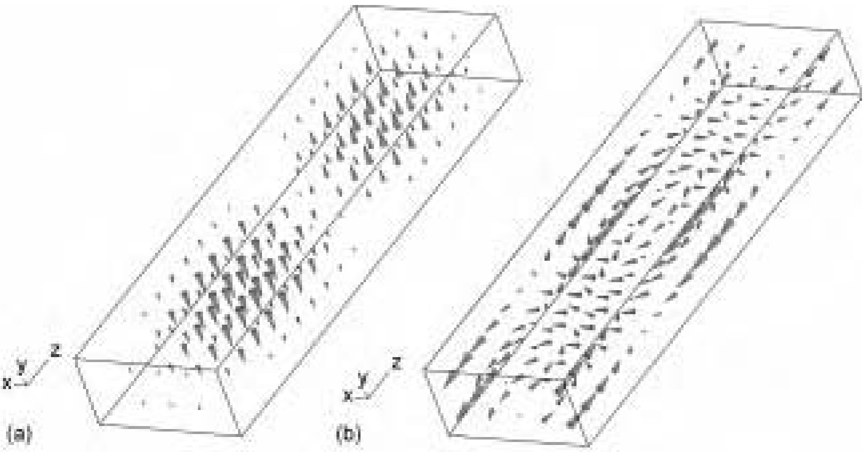

**Fig. 1.5** (a) Electric and (b) magnetic field configurations in a TE10 rectangular waveguide (adapted from Regier and Schubert, 2001).

### 1.4.3 Microwave applicators and tuners

The waveguide can itself be used as the applicator for microwave heating, when the material to be heated is introduced by wall slots and the waveguide is terminated by a matched load (Fig. 1.6). This configuration is called a travelling wave device, since the locations of the field maxima change with time. Radiation through the slots occurs only if wall current lines are cut and the slots exceed a certain dimension, which can be avoided (Roussy and Pearce, 1995).

More common in the food industrial and domestic field are standing wave devices described in the next section, where the microwaves irradiate by slot arrays (that cut wall currents) or horn antennas (specially formed open ends) of waveguides.

For receiving a high power absorption and few back-reflections of microwaves from the applicator to the source, the impedance of the load-containing applicator has to be matched with the corresponding impedance of the source and the waveguide. In order to achieve such a situation, tuners are introduced. Tuners are waveguide components used to match the load impedance to the impedance of the waveguide. Tuners minimise the amount of reflected power, which results in the most efficient coupling of power to the load.

Owing to changing of the load during processes, this matching has to be controlled continuously or optimised for a mean load. The rest of the reflected power has to be prevented from coming back to and overheating the microwave source. Therefore circulators – directionally dependent microwave travelling devices – are used that let the incident wave pass and guide the reflected wave into an additional load (in most cases water). As a side effect, by heating this load the reflected power can also be determined.

Common applicators can be classified by type of field configuration into three types: near-field, single-mode and multi-mode applicators.

*Near-field applicators*

In the case of near-field applicators the microwaves originating from a horn antenna or slot arrays directly 'hit' the product to be heated. The power should

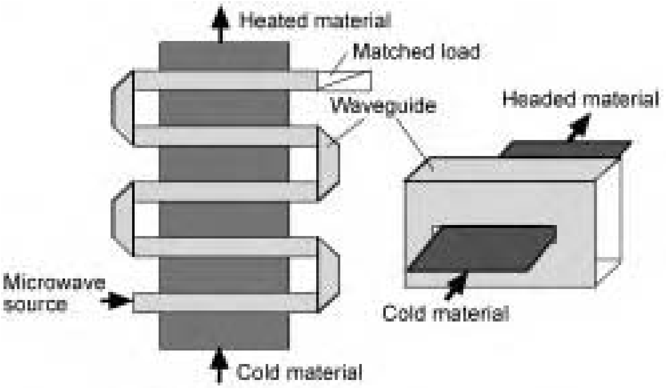

**Fig. 1.6** Example of a travelling wave device (adapted from Roussy and Pearce, 1995).

be set to a level that can be practically completely absorbed by the product, so that only a small proportion of the power is transmitted and transformed into heat in dielectric loads (usually water) behind the product. As in the case of the travelling wave device, in this case standing waves do not exist. Consequently a relatively homogeneous electrical field distribution (depending on the mode irradiated from the waveguide) within a plane orthogonal to the direction of propagation of the wave can be achieved.

*Single-mode applicators*

Near-field applicators as well as travelling wave devices work best with materials with high losses. In order to heat substances with low dielectric losses effectively by microwaves, applicators with resonant modes, which enhance the electric field at certain positions, are better suited. The material to be heated should be located at these positions, where the electric field is concentrated. Single-mode applicators consist generally of one feeding waveguide and a tuning aperture and a relatively small microwave resonator with dimensions in the range of the wavelength. As in the case of dielectric measurements by resonators (Chapter 3), a standing wave (resonance) exists within the cavity at a certain frequency. The standing wave yields a defined electric field pattern, which can then be used to heat the product. It has to be noted that this type of applicator has to be well matched to the load, since the insertion of the dielectric material naturally shifts the resonant modes. An example of such a system is shown in Fig. 1.7, where a cylindrical TM010 field configuration with high electric field strength at the centre is used to heat a cylindrical product that could be transported through tubes (e.g. liquids).

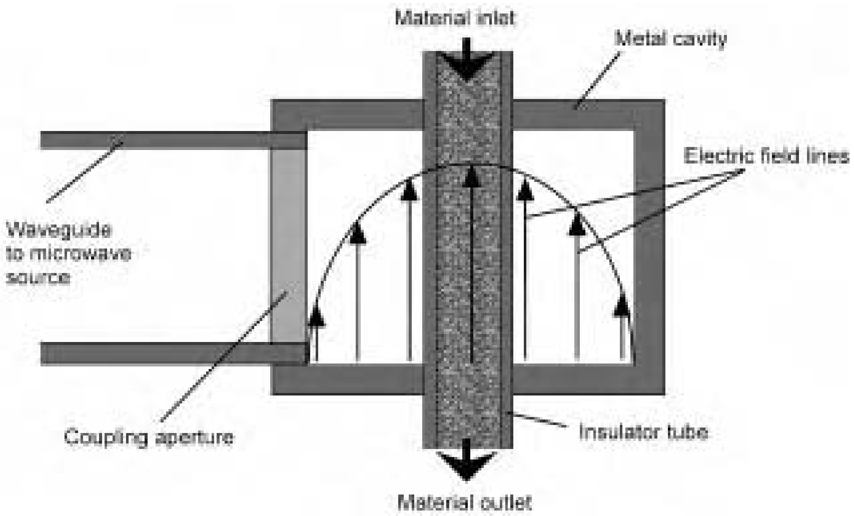

**Fig. 1.7** A TM010 flow applicator schematically, as an example of a single-mode device (adapted from Regier and Schubert, 2001).

The small dimensions of the applicator are necessary in order to avoid different modes from the one used, since the number of modes per frequency range increases very rapidly with the dimensions of the cavity.

### *Multi-mode applicators*

Increasing the dimensions of the cavity causes a fast transition from the single-mode to the multi-mode applicator, owing to the strong increase in mode density with applicator size. Additionally it has to be taken into account that common microwave power generators such as magnetrons do not emit a single frequency but rather a frequency band.

In industrial as well as domestic applications, multi-mode applicators play by far the most important role, since both the majority of conveyor-belt-tunnel applicators and domestic microwave ovens are of the multi-mode type due to their typical dimensions. Despite the high number of stimulated modes, often a non-homogeneous field distribution that is constant in time will develop. This field distribution depends mainly on the cavity, the product geometry and the dielectric properties of the material to be processed. In contrast to single-mode application, normally this inhomogeneous field distribution, which would result in an inhomogeneous heating pattern, is not desired, since it is difficult to control. An undesired inhomogeneous heating pattern can be prevented by changing the field configuration either by varying cavity geometries (e.g. mode stirrer) or by moving the product (on a conveyor belt or turntable); this also influences the field distribution.

Industrial applications mostly need continuous processing due to the high throughputs desired. Therefore continuous microwave applicators have been developed, starting in 1952 with the first conveyor belt oven patent (Spencer, 1952), though because of the lack of high-power microwave generators, their industrial use did not get under way until nearly 10 years later.

Today's industrial ovens (a more complete overview can be found in the corresponding chapters) may be differentiated into two groups by the number and power of microwave sources: high-power single-magnetron and low-power multi-magnetron devices. Whereas for a single-mode unit only a single source is possible, in all other systems (multi-mode, near-field or travelling wave system) the microwave energy can be irradiated optionally by one high-power magnetron or several low-power magnetrons. Whereas common industrial high-power magnetrons have longer operating lifetimes, low-power magnetrons have the advantage of very low prices, due to the high production numbers for the domestic market.

As mentioned above, an important hurdle for all microwave ovens, especially continuous ones, is the avoidance of leakage radiation through the product inlet and outlet. For fluids or granular products with small dimensions (centimetre range), the legislative limits can be guaranteed by the small inlet and outlet sizes together with the absorption in the entering product, sometimes with additional dielectric loads just in front of the openings. In the case of larger product pieces, inlet and outlet gates that completely close the microwave application device

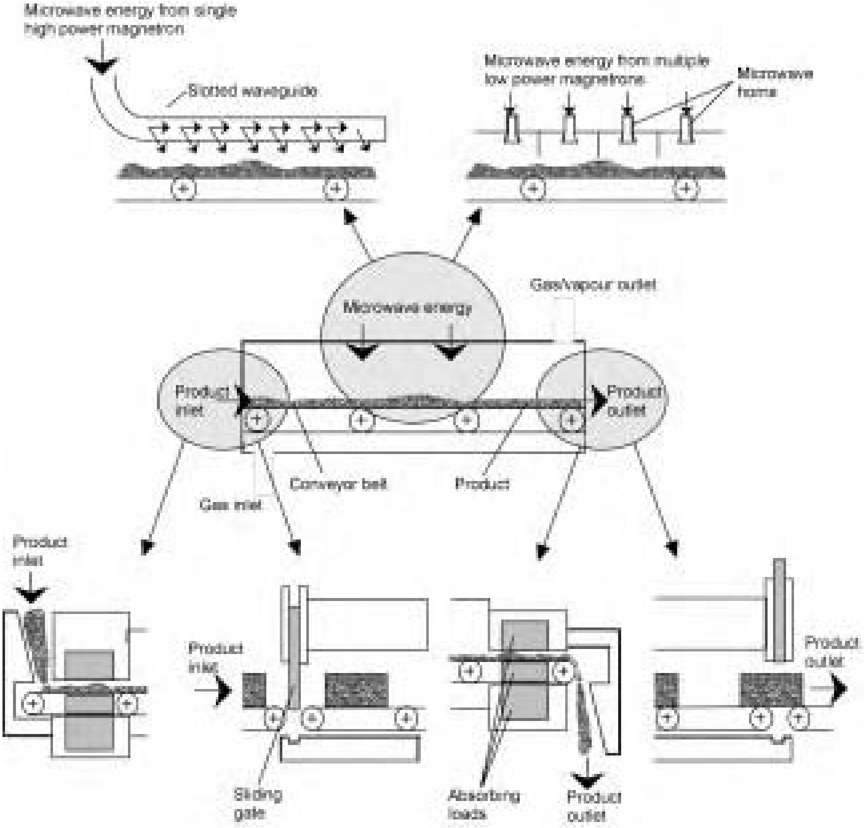

**Fig. 1.8** Continuous conveyor belt device, with different product input and output systems and various microwave energy inputs (adapted from Regier and Schubert, 2001).

have to be used. A conveyor belt oven with its alternative power sources and openings is shown schematically in Fig. 1.8.

## 1.5 Summary

In this chapter microwaves are introduced as electromagnetic waves of frequencies between 300 MHz and 300 GHz. The 'technical' microwaves used for processing are regulated by the ISM bands and by certain maximum emission levels and exposure limits for humans. The chapter then presents some theoretical aspects of the electromagnetic theory, starting from Maxwell's and the constitutive material equations, though the general wave equations to example solutions such as the plane wave, the exponentially damped wave and Fresnel's reflection formulas. Finally, the general setup of microwave processing equipment, consisting of a microwave source (the magnetron), a waveguide and an applicator, is depicted, in which at certain points the different possibilities are classified.

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## 1.7 Appendix: notation

Because they are commonly used in different fields, some of the variable names are ambiguous, but their meaning should become clear in the particular context of the equations.

| | |
|---|---|
| $a$ | width of waveguide |
| $b$ | height of waveguide |
| $\vec{B}$ | magnetic flux density |
| $c$, $c_0$ | velocity of light, in vacuum |
| $\vec{D}$ | electric flux density |
| $\hat{e}_i$ | unit vector in the direction of $i$ |
| $\vec{E}$ | electric field |
| $f$ | frequency, constant |
| $g$ | constant |
| $\vec{H}$ | magnetic field |
| $h$ | constant |
| $h$ | Planck’s constant |
| $i$ | imaginary unit |
| $\vec{j}$ | electric current density |
| $\vec{k}, k$ | wave vector, absolute value |
| $m$ | constant |
| $n$ | refractive index, constant |

| | |
|---|---|
| $\Re(x)$ | real part of $x$ |
| $t$ | time |
| $\vec{x} = (x, y, z)$ | local vector |
| | |
| $\alpha, \alpha_\mathrm{r}$ | angle of incidence, angle of reflection |
| $\beta$ | angle of refraction |
| $\delta_E$ | electric field attenuation length |
| $\delta_p$ | power attenuation length |
| $\epsilon_0$ | dielectric constant of vacuum |
| $\epsilon = \epsilon' - i\epsilon''$ | relative permittivity |
| $\kappa$ | damping constant |
| $\lambda$ | wavelength |
| $\mu$ | relative permeability |
| $\mu_0$ | permeability of vacuum |
| $\rho$ | charge density |
| $\sigma$ | conductivity |
| $\omega$ | circular frequency |

# 2

# Dielectric properties of foods

**J. Tang, Washington State University, USA**

## 2.1 Introduction

The distribution of electromagnetic (EM) energy in radio frequency (RF) and microwave (MW) heating systems is governed by Maxwell's equations with appropriate boundary conditions defined by the configuration of the systems and the interfaces between the treated materials and remaining space. The dielectric properties of the materials are the main property parameters of the Maxwell equations and, therefore, significantly influence the efficiency of EM energy coupled into the materials, EM field distribution, and conversion of EM energy into thermal energy within those materials. From an engineering viewpoint, dielectric properties are the most important physical properties associated with RF and MW heating. It is critical to have knowledge of the dielectric properties of materials in product and process development and, especially, in the modern design of dielectric heating systems to meet desired process requirements. The need for such knowledge becomes even more apparent with the advance of computer modeling tools (Palombizio and Yakovlev, 1999), which are increasingly used in the design of RF and MW application systems and in the development of RF or MW heating processes as a result of sharply increased computation power in affordable personal computers and workstations (Pathak *et al.*, 2003; Chan *et al.*, 2004).

RF frequencies (13.56, 27.12, 40.68 MHz) and MW frequencies (896, 915, 2375 and 2450 MHz) allocated in different countries for industrial, scientific and medical (ISM) uses are in relatively close proximity over the electromagnetic spectrum. Both RF and MW heating are used extensively in industrial food processing applications. To fully understand the influence of various factors on the dielectric properties of foods, it is more appropriate to discuss the dispersion mechanisms over a relatively wide EM spectrum that covers RF and MW frequencies than to focus only on narrow MW frequency bands. Therefore, this chapter discusses the dielectric behaviors of food materials over both RF and MW frequencies, but with more focus on the latter.

## 2.2 Dielectric properties of foods: general characteristics

For further theoretical background the reader is referred to Chapter 1.

The dielectric properties of a material are described by the complex relative permittivity ($\epsilon^*$ relative to that of free space) in the following relationship:

$$\epsilon^* = \epsilon' - j\epsilon'' \qquad [2.1]$$

where $j = \sqrt{-1}$. The real part $\epsilon'$ is the dielectric constant that reflects the ability of the material to store electric energy when in an electromagnetic field; the imaginary part $\epsilon''$ is the dielectric loss factor that influences the conversion of electromagnetic energy into thermal energy. The ratio of the real and imaginary parts of permittivity represents another important parameter, the tangent of loss angle ($\tan \delta_e = \epsilon''/\epsilon'$), which along with the dielectric constant determines the attenuation of microwave power in foods.

When exposed to an EM field, the amount of thermal energy converted in food is proportional to the value of the loss factor $\epsilon''$. The increase in temperature ($\Delta T$), without consideration of heat transfer, can be calculated from (Nelson, 1996):

$$\rho C_p \frac{\Delta T}{\Delta t} = 5.563 \times 10^{-11} f E^2 \epsilon'' \qquad (5.563 * 10^{-11} = 2\pi\epsilon_0) \qquad [2.2]$$

where $C_p$ (J kg$^{-1}$ °C$^{-1}$) is the specific heat of heated material, $\rho$ (kg m$^{-3}$) is the density, $E$ (V m$^{-1}$) is electric field intensity, $f$ (Hz) is frequency, $\Delta t$ (s) is time increment, and $\Delta T$ (°C) is the temperature rise.

As a result of EM energy dispersion, the electric field strength decreases with distance ($z$ in Fig. 2.1) from the entry surface of a large dielectric material (see Chapter 1):

$$E = E_0 \mathrm{e}^{-\alpha z} \qquad [2.3]$$

The degree of decay is determined by the attenuation factor ($\alpha$), which in turn is a function of the dielectric properties of the material (von Hippel, 1954):

$$\alpha = \frac{2\pi}{\lambda_0}\left[\frac{1}{2}\epsilon'\left(\sqrt{1+\left(\frac{\epsilon''}{\epsilon'}\right)^2} - 1\right)\right]^{\frac{1}{2}} \qquad [2.4]$$

where $\lambda_0$ is the free space wavelength and $\lambda_0 = c/f$. $c$ is the speed of light in free space ($c = 3 \times 10^8$ m s$^{-1}$).

According to eqn 2.2, thermal energy converted from EM energy in a material is proportional to the square of the electric field strength. Substituting $E$

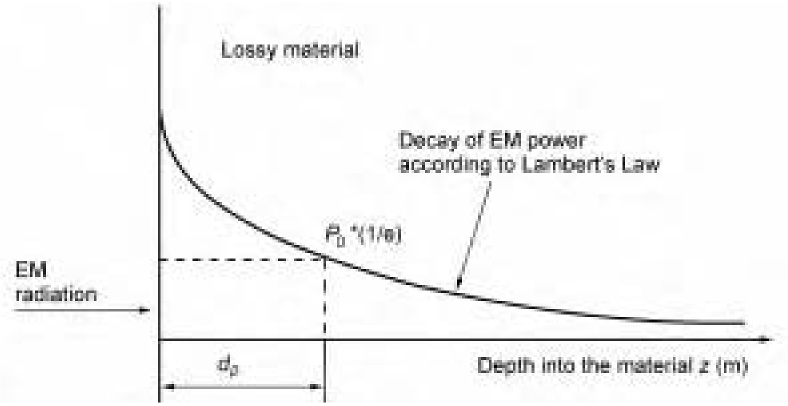

**Fig. 2.1** Typical penetration depth inside a large-sized material.

in eqn 2.3 by power $P$, one obtains:

$$P = P_0 \mathrm{e}^{-2\alpha z} \tag{2.5}$$

The *penetration depth* of microwaves is defined as the depth where the dissipated power is reduced to 1/e (Euler's number e ≈ 2.718) of the power entering the surface (Fig. 2.1). The penetration depth $d_p$ in metres of RF and microwave energy in a food can be calculated by (von Hippel, 1954):

$$d_p = \frac{c}{2\pi f \sqrt{2\epsilon' \left[ 1 + \sqrt{\left( \frac{\epsilon''}{\epsilon'} \right)^2} - 1 \right]}} \tag{2.6}$$

The penetration depth of microwaves into a material is thus inversely proportional to the frequency; that is, shorter-wave EM waves have less penetration than longer waves. In addition, EM waves do not penetrate deeply into moist foods (Metaxas and Meredith, 1983) where both the dielectric constants and loss factors are relatively high. Penetration depth is an important concept that is often used to assess whether an EM field at a certain frequency can provide relatively uniform heating in a given food product.

## 2.3 Factors influencing dielectric properties

The dielectric properties of a given food are affected by many factors, including frequency, temperature, moisture content and other food compositions, in particular salt and fat contents. Mechanisms that contribute to the dielectric loss in biological materials, in general, include polar, electronic, atomic and Maxwell–Wagner responses of those materials in EM fields (Metaxas and Meredith, 1983). In foods, these are reflected in the oscillatory migration of charged ions in free solutions or intact plant or animal issues, rotation of small

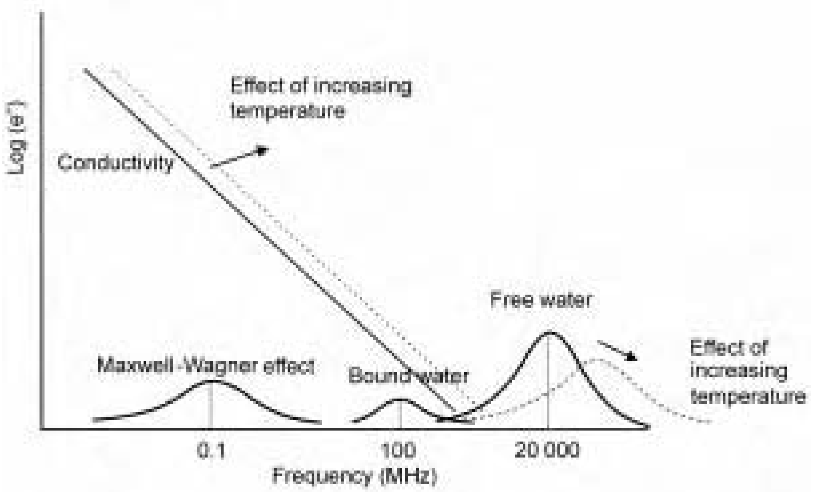

**Fig. 2.2** Contributions of various mechanisms of the loss factor ($\epsilon''$) of moist materials as a function of frequency (*f*) (adapted from Tang *et al.*, 2002). The critical frequencies are not accurate and show only the relative locations of the peaks.

polar molecules such as water and alcohols, and relaxation of protein side chains and bound water over a large range of frequency spectrums from 1 MHz to over 30 000 MHz (Grant *et al.*, 1978). Some of these dispersions are illustrated in Fig. 2.2 (see also Hasted, 1973). The dominant loss mechanisms at RF and microwave frequencies of practical importance to industrial dielectric heating of foods are ionic conduction and dipole rotation (Ryynänen, 1995):

$$\epsilon'' = \epsilon''_d + \epsilon''_\sigma = \epsilon''_d + \frac{\sigma}{\epsilon_0 \omega} \qquad [2.7]$$

where subscripts $d$ and $\sigma$ stand for contributions of dipole rotation and ionic conduction, respectively, $\sigma$ (S m$^{-1}$) is the ionic conductivity, $\omega$ (rad s$^{-1}$) is the angular frequency, and $\epsilon_0$ is the permittivity of free space or vacuum ($8.854 \times 10^{-12}$ F m$^{-1}$).

### 2.3.1 Frequency effects

Figure 2.2 illustrates the contribution of electric conduction and two polarization mechanisms, dipole and Maxwell–Wagner, to the dielectric loss factor of moist foods. Ionic conductivity plays a major role at lower frequencies (e.g., <200 MHz), whereas both ionic conductivity and the dipole rotation of free water are important at microwave frequencies. Maxwell–Wagner polarization arises from charge build-up in the interface between components in heterogeneous systems, such as plant or animal tissues or colloid systems. The Maxwell–Wagner polarization effect peaks at about 0.1 MHz.

For pure liquids with polar molecules, such as alcohols or water, polar dispersion dominates the frequency characteristics of dielectric properties.

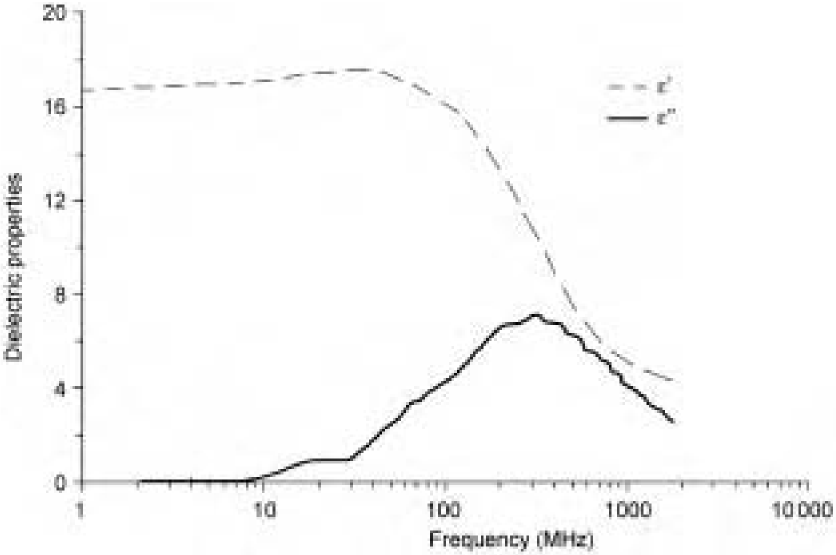

**Fig. 2.3** Dielectric constant ($\epsilon'$) and loss factor ($\epsilon''$) of butyl alcohol at 20 °C (adapted from Wang *et al.*, 2003b).

Figure 2.3 shows the frequency response of the dielectric properties of butyl alcohol ($C_4H_9OH$), where a broad peak in $\epsilon''$ over the frequency spectrum between 10 and 30 000 MHz represents the polar dispersion of the four carbon polar molecules in pure liquid form. The Debye model (1929) can be used to describe the general frequency-dependent behavior of pure liquids:

$$\epsilon^* = \epsilon_\infty + \frac{\epsilon_s - \epsilon_\infty}{1 + \omega^2\tau^2} - j\frac{(\epsilon_s - \epsilon_\infty)\omega\tau}{1 + \omega^2\tau^2} \qquad [2.8]$$

where $\epsilon_\infty$ is relative permittivity when the frequency is infinitely high, $\epsilon_s$ is the static or zero frequency relative to permittivity, and $\tau$ is the relaxation time in seconds. The first two terms in eqn 2.8 represent the dielectric constant; the value of the third term is the loss factor. That is:

$$\epsilon' = \epsilon_\infty + \frac{\epsilon_s - \epsilon_\infty}{1 + \omega^2\tau^2} \qquad [2.9]$$

$$\epsilon'' = \epsilon''_d = \frac{(\epsilon_s - \epsilon_\infty)\omega\tau}{1 + \omega^2\tau^2} \qquad [2.10]$$

The dielectric loss factor $\epsilon''_d$ reaches the maximum at a critical frequency $f_c$ related to the relaxation time $\tau$, where $f_c = 1/2\pi\tau$. Larger molecules in general are less mobile and have longer relaxation times compared to smaller molecules. Critical frequency, therefore, decreases with increasing molecular weight.

Figure 2.4 illustrates the influence of the molecular weight of pure alcohols on the frequency dependence of their dielectric properties. As the molecular weight increases from one-carbon alcohol (methanol, $CH_3OH$) to five-carbon alcohol (pentanol, $C_5H_{11}OH$), the critical frequency decreases from about

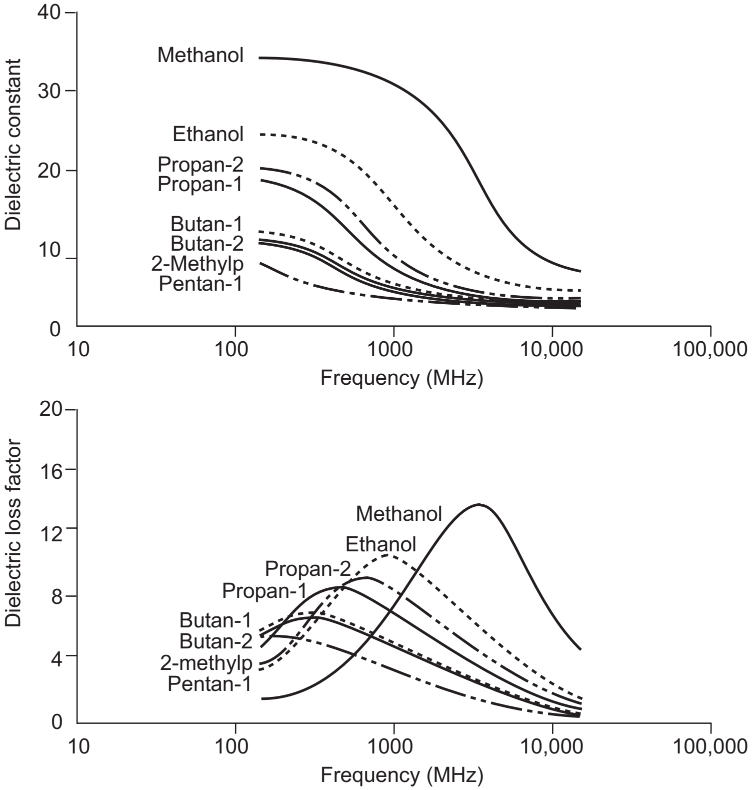

**Fig. 2.4** Influence of molecular weight on the dielectric behaviors of alcohols (adapted from Gabriel *et al.*, 1998).

5000 MHz to about 200 MHz, while the peak of $\epsilon''$ decreases from 14 to about 4. The value of the static dielectric constant $\epsilon_s$ also decreases with increasing molecular weights, mainly as the result of decreased polarity in the large alcohol molecules.

Water molecules are much smaller than those of alcohols. The relaxation time $\tau$ of pure water at 20 ºC is between 0.0071 and 0.001 48 ns, corresponding to a peak in $\epsilon''$ at about 16 000 MHz (Mashimo *et al.*, 1987). Figure 2.5 shows the polar dispersion characteristics of pure water at three temperatures. Compared to alcohols, water has a much larger static dielectric constant $\epsilon_s$ and peak value for the dielectric loss factor $\epsilon''$.

Water in nature and in food systems invariably contains impurities and dissolved ions. Water solutions with charged ions behave very differently from pure water with respect to dielectric characteristics, especially at low frequencies (e.g., <20 000 MHz at room temperature). The deviation of water solutions from pure water depends on the concentration of dissolved ions. Ionic conduction in water solutions containing dissolved ions plays an increasing role in dielectric heating with decreasing frequency, as governed by the second term of

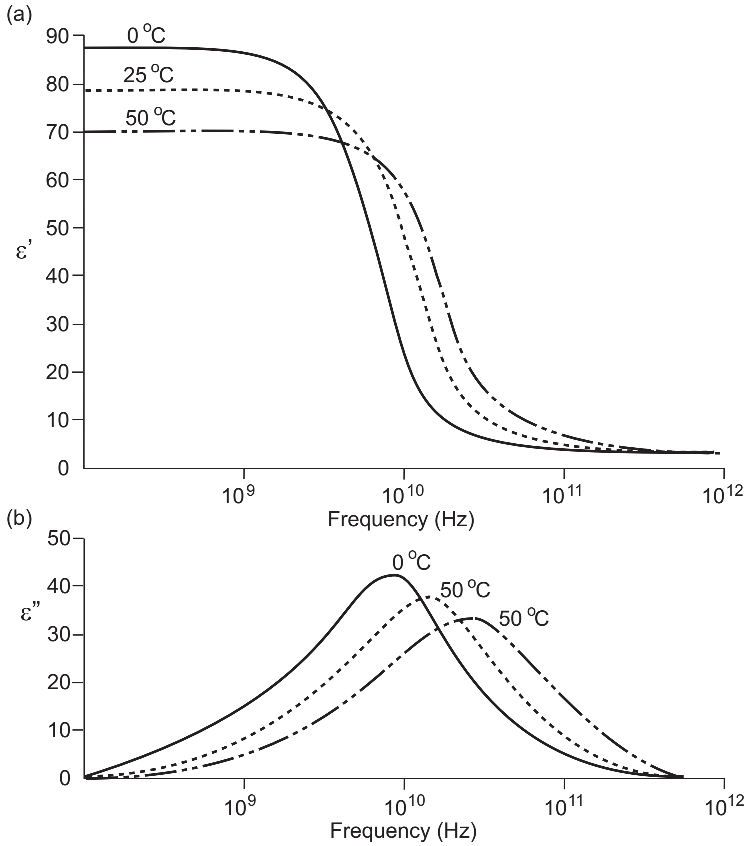

**Fig. 2.5** Effect of temperature on (a) the dielectric constant and (b) the loss factor of free water (adapted from Mudgett, 1985).

eqn 2.7. The combined effect of ionic conduction and dipole dispersion to the loss factor of 0.5 N sodium chloride solutions is illustrated in Fig. 2.6.

Water in various forms is an important constituent of moist foods. The frequency and temperature-dependent dielectric characteristics of pure water and water solutions determine the dielectric characteristics of moist foods. For moist foods with dissolved salt, ionic conduction plays a major role in the lower end of the RF and MW frequency range. This point is illustrated by Guan *et al.* (2004) for mashed potato of different salt contents (Fig. 2.7). In that study, directly measured dielectric loss factor $\epsilon''$ was compared with the calculated loss factor due to ionic conduction, $\epsilon''_\sigma$, using the second term of Eq. 2.7. The electric conductivity $\sigma$ in samples of mashed potato was measured with an electric conductivity meter. It is clear from Fig. 2.7 that at RF frequencies used in industrial heating (i.e., 10–50 MHz), the loss factors of mashed potato are mainly the result of the ionic dispersion and can be estimated directly from the

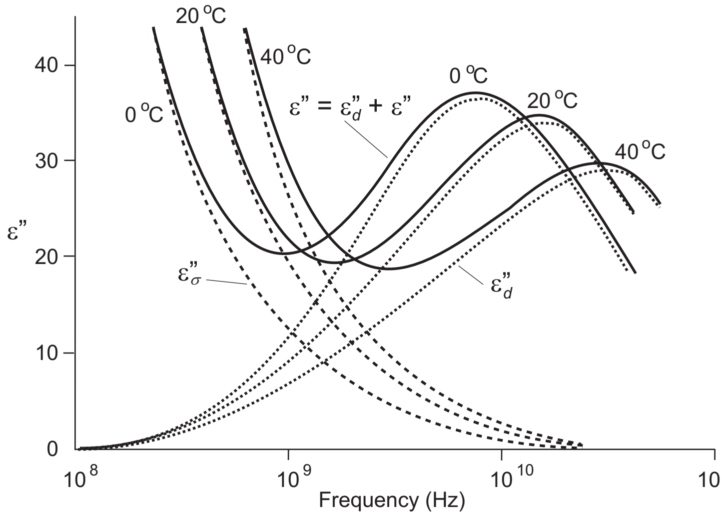

**Fig. 2.6** Effect of temperature on the dielectric loss factor ($\epsilon''$) of 0.5 N aqueous sodium chloride at three temperatures (adapted from Roebuck and Goldblith, 1972).

measurement of electric conductivity. At microwave frequencies of interest to microwave heating (i.e., 400–3000 MHz), the loss factor deviates from the linear log–log curve for $\log(\epsilon''_\sigma) = \log(\sigma/\epsilon_0\omega)$, demonstrating the importance of polar dispersion due to water molecules, especially in foods with little salt (Fig. 2.7).

In low-moisture foods, the relaxation of bound water becomes the major contributor to dielectric heating in the frequency range between 20 and 2000 MHz (see Figs 2.8 and 2.9). Water molecules bound to the polar sides of solid foods in monolayers or multi-layers are less flexible compared to free water, and have much longer relaxation times. For example, the $\epsilon''$ of a monolayer-bound water in lysozyme at room temperature peaked significantly lower than that of free water at 300 MHz. The $\epsilon''$ for the second layer water peaked at about 10 000 MHz (Fig. 2.8) which is close to that of free water (Fig. 2.6).

### 2.3.2 Temperature and salt effects

The influence of temperature on the dielectric properties of foods depends on many factors, including food composition, especially moisture and salt content, and the frequencies in question. In moist foods with little salt, dielectric characteristics are dominated by water at microwave frequencies. For pure liquids with an idealized sphere model for the molecules, the relaxation time $\tau$ in eqns 2.9 and 2.10 can be related to solution viscosity and temperature as the result of Brownian movement (von Hippel, 1954):

$$\tau = V\frac{3\nu}{kT} \qquad [2.11]$$

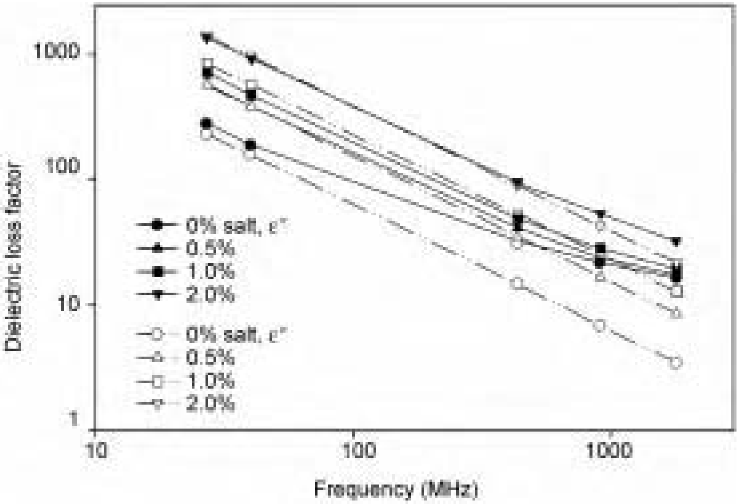

**Fig. 2.7** Measured dielectric loss factor $\epsilon''$ of mashed potato (moisture content 85.9% wet basis, temperature 20 ºC) and calculated loss factor due to ionic conduction, $\epsilon''_\sigma$ (adapted from Guan *et al.*, 2004).

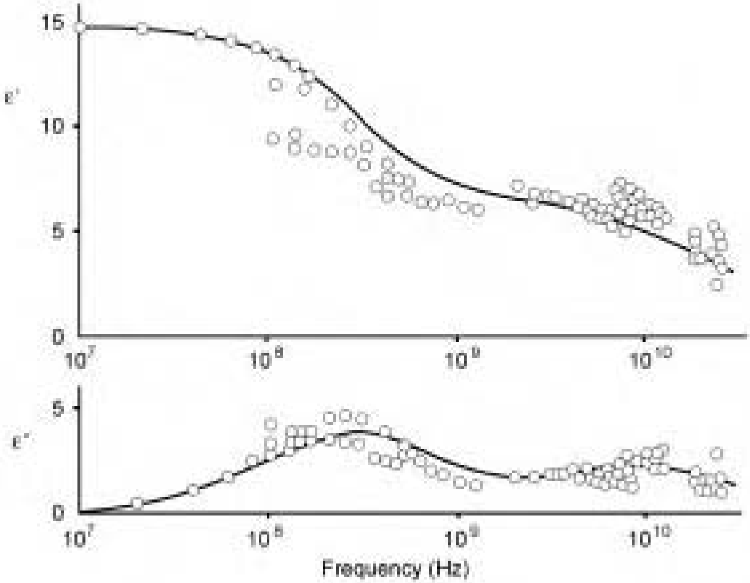

**Fig. 2.8** The dielectric constant ($\epsilon'$) and loss factor ($\epsilon''$) as a function of frequency for packed lysozyme samples containing nearly two layers of bound water at 25 ºC (adapted from Harvey and Hoekstra, 1972).

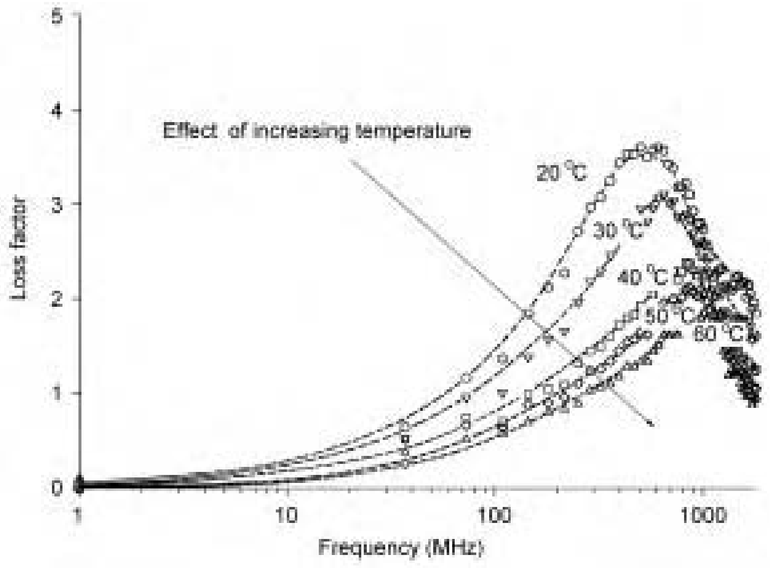

**Fig. 2.9** The dielectric loss factor of walnut kernels at 3% moisture as a function of frequency at five temperatures (adapted from Wang *et al.*, 2003a).

where $\nu$ is the viscosity, $T$ is the absolute temperature, $V$ is the volume of a molecule, and $k$ is the Boltzmann constant. The viscosity of a fluid decreases sharply with increasing temperature according to an Arrhenius approach (Macosko, 1994):

$$\nu = \nu_0 e^{E_a/R_g T} \qquad [2.12]$$

where $E_a$ is the activation energy and $R_g$ is the universal gas constant.

From the above analyses, the relaxation time $\tau$ of a pure liquid decreases sharply with increasing temperature, and the critical frequency ($f_c = 1/2\pi\tau$), which corresponding to the maximum $\epsilon''$, shifts towards the higher frequency region (e.g., in Fig. 2.2). This reduces the value of $\epsilon''$ of the liquid at a fixed frequency in the region lower than $f_c$. The influence of temperature on the dielectric characteristics of pure water is illustrated in Fig. 2.5. The loss factor of pure water at 2450 and 915 MHz (on the left side of the peaks in $\epsilon''$ in Fig. 2.5) decreases as the dispersion peak moves to higher frequencies with increasing temperature

Static dielectric constant reflects a dynamic equilibrium between polarization of molecules under a static electric field and Brownian movement. Increasing temperature results in increased Brownian movement which in turn reduces the static dielectric constant, as shown in Fig. 2.5 for pure water.

The influence of temperature on relaxation time has also been clearly observed in dry nuts with bound water. Figure 2.9 shows the loss factors of a typical dry nut (walnut kernels, 3% moisture content) over the frequency range from 1 to 1800 MHz at five temperatures. The $\epsilon''$ values are less than 1 at frequencies below

100 MHz, while the $\epsilon''$ value peaks in the range between 500 and 1000 MHz. The peak of $\epsilon''$ decreases with increasing temperature as the frequency corresponding to the peak $\epsilon''$ shifts to a higher value. Again, at any selected frequency less than $f_c$, the loss factor of walnut kernels decreases with increasing temperature. That is, for a given EM field intensity, higher-temperature walnuts will absorb less energy than cooler ones, resulting in improved heating uniformity.

The electric conductivity $\sigma$ in ionic solutions increases with temperature because of reduced viscosity (shown in eqn 2.12) and increased mobility of the ions (Trump, 1954; Stogryn, 1971). Thus, based on eqn 2.7, $\epsilon''_\sigma$ also increases with temperature. Figure 2.6 shows the combined contribution of ionic conduction and dipole dispersion of water molecules to the dielectric characteristics of a 0.5N sodium chloride solution as influenced by temperature. Below a frequency band around 2000 MHz, increasing temperature raises the dielectric loss factor of the solution because of the predominant role of ionic conduction at low frequencies. Between 2000 and 10 000 MHz, increasing temperature reduces the solution's dielectric loss factor as the peak of $\epsilon''$ moves towards higher frequency bands. This band of frequency corresponding to the transition (~2000 MHz in the case shown in Fig. 2.6) moves to a higher frequency range for solutions with increasing ionic concentrations.

The temperature and frequency-dependent dielectric characteristics of water solutions are clearly reflected in moist foods. For moist foods with salt, loss factors generally increase with increasing temperatures at RF and lower microwave frequencies, which often results in a phenomenon commonly referred to as 'thermal runaway' (Metaxas and Meredith, 1983). That is, a preferentially heated part of the food in an EM field accelerates its heating, often causing non-uniform heating.

Water molecules in ice are immobilized in well-defined matrices and behave similarly to bound water. Because the dielectric properties of ice are very small (Table 2.1), both the dielectric constant and loss factor of frozen moist foods are relatively low; their values depend, to a large extent, on the amount of water in the unfrozen state and the ionic conductivity of the free water.

Trends in the changes of loss factors for several selected foods as influenced by temperature and food composition at 3000 MHz are shown in Fig. 2.10. All frozen foods have a very low loss factor, but after thawing, the loss factor increases sharply, close to that of free water. The loss factor of distilled water and most moist foods decreases with temperatures at 3000 MHz. However, the loss factor of cooked ham, with high salt content, increases with temperature.

### 2.3.3 Moisture effects

Water in moist foods can be divided into three general categories: (1) free water in intercellular spaces, (2) multilayer water with mobility between free and bound water, and (3) monolayer water tightly bound to the polar sites of solid food components. Free water molecules in intercellular spaces have dielectric properties similar to those of liquid water, whereas bound water exhibits ice-like

**Table 2.1** The dielectric properties and penetration depth of selected foods (Tang *et al.*, 2002, or as indicated otherwise)

| Foods | | 915 MHz | | | 2450 MHz | | |
|---|---|---|---|---|---|---|---|
| | Temp. (°C) | $\epsilon'$ | $\epsilon''$ | $d_p$ (mm) | $\epsilon'$ | $\epsilon''$ | $d_p$ (mm) |
| *Air* | | 1.0 | 0 | | 1.0 | 0 | |
| *Water*: | | | | | | | |
| Distilled/deionized | 20 | 79.5 | 3.8 | 122.4 | 78.2 | 10.3 | 16.8 |
| 0.5% salt | 23 | 77.2 | 20.8 | 22.2 | 75.8 | 15.6 | 10.9 |
| Ice | −12 | — | — | — | 3.2 | 0.003 | 11 615 |
| *Corn oil* | 25 | 2.6 | 0.18 | 467 | 2.5 | 0.14 | 220 |
| *Fresh fruit and vegetables*: | | | | | | | |
| Apples (Red Delicious) | 22 | 60 | 9.5 | 42.6 | 57 | 12 | 12.3 |
| Potato | 25 | 65 | 20 | 21.3 | 54 | 16 | 9.0 |
| Asparagus | 21 | 74 | 21 | 21.5 | 71 | 16 | 10.3 |
| *Dehydrated fruit*[a] | | | | | | | |
| Apples (Red Delicious) | | | | | | | |
| %moisture (wet basis) | | | | | | | |
| 87.5% | 22 | 56.0 | 8.0 | 48.9 | 54.5 | 11.2 | 12.9 |
| 30.3% | 22 | 14.4 | 6.0 | 33.7 | 10.7 | 5.5 | 11.9 |
| 9.2% | 22 | 2.2 | 0.2 | 38.7 | 2.2 | 0.1 | 28.9 |
| 68.7% | 60 | 32.8 | 9.1 | 33.1 | 30.8 | 7.5 | 14.5 |
| 34.6% | 60 | 22.5 | 6.8 | 36.8 | 19.7 | 6.6 | 13.2 |
| 11.0% | 60 | 5.3 | 1.7 | 71.5 | 4.5 | 1.4 | 29.9 |
| *High-protein products*: | | | | | | | |
| Yogurt (pre-mixed) | 22 | 71 | 21 | 21.2 | 68 | 18 | 9.0 |
| Whey protein gel | 22 | 51 | 17 | 22.2 | 40 | 13 | 9.6 |
| Cooked ham[b] | 25 | 61 | 96 | 5.1 | 60 | 42 | 3.8 |
| | 50 | 50 | 140 | 3.7 | 53 | 55 | 2.8 |
| Cooked beef[c] | 25 | 76 | 36 | 13.0 | 72 | 23 | 9.9 |
| | 50 | 72 | 49 | 9.5 | 68 | 25 | 8.9 |

[a] From Feng *et al.* (2002).
[b] From Mudgett (1985).
[c] From Bircan and Barringer (2002).

dielectric properties. Dielectric properties of food, in general, decrease rapidly with decreasing moisture content to a critical moisture level. Below this moisture level, e.g. about 12% for diced apples at 22 °C (Fig. 2.11), the reduction in loss factor is less significant due to the bound water. High temperature can, however, increase the mobility of bound water, reducing this critical moisture level.

Because of the reduced loss factor with decreasing moisture content, dehydrated foods have less ability to convert electromagnetic energy into thermal energy. Conversely, during a microwave drying process, the wet part of the product is able to convert more microwave energy into thermal energy

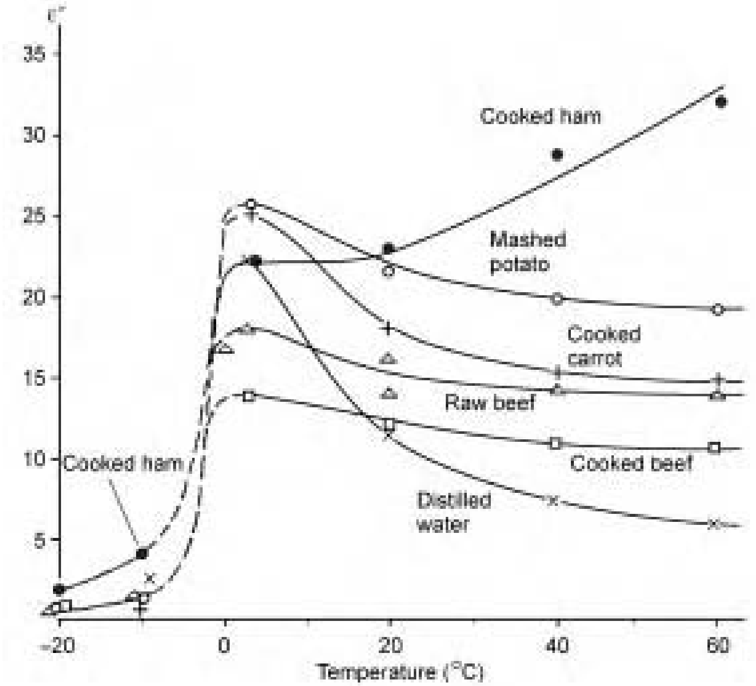

**Fig. 2.10** The dielectric loss factor ($\epsilon''$) of selected foods at 3000 MHz as affected by temperature (Bengtsson and Risman, 1971).

compared to the dry part, which tends to level off the uneven moisture distribution commonly experienced in hot air drying processes where the food particle interior is wetter than the surface. This would also significantly shorten drying time (Feng *et al.*, 2001).

## 2.4 Dielectric properties of selected foods

Table 2.1 lists the dielectric properties of several selected foods to demonstrate possible variations in the values of dielectric constants and loss factors among different groups of foods at two microwave frequencies, 915 MHz, used in North America and most parts of Asia for industrial heating, and 2450 MHz, used in domestic microwave ovens worldwide. The dielectric properties of those foods at 896 MHz (a frequency used in Europe instead of 915 MHz) are not much different from that at 915 MHz and are, therefore, not listed. The penetration depths of microwaves at the 915 MHz and 2450 MHz were calculated from the listed dielectric property data using eqn 2.6.

As shown in Table 2.1, distilled and deionized water has a much smaller dielectric loss factor at 915 MHz than at 2450 MHz, because 2450 MHz is closer to the frequency (~16 000 MHz) corresponding to the relaxation time of water

**Table 2.2** The dielectric properties and penetration depth of two prepared foods (Wang *et al.*, 2003c; Guan *et al.*, 2004)

| Foods | Temp. (°C) | 915 MHz $\epsilon'$ | 915 MHz $\epsilon''$ | 915 MHz $d_p$ (mm) | 2450 MHz $\epsilon'$ | 2450 MHz $\epsilon''$ | 2450 MHz $d_p$ (mm) |
|---|---|---|---|---|---|---|---|
| *Macaroni and cheese* | 20 | 40.2 | 21.3 | 16.0 | 38.8 | 17.4 | 9.7 |
| (60% moisture content,[a] | 40 | 40.9 | 27.3 | 12.8 | 39.3 | 19.0 | 9.0 |
| 0.6% salt) | 60 | 40.0 | 32.9 | 10.7 | 38.5 | 20.9 | 8.1 |
| | 80 | 39.5 | 39.7 | 9.1 | 37.6 | 23.7 | 7.2 |
| | 100 | 40.7 | 48.2 | 7.8 | 37.1 | 27.6 | 6.2 |
| | 121 | 38.9 | 57.4 | 6.7 | 35.6 | 31.9 | 5.4 |
| *Mashed potato* | 20 | 64.1 | 27.1 | 15.7 | 65.8 | 16.3 | 13.3 |
| (85.9% moisture content, | 40 | 65.7 | 22.8 | 18.8 | 63.7 | 14.4 | 14.8 |
| 0.8% salt) | 60 | 62.5 | 25.2 | 16.7 | 60.7 | 14.7 | 14.2 |
| | 80 | 59.9 | 27.6 | 15.0 | 58.0 | 15.4 | 13.2 |
| | 100 | 57.3 | 32.0 | 12.8 | 55.5 | 17.4 | 11.5 |
| | 121 | 54.5 | 38.1 | 10.6 | 52.8 | 20.1 | 9.6 |
| *Mashed potato* | 20 | 55.1 | 28.4 | 14.1 | 53.5 | 19.4 | 10.2 |
| (85.9% moisture, | 40 | 52.8 | 35.6 | 11.2 | 51.7 | 21.5 | 9.0 |
| 1.8% salt) | 60 | 49.4 | 43.4 | 9.1 | 48.3 | 24.7 | 7.7 |
| | 80 | 46.1 | 51.7 | 7.7 | 45.2 | 28.7 | 6.5 |
| | 100 | 46.7 | 69.3 | 6.1 | 46.3 | 37.5 | 5.1 |
| | 121 | 48.7 | 95.2 | 4.8 | 48.8 | 50.7 | 4.0 |

[a] All moisture contents were on a wet basis.

molecules at room temperature (see Fig. 2.5). But after adding 0.5% table salt, the ionic conduction sharply raises the value of the loss factor of water, much more at 915 MHz than at 2450 MHz (Table 2.1). Ice, having a very small loss factor, is almost transparent to microwaves. Oils are esters of long-chain fatty acids which have much less mobility compared to water molecules in response to oscillating electromagnetic fields. The dielectric constant and loss factor of oil are therefore very small compared to free water, as shown by the data for corn oil in Table 2.1.

The loss factor of apples is relatively low compared to potato and asparagus, mainly due to a difference in density (i.e., 0.76 for apple vs. 1.03 for potato, Venkatesh and Raghavan, 2004). The air voids in apples reduce the loss factor and increase the penetration depth of microwaves at 915 MHz and 2450 MHz.

The data for dehydrated apples in Table 2.1 illustrates the significant influence of moisture removal on the reduction in both dielectric constants and loss factors. The influence of temperature difference between 22 and 60 °C on the dielectric properties of dehydrated apples at a given moisture content is not as strong as the moisture content difference between 87.5% and 10%.

Variation in dielectric properties among high protein products can be as large

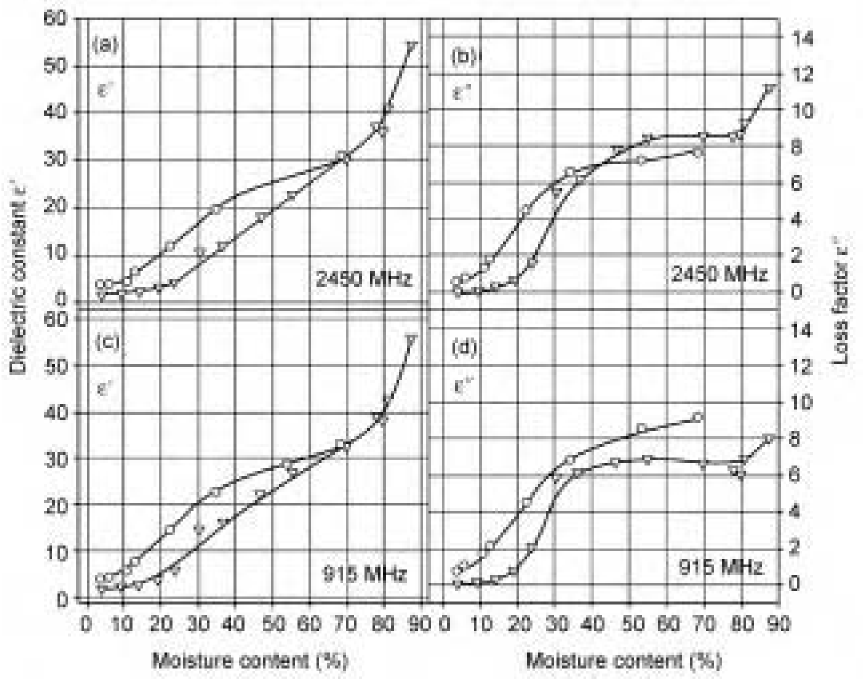

**Fig. 2.11** The dielectric properties of Red Delicious apples at 915 MHz and 2450 MHz as influenced by moisture content on a wet basis (adapted from Feng *et al.*, 2002).

as among other groups of food at 915 MHz and 2450 MHz. The data for cooked ham and beef demonstrate the importance of salt on the dielectric properties of meat products. The loss factor of cooked ham is much larger than that of cooked plain beef. The penetration depth of microwaves at 915 MHz and 2450 MHz in ham is less than 0.5 cm. Penetration depth of microwaves at 2450 MHz should be an important consideration when selecting the size and geometrical requirements of packaging for microwaveable prepared foods.

The influence of temperature and salt on the dielectric properties of two popular foods prepared following standard industrial practices (Guan *et al.*, 2004; Wang *et al.*, 2003c) is illustrated by experimental data in Table 2.2. The dielectric constants and penetration depth of microwaves in these foods decrease, while the loss factors increase, along with increase in temperatures at 915 MHz and 1800 MHz. Adding extra salt (i.e. from 0.8% to 1.8%) to mashed potato sharply reduces microwave penetration depth.

The experimental data listed in Tables 2.1 and 2.2 demonstrate the vast variations in dielectric properties and penetration depths of microwaves in different foods groups, as well as the high sensitivity of those properties to food composition, food structures (e.g., voids), and temperature.

Many attempts have been made to predict the dielectric properties of food systems from composition, temperature and frequency. Calay *et al.* (1995)

developed general polynomial equations to estimate the dielectric properties of grains, fruits and vegetables, and meat products based on moisture, salt, fat content and temperature at microwave frequencies between 900 and 3000 MHz. Equations for more than 50% of food materials have small coefficients of determination ($R^2$ between 0.70 and 0.82). Sun *et al.* (1995) compiled reported dielectric properties for fruits, vegetables, meats and fish with moisture contents greater than 60% an a wet basis (wb) in the frequency range between 2400 and 2500 MHz and at temperatures between 5 and 65 ºC. They used moisture and salt content as the main factors in the respective predictive equations. After fitting those data, they concluded that it was impossible to develop a generic composition-based equation for all food products. Yagmaee and Durance (2002) developed polynomial equations for the dielectric properties of aqueous solutions of NaCl (0 to 6%, w/w), D-sorbitol (0 to 18%, w/w) and sucrose (0 to 60%, w/w) at 21 ºC and 2450 MHz. For simple solutions with a single solute, the equations predicted well, but the effects of different species of solutes in mixed solutions were not additive. Sipahioglu and Barringer (2003) developed predictive equations at 2450 MHz for 15 vegetables and fruits using temperature, moisture and ash contents as dependent variables. They found it difficult to use general equations to predict the dielectric properties of vegetables and fruits as functions of composition and temperature.

In summary, it is generally recognized in the literature that there are difficulties in predicting the dielectric properties of complex food products and that direct dielectric property measurement needs to be made over specific composition, temperature and frequency ranges if accurate data are desired for the specific foods in question (Guan *et al.*, 2004).

## 2.5 Sources of further information and future trends

A large body of literature can be found on the dielectric properties of different materials. Von Hippel (1954) summarized early classic theoretical work on dielectrics and established a solid foundation for future research in this field. Grant and co-authors published a book in 1978 that provided insights into different dispersion mechanisms for biological molecules in solutions exposed to electromagnetic fields. The collected information and discussions presented in the book have advanced the understanding of the dielectric behaviors of food systems and influenced the work of many researchers. Kent (1987) compiled extensive data on the dielectric property of foods and agricultural commodities published up to 1986. Research on dielectric properties of foods and agricultural commodities has been driven mostly by the perceived benefits of microwave energy in various applications, including online measurement of food moisture content for process control (Kraszewski, 1977), microwave drying (Feng *et al.*, 2002), pest control (Nelson, 1996, 2003; Ikediala *et al.*, 2002; Wang *et al.*, 2003a,b), microwave heating and cooking (Bengtsson and Risman, 1971; Roebuck and Goldblith, 1972; Ohlsson *et al.*, 1974; Kent, 1977; Mudgett, 1985;

Ryynänen, 1995) and MW pasteurization and sterilization (Wang *et al.*, 2003c; Sipahioglu *et al.*, 2003; Guan *et al.*, 2004). Dielectric behavior has also been used to study protein denaturation or other changes in processed foods (Bircan and Barringer, 2002). The references listed above represent only a very small portion of the literature on dielectric properties of foods.

Experimental data published before the 1980s were mostly collected in specialized laboratories with strong expertise in electronics and microwave engineering. With available commercial measurement systems, such as Hewlett Packard (HP) (now Agilent Technologies) open-ended coaxial probe systems, many food research laboratories are now able to measure dielectric properties over a large range of frequency and temperature ranges. As a result, we have seen increasing numbers of publications on the dielectric properties of food materials, with more attention paid to the influence of food composition and temperature. However, because of the high sensitivity of dielectric properties to food composition and the large variety of foods, we still do not have adequate information for most microwave applications. Especially rare are the data over a temperature range that covers freezing and sterilization temperatures (e.g., up to 130 ºC), data that truly reflect physiochemical changes during cooking and reheating processes, and data over a wide range of temperature and moisture content experienced in microwave drying. These data are needed to fully understand the interaction between foods and electromagnetic energy and to improve results in computer simulation, product development, and system control of microwave pasteurization, sterilization, cooking, reheating and drying processes.

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# 3

# Measuring dielectric properties of foods

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## 3.1 Introduction

In the literature many different methods for the measurement of dielectric properties can be found, depending on the frequency range of interest and the values of the dielectric properties. In the microwave frequency range, most of the methods were originally developed for materials that are used in high-frequency and radio-frequency telecommunication devices. Thus, the majority of these techniques aim for materials with low losses in contrast to most (wet) food substances.

The principles of the determination of microwave dielectric properties were reviewed in Kaatze and Giese (1980), Engelder and Buffler (1991) and Rost (1978). This chapter presents an overview of the most common measurement techniques for dielectric properties of foods in the microwave frequency range. After the classification and description of the different methods on a phenomenological level, further analysis techniques, yielding more information on unknown dielectric properties, are presented. Summarising the main advantages and disadvantages should help to choose the best technique for the material and frequency range of interest.

In general, the measurement techniques can be divided into time domain and frequency domain methods; for food substances the frequency domain methods are more common and exact, due also to the availability of modern network analysers. Therefore, in this chapter only the frequency domain methods are presented.

The classification continues by differentiating between measurements in open and closed structures. Whereas for closed systems, one has to distinguish between transmission lines and resonators (which can be subdivided into completely filled and partially filled resonators), the common distinction in open-structure measurements is between open-ended probes and real free-space techniques.

## 3.2 Measurement techniques: closed structures

Closed systems mean that the electromagnetic waves are restricted in a confined space by metallic walls.

### 3.2.1 Transmission lines

As transmission lines, both coaxial lines as well as simple waveguides (commonly in rectangular or circular geometry) can be used. In order to measure dielectric properties within such transmission lines, the transmission line first has to be characterised without the material to be measured. After introducing the material, the measurement of the standing wave ratio (SWR) or of the reflection or transmission coefficients by network analysers (with wide frequency ranges) can yield the unknown dielectric properties of the material. Reflected waves are more commonly detected than transmission. In the case of SWR measurements, the shift of nodal positions of the developed standing wave and the node width related to SWRs, the sample and waveguide dimensions as well as the incident field mode are used by available computer programs (Nelson *et al.*, 1974) to determine the dielectric properties.

For these reflection measurements, two types of transmission line ends have been used: either a fixed shortening end, where the sample is placed directly, or a sliding short-circuit plunger. Examples of both types are shown in Fig. 3.1. The basics of the measurement were illustrated by Roberts and von Hippel (1946) and generalised and improved by Nelson *et al.* (1974) and Roussy *et al.* (1990).

In all cases, the material to be measured has to be geometrically well defined and fit exactly into the prepared sample places, in order to minimise errors that occur due to air gaps or twists. Additionally, there is a limit on the maximum permittivity of the material to be determined, in order to prevent the waveguide from containing field modes different from the one desired. Although special calibration methods to eliminate errors caused by unknown reflections in the waveguide exist, the above prerequisites often prevent these techniques from being used for food materials (Engelder and Buffler, 1991). Nevertheless, various successful measurements have been done on bulk cereals, seeds and powdered or pulverised materials, for example (Nelson, 1972, 1983; Nelson and You, 1989; You and Nelson, 1988).

### 3.2.2 Cavity resonators

Whereas in transmission lines, it is advantageous to measure materials with high losses, materials with low losses require a different measuring method, since

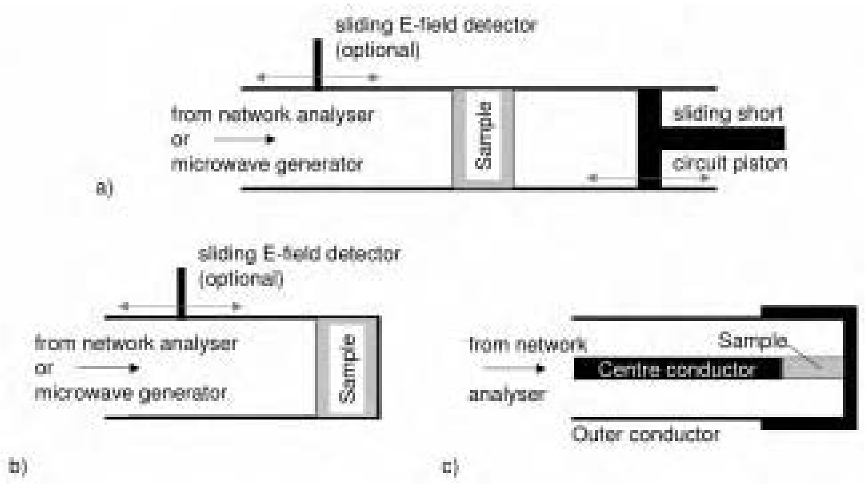

**Fig. 3.1** Various forms of transmission line for the determination of dielectric: (a) waveguide with sliding shortening; (b) waveguide (sample at shortened end); (c) coaxial line shortened (adapted from Roussy and Pearce, 1995).

attenuation by these materials is often too weak for exact permittivity calculations. Therefore cavity resonators are used instead. These are able to amplify the electric field (in certain regions) by the quality factor *Q* and thus the interaction of the electric field with the material characterised by the dielectric properties.

A resonator is a cavity enclosed by conducting (metallic) walls, in which electromagnetic standing waves can be excited by an oscillating coupling device. Common resonators for dielectric measurements are cuboid or circular cylinders, since for these geometries analytical solutions can be found for the standing waves based on Maxwell's equations with boundary conditions (for example, no electric field component parallel to conducting walls may exist). As in the case of measurements using transmission lines, for resonators only measurements at discrete, fixed (resonant) frequencies have to be performed. If measurements at different frequencies should be performed, either another resonant mode or even another resonator with varied geometrical dimensions must be chosen. Since the dielectric properties are actually determined by changing the resonance (resonant frequency and quality factor), the measurement frequency is even dependent on the material (see Fig. 3.2).

Thus, in order to determine the dielectric properties the resonant curve, which means the reflection or transmission coefficient of the resonator over the frequency, has to be determined. For this task network analysers can be effectively used, as sources of electromagnetic waves of defined frequency and as detectors of the reflections. One can distinguish between completely filled and partially filled resonators, depending on how much space is occupied by the dielectric material. Whereas for completely filled resonators cuboid and circular cylindrical resonators are common in the dielectric measurement of foods, in the

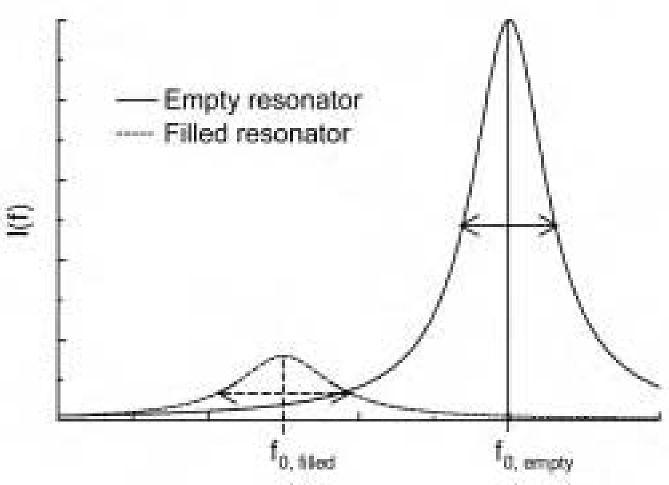

**Fig. 3.2** Resonant frequency $f_0$ shift, and broadening of the resonant curve of a resonator due to a dielectric filling. The arrows show the free width at half maximum $\Delta f_{1/2}$.

case of partially filled resonators the circular cylindrical form is preferred (Risman and Bengtsson, 1971; Bengtsson and Risman, 1971; Persch, 1997; Gallone *et al.*, 1996). For both types of cavities, two types of measurement are possible:

- An absolute measurement, which means that the dielectric properties are derived from a theoretical solution of the resonance in the cavity, by an (approximate) solution of Maxwell's equations
- A measurement by calibration, where at first the reactions (of frequency and quality factor) of the resonance on insertion of materials with known dielectrics are studied, yielding calibration curves, before inserting the material with the unknown properties.

As will be shown later, for completely filled cavities it is relatively simple to derive the descriptive theoretical formulas, so that the absolute measurement method is preferred. In partially filled resonators, this derivation is only possible for simple geometries where symmetries can be utilised: see subsection below on partially filled resonators, or Regier and Schubert (2000). Derivation of the formulas is at least much more complex, so that often the calibration method is used.

### *Completely filled resonators*

If both the real and the imaginary part of the dielectric properties to be measured are rather small, completely filled resonators are the most advantageous, since then the interaction between the electric field and the material and thus the sensitivity is maximised. Another strength of this form of resonator is its ease of construction and of the theoretical description of the resonance and thus its analysis yielding the dielectric properties.

The derivation of the resonance formulas is given in detail for the simplest case of a cuboid cavity resonator, in order to show the principle. As shown in Chapter 1, the wave equations (3.1, 3.2) for the electric and the magnetic field can be derived starting from Maxwell's equations:

$$\left(\Delta - \frac{1}{\mu\mu_0\epsilon\epsilon_0} \cdot \frac{\partial^2}{\partial t^2}\right)\vec{E}(\vec{r}, t) = 0 \qquad [3.1]$$

$$\left(\Delta - \frac{1}{\mu\mu_0\epsilon\epsilon_0} \cdot \frac{\partial^2}{\partial t^2}\right)\vec{B}(\vec{r}, t) = 0 \qquad [3.2]$$

Additionally, a dependence of the magnetic on the electric field and vice versa exists by Maxwell's equations (see Chapter 1, eqn 1.3 or Table 1.1). In the case of an enclosed metallic cavity, the boundary conditions of Table 1.2 are valid, so at the metallic boundaries no parallel component of the electric field and no orthogonal component of the magnetic flux may exist (3.3, 3.4):

$$\vec{E}_{\parallel} = 0 \qquad \text{at metallic walls} \qquad [3.3]$$

$$\vec{B}_{\perp} = 0 \qquad \text{at metallic walls} \qquad [3.4]$$

For the solution, we take the $x$-component of the electric field $E_x$ and use a separation approach:

$$E_x = f(x) \cdot g(y) \cdot h(z) \cdot \mathrm{e}^{-\mathrm{i}\omega t} \qquad [3.5]$$

where a time-harmonic behaviour is suggested (and only the real part of the solution is physically relevant). With this approach, the wave equation (3.1) yields:

$$f''(x)g(y)h(z)\mathrm{e}^{-\mathrm{i}\omega t} + f(x)g''(y)h(z)\mathrm{e}^{-\mathrm{i}\omega t} + f(x)g(y)h''(z)\mathrm{e}^{-\mathrm{i}\omega t} + \frac{\omega^2}{\mu\mu_0\epsilon\epsilon_0} f(x)g(y)h(z)\mathrm{e}^{-\mathrm{i}\omega t} = 0 \qquad [3.6]$$

$$\Rightarrow \frac{f''(x)}{f(x)} + \frac{g''(y)}{g(y)} + \frac{h''(z)}{h(z)} + \frac{\omega^2}{\mu\mu_0\epsilon\epsilon_0} = 0$$

Since every part of the sum is dependent on only one variable and the equation is valid for all combinations, these parts have to be equal to constants $\frac{f''}{f} = -k_x^2$, $\frac{g''}{g} = -k_y^2$, $\frac{h''}{h} = -k_z^2$, whereby:

$$-k_x^2 - k_y^2 - k_z^2 + \frac{\omega^2}{\mu\mu_0\epsilon\epsilon_0} = 0 \qquad [3.7]$$

Again a harmonic approach can be chosen:

$$\begin{aligned} f(x) &= \sin(k_x x + \varphi_x) \\ g(y) &= \sin(k_y y + \varphi_y) \\ h(z) &= \sin(k_z z + \varphi_z) \end{aligned} \qquad [3.8]$$

so that the general solution can be written as:

$$E_x(x,y,z,t) = A_x \sin(k_x x + \varphi_x) \sin(k_y y + \varphi_y) \sin(k_z z + \varphi_z) \mathrm{e}^{-\mathrm{i}\omega t} \qquad [3.9]$$

This solution can be easily generalised to $E_y$ and $E_z$ and has to fulfil the boundary conditions (3.3) and (3.4). In the case of a cuboid cavity bordered by metallic walls at $x = 0$ as well as $x = L_x$, $y = 0$ as well as $y = L_y$ and $z = 0$ as well as $z = L_z$, $E_x$ is parallel to the walls at $y = 0$, $y = L_y$, $z = 0$ and $z = L_z$, where $E_x$ has to vanish: $E_x = 0$. This means that the corresponding phase factors diminish: $\varphi_y = 0 = \varphi_z$, and the corresponding wave numbers have to satisfy eqn 3.10, with $m$ and $n$ natural numbers:

$$\begin{aligned} k_y &= \frac{m\pi}{L_y} \\ k_z &= \frac{n\pi}{L_z} \end{aligned} \qquad [3.10]$$

For the $y$- and $z$-components of the electric field, very similar equations but with generally different numbers $l$, $l'$, $m'$ and $n'$ (all natural numbers) and frequencies $(\omega', \omega'')$ are valid. Only the coupling by Maxwell's and the constitutive equations 1.2 and 1.6 yield the equality of $l = l'$, $m = m'$, $n = n'$ and $\omega = \omega' = \omega''$:

$$\begin{aligned} E_x &= A_x \cos\left(\frac{l\pi}{L_x} \cdot x\right) \sin\left(\frac{m\pi}{L_y} \cdot y\right) \sin\left(\frac{n\pi}{L_z} \cdot z\right) \mathrm{e}^{-\mathrm{i}\omega t} \\ E_y &= A_y \sin\left(\frac{l\pi}{L_x} \cdot x\right) \cos\left(\frac{m\pi}{L_y} \cdot y\right) \sin\left(\frac{n\pi}{L_z} \cdot z\right) \mathrm{e}^{-\mathrm{i}\omega t} \\ E_z &= A_z \sin\left(\frac{l\pi}{L_x} \cdot x\right) \sin\left(\frac{m\pi}{L_y} \cdot y\right) \cos\left(\frac{n\pi}{L_z} \cdot z\right) \mathrm{e}^{-\mathrm{i}\omega t}, \qquad l, m, n \in N_0 \end{aligned} \qquad [3.11]$$

and the coupling of the amplitudes $A_x$, $A_y$, $A_z$, so that only two of them are independent. The corresponding magnetic fields, which also satisfy the boundary conditions, can be determined by Maxwell's equations of Table 1.1. By adapting eqn 3.7 the so-called resonant frequencies $\omega$ or $f$ can be calculated by eqn 3.12a:

$$f_{lmn} = \frac{\omega_{lmn}}{2\pi} = \frac{\sqrt{\mu\mu_0\epsilon\epsilon_0}}{2} \sqrt{\frac{l^2}{L_x^2} + \frac{m^2}{L_y^2} + \frac{n^2}{L_z^2}} \qquad [3.12a]$$

The numbers $l$, $m$ and $n$ describe the resonant or eigenmode in which the resonator is applied. Thus, $l$, $m$ and $n$ are the numbers of local maxima of the electric field observed along the $x$-, $y$- and $z$-axis, respectively.

Conversely, eqn 3.12a shows that the dielectric filling of a resonator with known dimensions and applied mode changes the resonant frequency and thus the dielectric constant can be determined:

$$\epsilon = \frac{4f_{lmn}^2}{\mu\mu_0\epsilon_0\sqrt{\frac{l^2}{L_x^2}+\frac{m^2}{L_y^2}+\frac{n^2}{L_z^2}}} \qquad [3.13]$$

Whereas in cuboid resonators no special axis can be generally distinguished, in the case of circular cylindrical cavities this role is occupied by the cylinder axis. Thus, transversal electric (TE) and transversal magnetic (TM) modes, where no electric or no magnetic field component parallel to the cylinder axis exists, can be distinguished.

Similar derivations for circular cylindrical cavities with radius $R$ and height $L_z$ yield:

$$f_{lmn}^{TE} = \frac{\omega_{lmn}}{2\pi} = \frac{\sqrt{\mu\mu_0\epsilon\epsilon_0}}{2}\sqrt{\left(\frac{\alpha_{lm}}{\pi R}\right)^2+\frac{n^2}{L_z^2}} \quad \text{for TE modes} \qquad [3.12b]$$

$$f_{lmn}^{TM} = \frac{\omega_{lmn}}{2\pi} = \frac{\sqrt{\mu\mu_0\epsilon\epsilon_0}}{2}\sqrt{\left(\frac{\alpha_{lm}}{\pi R}\right)^2+\frac{n^2}{L_z^2}} \quad \text{for TM modes} \qquad [3.12c]$$

Due to the cylindrical symmetry, Bessel functions are needed as field solutions, and the *m*th zeros of the Bessel function of order l, $\alpha_{lm}$, and of its first derivative, $\alpha'_{lm}$, play a role in the resonant frequency.

For practical purposes, only modes with very low mode numbers *l*, *m* and *n* are chosen, since the mode density (the number of modes per frequency interval) strongly increases with these numbers and thus ambiguities and even degenerations are more prominent.

Considering the dielectric losses, the resonant curve is not only one peak at one discrete resonant frequency, but a resonant curve with a finite line width (or a finite quality factor). This resonant curve can be described by a quadratic Lorentzian line (eqn 3.14) (see Fig. 3.3):

$$I(f) \propto \frac{f_0^2}{(f-f_0)^2+\left(\frac{f_0}{2Q}\right)^2} \qquad [3.14]$$

with $f_0$ the resonant frequency and $Q$ the quality factor. This means that the intensity at the resonant frequency is scaled by a factor $Q^2$.

If $\Delta f_{1/2}$ means the full width at half maximum, the quality factor can be derived as:

$$Q = \frac{f_0}{\Delta f_{1/2}} \qquad [3.15]$$

Nevertheless, experimentally a fit of a (modified) Lorentzian line to the measured resonant curve gives more reliable results than only taking the two parameters' resonant frequency and full width at half maximum. By introducing dielectric losses the quality factor of the resonator can be calculated (Metaxas and Meredith, 1983) by:

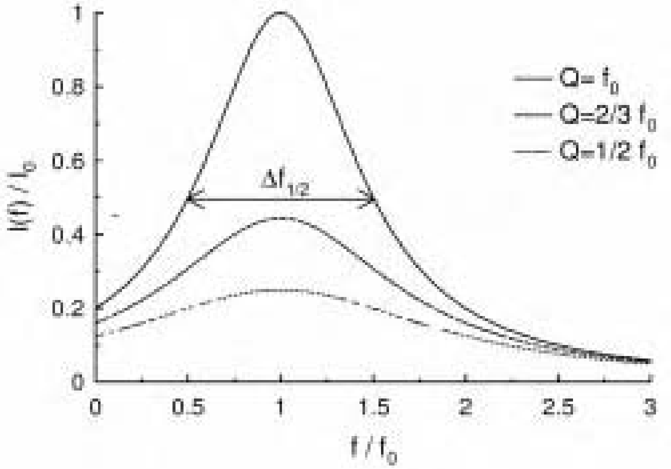

**Fig. 3.3** Quadratic Lorentzian curves with quality factor as parameter.

$$Q_{\text{loss}} = \frac{\epsilon'}{\epsilon''} + \frac{\iiint_{V_{\text{empty}}} |\vec{E}|^2 \, \mathrm{d}V}{\iiint_{V_{\text{filled}}} |\vec{E}|^2 \, \mathrm{d}V} \overset{\text{completely}}{=} \frac{\epsilon'}{\epsilon''} \qquad [3.16]$$

In the case of a completely filled cavity the integral in the numerator vanishes and the equation becomes very easy. As well as the losses in the dielectric material, broadening the resonance, losses in the non-ideally conducting cavity walls, which are also present in the empty cavity (and which are assumed to stay nearly unchanged for one mode), have to be taken into account by an empty quality factor empty $Q_{\text{empty}}$. Thus, the measured quality factor $Q$ is determined by:

$$\frac{1}{Q} = \frac{1}{Q_{\text{empty}}} + \frac{1}{Q_{\text{loss}}} = \frac{1}{Q_{\text{empty}}} + \frac{\epsilon''}{\epsilon'} \qquad [3.17]$$

Accordingly, the dielectric loss factor can be calculated from eqn 3.18:

$$\epsilon'' = \epsilon' \left( \frac{1}{Q} - \frac{1}{Q_{\text{empty}}} \right) \qquad [3.18]$$

Thus measuring the quality factor of the empty and the filled resonator yields the dielectric loss factor, assuming the real part has been determined earlier by the line shift (eqn 3.13).

Although the governing equations 3.12 and 3.18 are relatively simple for this kind of completely filled resonator, also in this case calibration methods have often been used (Risman and Bengtsson, 1971).

In the following section some governing equations for special (simple geometric) partially filled cavities are presented as well as other geometries discussed in the literature in which exclusively calibration methods are common.

*Partially filled resonators*

The solution of Maxwell's equations or the following wave equations for partially filled cavities starts in a very similar way to the completely filled case. The only difference is to include the boundary conditions at the interfaces between the dielectric filling and the empty space. Analytically, this can only be covered for simple geometries or symmetries, nevertheless yielding complicated equations. For cuboid cavities, this means that the dielectric material has to be located directly in front of one metallic wall, whereas for the cylindrical geometry concentric dielectric fillings are appropriate (see Fig. 3.4). The following argument is restricted to the latter cases, which are much more common in practice.

For the concentric circular cylinder geometry the governing equations can be found in Metaxas (1974, 1996) for TM010 mode, and in Regier and Schubert (2000) and Regier (2003) for TE011 mode. In both cases, TM010 and TE011, a completely closed analytical expression for $\epsilon'$ cannot be derived, but the numerical solution is an easy task.

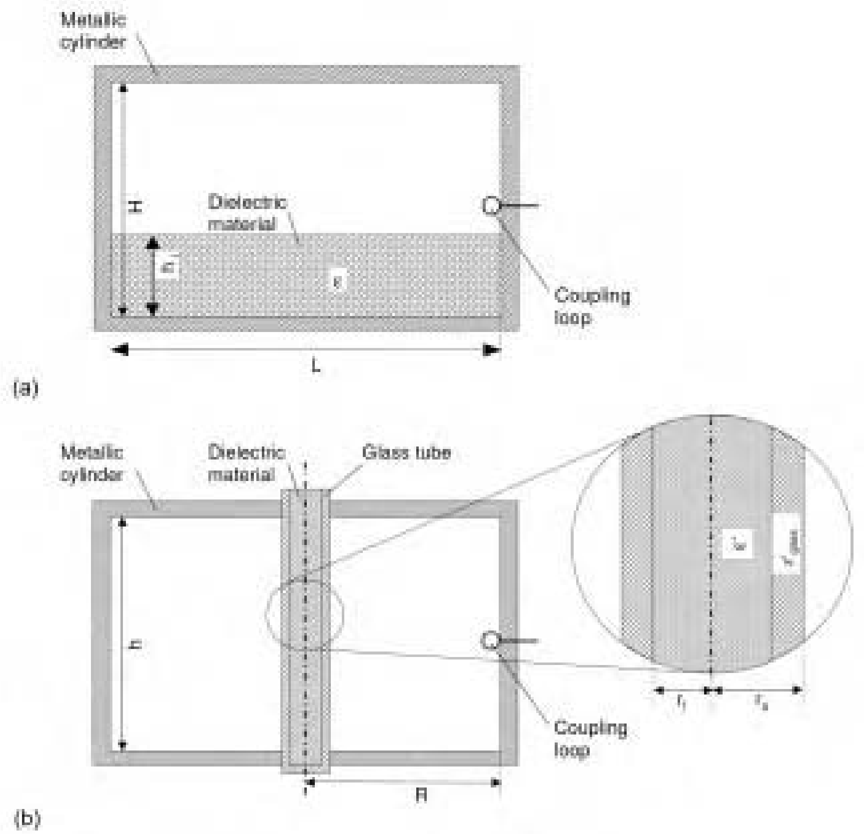

**Fig. 3.4** Typical geometries for the determination of dielectric properties in partially filled cavities: (a) cuboid geometry; (b) concentric cylinder geometry.

The disadvantage of the TM010 mode is its maximum electric field value at the cylinder axis, just where the dielectric sample has to be placed. On the one hand, this yields a strong interaction, even with low loss and low dielectric constant materials, allowing accurate measurements on these materials. On the other hand, the strong decrease of the resonant frequency may move it outside the frequency range of interest. Besides, even for moderately lossy materials, the strong damping necessitates very small sample tubes, down to a diameter of 0.6 mm (Metaxas and Meredith, 1983), which are not well suited for often heterogeneous food materials such as emulsions or granules.

Thus, for materials with higher dielectric constants and losses the cylindrical cavity in TE011 mode with central dielectric filling is much better suited. For TE011 the electric field minimum is just at the centre axis (Regier and Schubert, 2000), so that the dielectric field interaction is strongly reduced. Therefore the resonant frequency (the frequency where the measurement takes place) of the filled resonator is changed only marginally, but strongly enough for the accurate determination of the dielectric constant; the damping by dielectric losses is also analysable, though moderate. This makes it possible to use glass tubes of larger radii than in TM010 mode, so that also more heterogeneous materials, such as powders or granules are characterisable.

## 3.3 Measurement techniques: open structures

In contrast to the closed structures explained above, the open structure techniques have the advantage of covering not only discrete frequencies but of characterising the material over a large frequency range. This is due to the fact that in open structures with negligible multiple reflections, no characteristic modes for wave propagation exist and therefore wave propagation, transmission and reflection are possible at (more or less) every frequency.

### 3.3.1 Free-space techniques

Although free-space systems with open structures have some advantages in terms of the possible geometry, heterogeneity of samples and contactless measurements, in most cases free-space techniques are not often preferred for food substances, unlike the characterisation of ceramic composite materials (Maurens *et al.*, 1992; Musil and Zacek, 1986). This is due to the fact that high microwave power (to be prevented for measurements) would be necessary owing to generally high dielectric losses within the food. Nevertheless in some cases free-space techniques have been used, especially at high frequencies above 4 GHz (Kraszewski and Nelson, 1990).

Common to all free-space techniques is the position of the unknown sample between the transmitting and receiving antennas. Similar to the waveguide techniques, the complex permittivity is determined from amplitude and phase variations of (mostly) plane waves transmitted through or reflected by the sample. The simplest measurement setup is a slab of the dielectric material with parallel plane surfaces. The sample dimensions have to be chosen large enough so that edge diffraction effects are negligible and the governing equations remain simple. In order to reduce the necessary sample dimensions, the transmitted or reflected wave is focused by dielectric lenses (Musil and Zacek, 1986) or specially formed metallic reflectors (Maurens *et al.*, 1992). Additionally, these setups help to produce a plane wave (defined by an identical phase in a plane perpendicular to the wave propagation) from an incident spherical wave as supplied by a microwave horn antenna (Maurens *et al.*, 1992, and references therein). By a calibration routine errors due to multiple reflections between the horns and the sample's surface have to be eliminated.

Whereas the dielectric lens has the disadvantage of a limited bandwidth due to the frequency dependence of the diffraction index or of the dielectric properties (the so-called dispersion), for metallic reflectors shadow effects of the feed horn may be problematic. The two typical setups are shown in Fig. 3.5. They consist of a PC controlling a network analyser (or a generator and detector) that produces and detects the electromagnetic waves of defined frequency. In both cases, the waves are emitted by one of the horn antennas. Either the dielectric lens or the ellipsoidal reflector (one of the foci of the reflector is at the

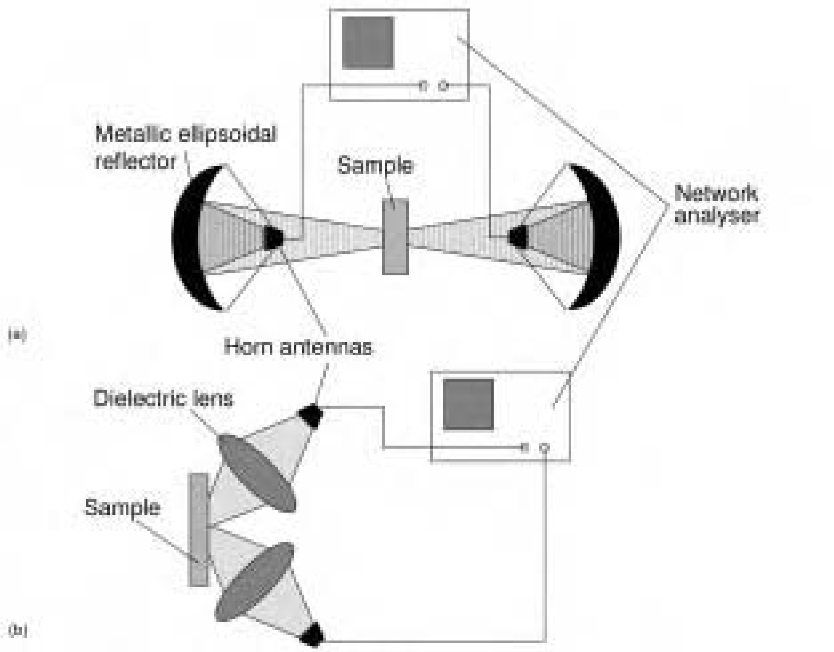

**Fig. 3.5** Typical setups for free-space measurement techniques: (a) transmission measurements; (b) reflection measurements. Although the transmission measurement is shown here with metallic ellipsoidal reflectors and the reflection measurement with dielectric lenses, each type can be operated in the same way with the other method, respectively.

position of the horn, the other being located at the sample's position) focuses the wave to the position of the sample. The interaction of the electromagnetic wave with the sample characteristically changes the amplitude and phase of the wave that is received by the receiver horn and detected and analysed by the network analyser and the PC.

### 3.3.2 Open-ended coaxial probe

The open-ended coaxial probe is generally also an open structure method or even a 'free-space' method, but is normally not described in that way. Since this method is used very often in the dielectric measurement of foods, it is described here in more detail.

The source (and detector) of electromagnetic waves of defined frequency is again a network analyser. The generated waves are coupled into a coaxial line which has an open end, formed as a tip, that is in direct contact with the material under test (see Fig. 3.6).

Thus to a first approximation (Stuchly and Stuchly, 1980), the impedance $Z$ of the probe is assumed to be purely capacitive and consists of two parallel capacitances, one within the probe $C_0$ (which is unchanged by a sample) and the second one the fringing field capacitance $C_\mathrm{f} = \epsilon C_{\mathrm{f},0}$, which is linearily correlated with the permittivity of the sample:

$$C = C_0 + C_\mathrm{f} = C_0 + \epsilon C_{\mathrm{f},0} \tag{3.19}$$

On the one hand the impedance of the system $Z$ can be expressed by the capacitance:

$$Z = \frac{1}{\mathrm{i}\omega C} = \frac{1}{\mathrm{i}\omega(C_0 + \epsilon C_{\mathrm{f},0})} \tag{3.20}$$

On the other hand, the impedance can be calculated from the line's characteristic impedance $Z_0$ and the complex voltage reflection coefficient $\Gamma = \Gamma_0 e^{\mathrm{i}\varphi}$:

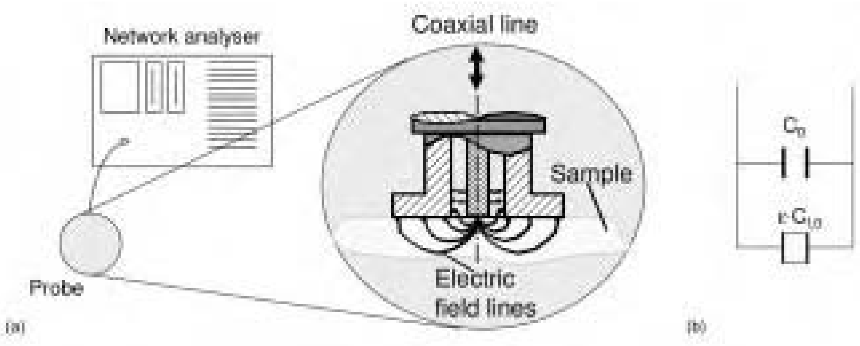

**Fig. 3.6** (a) Schematic view of an open-ended coaxial line measurement setup; (b) the equivalent circuit of the probe.

$$Z = Z_0 \cdot \frac{1 + \Gamma}{1 - \Gamma} \tag{3.21}$$

Taking eqns 3.20 and 3.21, separating real and imaginary parts and solving for $\epsilon'$ and $\epsilon''$ yields:

$$\begin{aligned} \epsilon' &= \frac{-2\Gamma_0 \sin\varphi}{\omega C_{\mathrm{f},0} Z_0 (1 + 2\Gamma_0 \cos\varphi + \Gamma_0^2)} - \frac{C_0}{C_{\mathrm{f},0}} \\ \epsilon'' &= \frac{1 - \Gamma_0^2}{\omega C_{\mathrm{f},0} Z_0 (1 + 2\Gamma_0 \cos\varphi + \Gamma_0^2)} \end{aligned} \tag{3.22}$$

These equations are relatively simple, but are only valid for certain assumptions (Grant *et al.*, 1989): the capacitances $C_0$ and $C_{\mathrm{f},0}$ have to be frequency independent and also independent from the permittivity of the sample and the probe does not launch propagation radiation. Since these assumptions are not strictly fulfilled in most cases, alternative concepts are also proposed (Grant *et al.*, 1989), but they are much more complicated and thus not so popular. The unknowns $C_0$ and $C_{\mathrm{f},0}$ and the line's characteristic impedance are calculated by calibration measurements of three known conditions. In most cases, an open end, a metallic short cut and a test substance with known dielectric properties (mostly water) are taken. In practice, these systems cover a frequency range between 200 MHz and 20 GHz. At lower frequencies, the accuracy decreases markedly, but adapted probe geometries (Stuchly *et al.*, 1986) may overcome this disadvantage. Nevertheless, the probe has a limited accuracy, especially at low values of $\epsilon'$ and $\epsilon''$ (compared to resonator systems), but such precision is usually adequate for microwave heating work (Engelder and Buffler, 1991). Its main advantage is its ease of use due to its commercial availability (Hewlett Packard, 1993); and, apart from a flat surface of the size of the probe (several centimetres, which can indeed be problematic) and a minimum sample thickness $h_{\mathrm{min}}$ (Hewlett Packard (1993) mentions the empirical formula $h_{\mathrm{min}} = 20\,\mathrm{mm}/\sqrt{|\epsilon|}$), no particular sample shape is needed.

## 3.4 Further analysis of dielectric properties

Although there are numerous methods to characterise the material dielectrically, as shown above, sometimes some more information can be gained from the already existing data. Two examples are covered here: the interpolation or extrapolation of dielectric properties of mixtures, and the relations between the real and the imaginary parts of dielectric properties of the material. The first method helps either to estimate the dielectric properties of mixtures starting from the pure material values or to infer the pure material values from measured data on mixtures with varied composition. The second method shows how the real and imaginary parts of the dielectric properties are coupled by Kramers–Kronig relations, so that the real part can be determined when the frequency-dependent imaginary part is known, and vice versa.

### 3.4.1 Dielectric properties of mixtures

Food material is often a complex mixture of several constituents of varying concentrations. In order to avoid too many experiments, one may try to predict the dielectric properties of a mixture from the value of the pure components. On the other hand, sometimes the pure component values are needed, but cannot be measured easily, as in the case of pulverised or granular sample, so that each measurement of dielectric properties gives values for the mixture of air and sample, but not the pure solid value. For both cases, models and formulas have been developed and can be found in the literature. Beside purely empirical formulas, which have a very limited area of validity (limited to a particular material), some more theoretical equations exist and are presented here.

Since not all of these models go into the details of molecular dynamics, they can only cover practically noninteracting mixtures such as dispersions; on the other hand, for interacting mixtures such as water–alcohol mixtures, at the moment no simple general approaches can be found; the reader is referred to molecular dynamic modelling.

Wiener (1913) based his equations on the simple model of a plate capacitor, in which layers of different dielectric media with corresponding volume fractions exist. Depending on the layer arrangement, parallel or orthogonal to the capacitor plates, the equivalent circuit of serial or parallel capacitors, respectively, yields eqns 3.23 and 3.24 for the dielectric properties of the mixture:

$$\frac{1}{\epsilon_m} = \frac{\Phi_2}{\epsilon_2} + \frac{1-\Phi_2}{\epsilon_1} \qquad [3.23]$$

$$\epsilon_m = \Phi_2 \epsilon_2 + (1-\Phi_2)\epsilon_1 \qquad [3.24]$$

Since real mixtures are usually not of a layered kind, by combining these equations with a shape coefficient $u$, the universal Wiener equation is formed:

$$\frac{\epsilon_m - \epsilon_1}{\epsilon_m + u\epsilon_1} = \Phi_2 \cdot \frac{\epsilon_2 - \epsilon_1}{\epsilon_2 + u\epsilon_1} \qquad [3.25]$$

Fricke (1955) created a model for the calculation of the conductivity that was used by Mudgett *et al.* (1974) for the calculation of the dielectric loss of a mixture, due to the strong relationship (see Chapter 1) between loss factor and conductivity. Valid for mixtures with a high dielectric continuous phase (1) and a low dielectric dispersed phase (2), eqn 3.26 also has a shape coefficient, called $a$, that takes the value $a = 2$ for spheres (as in an emulsion) and $a = 1$ for needle-shaped objects:

$$\epsilon_m = \epsilon_1 \cdot \frac{\epsilon_2(1 + a\Phi_2) + \epsilon_1 a(1-\Phi_2)}{\epsilon_1(a + \Phi_2) + \epsilon_2(1-\Phi_2)} \qquad [3.26]$$

From a mathematical point of view, a suitable function for the dielectric property of the mixture from the values of the pure substances should be continuous, monotonic and differentiable for all variables $\epsilon_1$, $\epsilon_2$ and $\Phi_2$. Moreover, it should be applicable to mixtures of mixtures.

Beside eqn 3.27 from Lichtenecker and Rother (1931):

$$\ln \epsilon_m = \Phi_2 \ln \epsilon_2 + (1 - \Phi_2) \ln \epsilon_1 \qquad [3.27]$$

equations of the following type may be possible:

$$\epsilon_m^y = \Phi_2^x \epsilon_2^y + (1 - \Phi_2)^x \epsilon_1^y \qquad [3.28a]$$

An example in which that kind of equation is commonly applied is the case of the mixture of granular or pulverised material with air (Nelson, 1996). When the air mass is neglected, the approximate equation 3.28b with bulk density $\rho$ and solid density $\rho_{\text{solid}}$ may be derived, using the exponents $x = 3$ and $y = 1$:

$$\epsilon_m \propto \left(\frac{\rho}{\rho_{\text{solid}}}\right)^3 \qquad [3.28b]$$

This equation may be helpful when the dielectric properties of a solid material are of interest but only pulverised formulations are available. Taking measurements of the material with varying bulk density may yield the required values by extrapolation to the solid dielectric property, using eqn 3.28a. In Fig. 3.7 this is shown using the example of limestone powders (Regier, 2003).

A comparison of the validity in the case of emulsions and suspensions can be found, for example, in Erle *et al.* (2000) or for granular material in Nelson (1996). It can be concluded that no general formula for the exact description of the dielectric property of mixtures exists; instead, for each product the most suitable expression has to be found. Nevertheless all of the above equations give an approximate first estimation of the dielectric properties of mixtures that may already be helpful for further calculations.

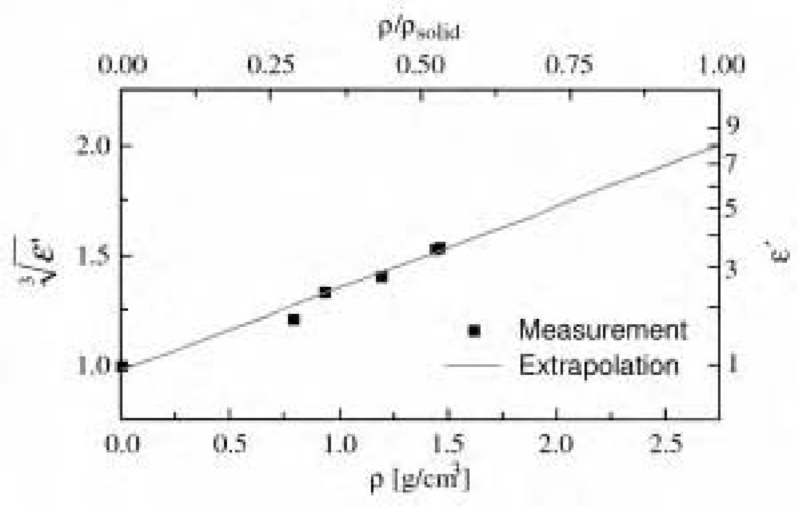

**Fig. 3.7** Extrapolation of density-dependent measurement of dielectric constant of limestone to determine the solid value. The extrapolation yields a dielectric constant of $\epsilon' = 8.0$, which agrees well with the literature value of 7.6 (Nelson, 1996).

### 3.4.2 Relations between real and imaginary parts of dielectric properties

As shown in Chapter 1, the dielectric property $\epsilon$, or more precisely the susceptibility $\chi = \epsilon - 1$, is responsible for a linear response of the material, the so-called polarisation $\vec{P}$, to an outer electric field $\vec{E}$. In the following, purely homogeneous behaviour is suggested, so that only the absolute values $E$ and $P$ are important.

Although, in most cases, historical dependence is neglected, i.e.

$$P(t) = \chi(t) \cdot E(t) \tag{3.29}$$

a more general approach is the convolution:

$$P(t) = \int_{-\infty}^{+\infty} \chi(t - t') \cdot E(t') \, \mathrm{d}t \tag{3.30}$$

This means that the response of the material at time $t$, the polarisation, consists of reactions to electric fields at time $t'$.

If the variables $E$, $P$ and $\chi$ are Fourier-transformed to the variables $\tilde{E}$, $\tilde{P}$ and $\tilde{\chi}$, e.g. for $E$:

$$\begin{aligned} \tilde{E}(\omega) &= \int_{-\infty}^{+\infty} E(t) \cdot \mathrm{e}^{\mathrm{i}\omega t} \, \mathrm{d}t \\ E(t) &= \frac{1}{2\pi} \int_{-\infty}^{+\infty} \tilde{E}(\omega) \cdot \mathrm{e}^{-\mathrm{i}\omega t} \, \mathrm{d}\omega \end{aligned} \tag{3.31}$$

for the transformed variables the convolution of eqn 3.29 becomes a simple product:

$$\tilde{P}(\omega) = \tilde{\chi}(\omega) \cdot \tilde{E}(\omega) \tag{3.32}$$

Another physical assumption is the causality of $\chi(t)$, which means that for the effect at time $t$ only reasons $E(t')$ before the effect ($t' \leq t$) are considered. This yields:

$$\chi(t - t') \equiv 0, \quad \text{if } t' > t \tag{3.33}$$

Thus, the Fourier transformation for $\tilde{\chi}(\omega)$ becomes:

$$\tilde{\chi}(\omega) = \int_{0}^{\infty} \chi(t) \cdot \mathrm{e}^{\mathrm{i}\omega t} \, \mathrm{d}t = \tilde{\chi}' + \mathrm{i}\tilde{\chi}'' \tag{3.34}$$

Since $\chi(t)$ is defined as a real function, there has to be a dependency between the real part $\tilde{\chi}'$ and the imaginary part $\tilde{\chi}''$ of the susceptibility. Additionally $\tilde{\chi}(\omega)$ has to be analytic for $\Im(\omega) > 0$, bounded for $\omega \in R$ and should diminish asymptotically ($\lim_{\omega \to \infty} \tilde{\chi}(\omega) = 0$), which is physically satisfied.

By functional theory the correlation between the real part $\tilde{\chi}'$ and the imaginary part $\tilde{\chi}''$ of the susceptibility in terms of dielectric properties may be expressed as:

$$\begin{aligned}\epsilon'(\omega) &= \tilde{\chi}'(\omega) + 1 = \frac{1}{\pi}\int_{-\infty}^{+\infty} \frac{\epsilon'(\omega)}{\omega' - \omega}\,\mathrm{d}\omega' + 1 \\ \epsilon''(\omega) &= -\tilde{\chi}''(\omega) = \frac{1}{\pi}\int_{-\infty}^{+\infty} \frac{\epsilon'(\omega) - 1}{\omega' - \omega}\,\mathrm{d}\omega'\end{aligned} \tag{3.35}$$

In both cases the integral is defined as Cauchy's main value:

$$\int_{-\infty}^{+\infty} \frac{X}{\omega' - \omega}\,\mathrm{d}\omega' \equiv \lim_{\delta \to 0^+}\left[\int_{-\infty}^{\omega-\delta} \frac{X}{\omega' - \omega}\,\mathrm{d}\omega' + \int_{\omega+\delta}^{+\infty} \frac{X}{\omega' - \omega}\,\mathrm{d}\omega'\right] \tag{3.36}$$

Thus, if the frequency dependence of either the real or the imaginary part is known, for example by measurement, that of the other part can be calculated. Although this has not been very common up to now, some special examples can be found, for example to distinguish between various parts of dielectric losses (ionic, dipolar, electronic, etc.): see, for example, Steeman and van Turnhout (1997).

## 3.5 Summary

In this chapter several methods for the measurement of dielectric properties at microwave frequencies have been presented. After the classification of the different types as closed and open structures, the most prominent examples are shown. The application areas as well as the advantages and disadvantages of the different methods are given, so that the most suitable technique for the particular measurement problem can be chosen. Additionally, some information is given for the further analysis of dielectric property measurements. On the one hand, the possibilities of mixture equations to predict dielectric properties of mixtures as well as of the pure substances have been shown. On the other hand, the Kramers–Kronig relation has been derived to extract information on the real part of the permittivity, when the frequency-dependent imaginary part is known, and vice versa.

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## 3.7 Appendix: notation

| | |
|---|---|
| $a$ | shape coefficient |
| $A_x, A_y, A_z$ | electric field amplitude coefficients |
| $\vec{B}$ | magnetic flux density |
| $C, C_0, C_\mathrm{f}, C_{\mathrm{f},0}$ | capacity, inner capacity, fringing field capacity, fringing field capacity without dielectric sample |
| $\vec{E}$ | electric field |
| $f_0, f_{lmn}$ | resonant frequency |
| $f_{0,\mathrm{empty}}$ | resonant frequency of empty cavity |
| $f_{0,\mathrm{filled}}$ | resonant frequency of filled cavity |
| $f, g, h$ | functions |
| $h_\mathrm{min}$ | minimal sample thickness |
| $\mathrm{i}$ | imaginary unit |
| $I$ | intensity |
| $\Im(x)$ | imaginary part of $x$ |
| $k_x, k_y, k_z$ | wave number in $x$-, $y$- and $z$-directions |
| $L_x, L_y, L_z$ | length in $x$-, $y$- and $z$-directions |
| $l, m, n$ | natural ‘quantum’ numbers |
| $\vec{P}$ | electric polarisation |
| $Q$ | quality factor |
| $Q_\mathrm{empty}$ | quality factor of empty cavity |

| | |
|---|---|
| $Q_{\text{loss}}$ | quality factor due to dielectric losses |
| $\vec{r} = (x, y, z)$ | local vector |
| $R$ | cylinder radius |
| $\Re(x)$ | real part of $x$ |
| $t$ | time |
| $u$ | shape coefficient |
| $x, y$ | constant exponents |
| $\alpha_{1\text{m}}$ | *m*th zero of Bessel's function of order 1 |
| $\alpha'_{1\text{m}}$ | *m*th zero of the first derivative of Bessel's function of order 1 |
| $\Delta f_{1/2}$ | free width at half maximum |
| $\Gamma$ | voltage reflection coefficient |
| $\epsilon_0$ | dielectric constant of vacuum |
| $\epsilon = \epsilon' - \text{i}\epsilon''$ | relative permittivity |
| $\varphi, \varphi_x, \varphi_y, \varphi_z$ | phase constants |
| $\Phi$ | volume fraction |
| $\mu$ | relative permeability |
| $\mu_0$ | permeability of vacuum |
| $\rho$ | bulk density |
| $\rho_{\text{solid}}$ | solid density |
| $\chi = \epsilon - 1$ | electric susceptibility |
| $\omega$ | circular frequency |

# 4

# Microwave heating and the dielectric properties of foods

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## 4.1 Introduction

Thermal technology dictates the quality, economics and environmental impact of most processing plant. It is by far the most sensitive aspect of food processing. Green engineering regulations call for more efficient energy usage and more environment-friendly raw materials as well as effluents. Efficiency demands minimal processing of materials, especially nutritive foods. Hence, electric heating technologies such as radio frequency, microwave, ohmic and infrared are being considered; among them microwave shows a highly promising future (Chan and Reader, 2000). They are energy efficient and can operate in combination modes.

Microwaves are electromagnetic waves with frequencies ranging from 300 MHz to 300 GHz (Singh and Heldman, 2001). Certain frequencies within this range of the electromagnetic spectrum are set aside by the International Telecommunications Union for Industrial, Scientific, Medical and Domestic use. These so-called ISM & D bands are at 2450 MHz, 915 MHz, and a few other frequencies according to geographic location. By far the most common in North America and Europe is 2450 MHz, which is the frequency at which most domestic microwave ovens operate. These waves propagate with a 'time interval between peaks' during oscillation, ranging from $3 \times 10^{-8}$ to $3 \times 10^{-11}$ seconds (Venkatesh and Raghavan, 2004).

This range coincides with the temporal sequence of events at atomic and molecular transitions such as reactions in water, molecular dissociation and, most importantly (for industrial microwave technology), dielectric relaxation in water. The dielectric relaxation of water may vary from 100 MHz for bound water to 18 GHz for pure water (Miura *et al.*, 2003) and this is the property that

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is studied extensively when heating effects of microwaves are investigated. The most effective conversion of microwave energy to thermal energy in biological materials (or otherwise moist materials) will occur in this frequency range.

## 4.2 Microwave heating and the dielectric properties of foods (see also Chapter 1)

Microwave energy is transported as an electromagnetic wave in certain frequency bands in the range between about 0.3 GHz and 300 GHz. When microwaves impinge on a dielectric material, part of the energy is transmitted, part reflected and part absorbed by the material where it is dissipated as heat. Heating is due to 'molecular friction' of permanent dipoles within the material as they try to reorient themselves with the oscillating (electrical) field of the incident wave. The power generated in a material is proportional to the frequency of the source, the dielectric loss of the material, and the square of the field strength within it. A material is subjected to microwave energy in a device known as an applicator or cavity. Considering all these features, it is possible to identify those candidate materials and processes that can use microwave heating effectively and understand microwave ingredient interaction mechanisms. Only after such a step is taken can microwave heating be exploited fully in terms of its unique characteristics, which include the facts that no contact is required between the energy source and the target and that heating is volumetric, rapid and highly specific in nature.

International convention dictates that microwave ovens (and other industrial, scientific and medical microwave applications) operate at specific frequencies, the most favoured being 2.45 GHz. At this frequency the electric field swings the orientation of water molecules $10^9$ times every second, creating an intense heat that can escalate as quickly as 10 ºC per second (Lew *et al.*, 2002). Water being the predominant component of biological materials, its content directly influences heating. However, there are minor contributions from a host of other factors (Schiffmann, 1986): heating is accelerated by ionic effects (mostly salt content) and specific heat of the composite material (Decareau, 1992). Specific heat is an important property in the thermal behaviour of a food subjected to microwaves. Produce with low specific heat may heat very rapidly, and even faster than water of the same weight. Oil heats faster than water due to its much lower specific heat (Schiffmann, 1986). Hence for oily materials, the influence of specific heat becomes the determining factor in microwave heating, owing to the low specific heat of oils, often less than half that of water (Ohlsson, 1983).

## 4.3 Microwave interactions with dielectric properties (see also Chapter 1)

When an oscillating electrical field is applied to a polar dielectric, the dipoles within the material attempt to align themselves (polarize) with the field. The rate of change of polarization represents a displacement current in the dielectric and the product of this and the applied field gives the power generated as heat. Averaged over a cycle, the power 'lost' in the material (i.e. dissipated as heat) depends on the phase angle between the applied field and the polarization. For most dielectrics the lag depends on the flexibility of the molecules that house the dipoles, and the randomization effect of temperature.

### 4.3.1 Power dissipated

The fundamental electric property of a material is the complex relative permittivity $\epsilon^*$ where

$$\epsilon^* = \epsilon' - j\epsilon'' \qquad [4.1]$$

The real part of $\epsilon^*$, $\epsilon'$, is called the permittivity, and the imaginary part, $\epsilon''$, is called the loss factor. The ratio $\epsilon''/\epsilon'$ is called the loss tangent, written as $\tan\delta$, with $\delta$ being the phase lag.

The power dissipated per unit volume can be written as:

$$P = \omega\epsilon_0\epsilon'(\tan\delta)E_{\text{rms}}^2 = 2\pi f\epsilon_0\epsilon'' E_{\text{rms}}^2 \qquad [4.2]$$

where $\epsilon_0$ is the permittivity of free space ($8.85 \times 10^{-12}$ F/m), $f$ is the microwave frequency (Hz) and $E$ is the electrical field strength (V/m) in the material.

For completeness, the total loss in a material is made up of the dielectric loss (from polarization) and the conductive (ohmic) loss, as follows:

$$\epsilon_t'' = \epsilon'' + \frac{\sigma}{\omega\epsilon_0} \qquad [4.3]$$

where $\sigma$ is the electrical conductivity of the material

For metals, the polarization loss is zero and for dielectrics having no conductive losses the conductivity term is zero. In the absence of any other energy processes, the conservation of energy equation for heat transfer in one direction ($x$), through a plane slab of material exposed to microwave energy, may be written as:

$$\frac{\mathrm{d}T}{\mathrm{d}t} = \frac{\mathrm{d}}{\mathrm{d}x}\left(\alpha\frac{\mathrm{d}T}{\mathrm{d}x}\right) + \frac{2\pi\epsilon_0\epsilon'' E^2}{C_{\text{p}}} \qquad [4.4]$$

where $C_{\text{p}}$ is the specific heat capacity of the material. If all the parameters in the microwave source term are independent of location ($x$), this term is constant, and its contribution is to cause the temperature of the material to increase linearly and uniformly with time. It is this that gives rise to the notion of volumetric heating. If, in addition, the boundary condition at the surfaces is represented by a convective heat transfer coefficient and the surrounding medium is at the original temperature of the material, the material will be hotter in the middle than at the edges. This gives rise to the notion that microwave energy heats from the inside out.

Thus the initial increase in temperature depends on the size of the microwave source term, and, in order to maximize this, it would seem desirable to plan that the electrical field, the frequency and the loss factor of the material should all be as large as possible. However, for all practical (commercial) purposes the frequency is fixed within the ISM & D range, the upper limit of the field is determined by the dielectric strength of the substrate or the surrounding air (20–30 kV/m) and the upper limit of the loss factor is determined by the rate of absorption of microwave energy through the material.

### 4.3.2 Field strength within a material

Field strength $E$ varies with position in the material. For a plane wave, this relationship can be expressed in terms of the depth of material, $D_\mathrm{p}$, over which the incident power is reduced by a factor of 1/e:

$$D_\mathrm{p} = \frac{1}{\omega}\left[2\mu_0\mu'\epsilon_0\epsilon'\left(\sqrt{1+(\tan\delta)^2}-1\right)\right]^{-1/2} \approx \frac{\lambda_0}{2\pi}\frac{\sqrt{\epsilon'}}{\epsilon''} \qquad [4.5]$$

Here $\mu_0$ is the magnetic permeability of free space ($1.25 \times 10^{-6}$ H/m) and $\mu'$ the magnetic permeability of the material which, typically, is taken as 1.0, and $\lambda_0$ is the free space wavelength.

This approximation applies to a low loss dielectric material. Note that the attenuation of an incident wave is more commonly expressed as the depth over which the incident electrical field falls by a factor of 1/e. This so-called skin depth, $d$, is inversely proportional to the attenuation constant of the wave, $a$. Numerically, $D_\mathrm{p} = d/2$.

### 4.3.3 Using microwave heating effectively

For even quasi-volumetric heating, the size of a target material should be of the same order as $D_\mathrm{p}$ and, for preference, considerably less.

A relatively simple measure of the effectiveness of microwave heating is to compare the rate of heat conduction with the rate of heat generation. For a plane slab, this gives a value $m$, where

$$m = \frac{\omega\epsilon_0\epsilon'' E^2 x^2}{k\Delta T} \qquad [4.6]$$

That is to say, microwave heating is favoured for thick materials (large $x$) with high dielectric loss factor and low thermal conductivity ($k$) and where a large temperature gradient is undesirable. Here, it is assumed that $D_\mathrm{p} \gg x$ so that the field is substantially constant throughout.

## 4.4 Measuring microwave heating

Industrial microwaves are relatively high frequency applications. At these frequencies electronic components do not behave normally. The electronic circuits are therefore visualized as guides for waves. Measurements are made in terms of power transmitted and reflected and not voltage and current.

Even as accurate measurements challenge the microwave engineer, there are basic areas such as efficient conversion of microwave energy to thermal energy and its numerical modeling that leave many experts still guessing. Quoting Meredith (1998), 'numerical analysis . . . is a topic requiring great professional skill and generally remains within the ambit of university/industrial research. It is a potential trap for the unwary, readily producing incorrect but plausible results'. What follows is hence a summarized introduction of governing equations.

The heat generated by microwaves is represented in a conduction equation as given in eqn 4.7:

$$\rho C_{\mathrm{p}} \frac{\partial T}{\partial t} = \lambda \nabla^2 T + Q \qquad [4.7]$$

This simplistic case has to be expanded with terms for convection and transport in order to get an accurate numerical solution.

The source term for heat generation being in the form of an *electromagnetic field* (microwave), it is a function of field frequency and absorbed power by foods.

The two equations used for deriving the field equations for microwaves are Ampère's law (eqn 4.8) and Faraday's Law (eqn 4.9), both of which are Maxwell's electromagnetic equations:

$$\nabla \times H = \sigma E + \frac{\partial D}{\partial t} \qquad [4.8]$$

relates magnetic field ***H*** to the electric flux density ***D***, while

$$\nabla \times E = \frac{\partial B}{\partial t} \qquad [4.9]$$

relates electric field ***E*** to the flux density ***B***.

We can, however, choose a mode of the microwaves such that the magnetic component is eliminated. For a dielectric material we then get eqn 4.10:

$$\nabla^2 E = \mu \epsilon \frac{\partial^2 E}{\partial t^2} \qquad [4.10]$$

Here $\mu$ is the permeability representing the interaction with the magnetic field, and $\epsilon$ is the dielectric constant representing the interaction of non-conducting material with the electric field. The power dissipated per unit volume is manifested as heat $Q$. Hence we have eqn 4.11 for the heat generated in the microwave.

$$Q = \frac{1}{2} \sigma_{\mathrm{e}} |E|^2 \qquad [4.11]$$

The conductivity term $\sigma$ includes the d.c conductivity (zero in this case) and an imaginary part of the permittivity $\epsilon$ or the loss factor.

This is the starting point for any industrial microwave heating calculation, whether for food or non-food application. However, when we consider foods we need to include innumerable influencing factors and corrections for unknowns. It is easier to model non-food processing. When it comes to foods the basic difference (analogous to the difference between plastic dolls and real humans) is the fact that foods come in infinite variety, no two compositions and dimensions remaining alike.

## 4.5 Microwave heating variables

The microwave heating rates and potential non-uniformity are functions of oven factors and load characteristics (size, shape, dielectric properties, etc.). Any change in those parameters significantly affects the microwave heating process (Peyre *et al.*, 1997). The most interesting and applied mechanisms include dielectric polarization, dipolar polarization, interfacial polarization, conduction effects, and combination effects.

It has long been known that materials may be heated with the use of high frequency electromagnetic waves. The heating effect arises from the interaction of the electric field component of the wave with charged particles in the material. Two major effects are responsible for the heating which results from this interaction. If the charged particles are free to travel through the material (electrons in a sample of carbon, for example), a current will be induced which will travel in phase with the field. If, on the other hand, the charged particles are bound within regions of the material, the electric field component will cause them to move until opposing forces balance the electric force. The result is a dipolar polarization in the material. Conduction and dipolar polarization may both give rise to heating under microwave irradiation, and are discussed in more detail below.

It is important to note that microwave heating is quite distinct from microwave spectroscopy. The latter is a quantum phenomenon in which photons of particular energies (and therefore frequencies) excite the rotation levels of gas phase molecules. Whilst the absorption of microwaves in solid and liquid samples is frequency dependent, it is by no means quantized and does not depend upon the direct absorption of microwave photons. Rather, the material behaves as though reacting to a high frequency electric field, and so may be subjected to classical analysis. Details of this analysis are beyond the scope of this chapter, although some of its chemically significant aspects will be introduced in the following sections.

### 4.5.1 Dielectric polarization

The inability of partially bound charges to follow the rapid changes in a high frequency electric field gives rise to microwave heating. The total polarization of the material arising from the displacement of charges may be expressed as the sum of a number of components resulting from the displacement of electron charges in relation to the nuclei in a material, and the displacement of nuclei relative to one another in materials with unequal charge distributions. Polarization of both operates on timescales which are very much smaller than that required for microwave frequency field reversals, and therefore follow microwave frequency fields almost exactly. As such they do not contribute to the microwave heating effect.

### 4.5.2 Reorientation of polar molecules/other permanent dipoles in the material

This is the most important of the polarization phenomena in relation to microwave heating. The role of the interfacial polarization (Maxwell–Wagner) effect $\boldsymbol{a}_{\mathrm{i}}$, which results from interfacial phenomena in inhomogeneous materials, is limited at microwave frequencies, and in general its contribution is limited. In those cases where it is thought to be important, theoretical studies are impossible due to the large number of variables involved.

A useful dielectric parameter, the loss angle $\delta$, is commonly used in the literature, and is more usually given in the form of its tangent. It is related to the complex dielectric constant by $\tan \delta = \epsilon''/\epsilon'$. The angle $\delta$ is the phase difference between the electric field and the polarization of the material. Magnetic polarization may also contribute to the heating effect observed in materials where magnetic properties exist, and a similar expression for the complex permeability of such materials may be formulated.

### 4.5.3 Dipolar polarization

Dipolar polarization is the phenomenon responsible for the majority of microwave heating effects observed in solvent systems. In substances such as water, the different electronegatives of individual atoms result in the existence of a permanent electric dipole on the molecule. The dipole is sensitive to external electric fields, and will attempt to align with them by rotation, the energy for this rotation being provided by the field. This realignment is rapid for a free molecule, but in liquids instantaneous alignment is prohibited by the presence of other molecules. A limit is therefore placed on the ability of the dipole to respond to a field, which affects the behaviour of the molecule with different frequencies of electric field.

Under low frequency irradiation, the dipole may react by aligning itself in phase with the electric field. Whilst the molecule gains some energy by this behaviour, and some is also lost in collisions, the overall heating effect is small. Under the influence of a high frequency electric field, on the other hand, the dipoles do not have sufficient time to respond to the field, and so do not rotate. As no motion is induced in the molecules, no energy transfer takes place, and therefore, no heating.

Between these two extremes, at frequencies which are approximately those of the response times of the dipoles, is the microwave region. The microwave frequency is low enough that the dipoles have time to respond to the alternating field, and therefore to rotate, but high enough that the rotation does not precisely follow the field. As the dipole reorients to align itself with the field, the field is already changing, and a phase difference exists between the orientation of the field and that of the dipole. This phase difference causes energy to be lost from the dipole in random collisions, and to give rise to dielectric heating.

The range of frequencies over which the dielectric loss is non-zero, indicating that microwave absorption occurs, is relatively large. This is in contrast to the line-widths of quantum spectroscopic absorption, which are typically of the order of nanometres. There is a clear maximum in the dielectric loss for water at a frequency of approximately 20 GHz, the same point at which the dielectric constant $\epsilon'$ goes through a point of inflexion as it decreases with increasing frequency. The 2.45 GHz operating frequency of domestic ovens is selected to be some way from this maximum in order to limit the efficiency of the absorption. Too efficient absorption by the outer layers would inevitably lead to poor heating of the internal volume in large samples.

In solids, the molecular dipoles are no longer free to rotate as they are in liquids, but are restricted to a number of equilibrium positions, separated by potential barriers. Theoretical treatments of this behaviour have been formulated and are similar to those developed for liquids. The simplest model for this behaviour assumes that there are two potential wells separated by a potential barrier of energy. This represents the two possible orientations of the dipole.

### 4.5.4 Maxwell–Wagner (interfacial) polarization

Where a dielectric material is not homogeneous, but consists of inclusions of one dielectric in another, it is still possible to treat the material theoretically. If the dielectric properties and geometry of the inclusions are known, it is possible to arrive at expressions for the dielectric behaviour of the bulk sample. The reverse problem – that of determining the dielectric properties of the components from that of the system – is generally insoluble except in the simplest of cases. The addition of dissolved salts in water markedly affects the dielectric properties as conduction increases, and may become important enough to swamp the dielectric losses. On the other hand, the dielectric losses of the majority of solids arise predominantly from these conduction terms, and may be strongly affected by temperature.

## 4.6 Product formulation to optimize microwave heating

What consumers desire and the realities are often at opposite ends. Working families want healthy processed foods that are easy and rapid to prepare (microwaveable is favoured), and they want their foods to look, smell, and most of all taste as good as those which come out of an oven. In order to accomplish this, more care is needed in the formulation of microwaveable foods.

Companies are no longer content with adapting existing products for microwave cooking. Products are beginning to be designed specifically for microwaves, whether by means of changes in packaging or changes within product formulation. Cylindrical-shaped products, for example, reduce the number of sharp edges and therefore reduce the uneven heating pattern. Browning of the product may be addressed by changes in packaging and the use of susceptors that collect microwave energy and concentrate the heat produced at the surface. It is also important to understand how composition varies the heating profile of different food products. If these drawbacks are addressed, the opportunity to develop products that can be fully cooked by microwave technology is possible.

There is a considerable increase in availability and choice of convenience microwaveable prepared foods in today's grocery stores. Product development has focused on both quality and safety aspects, targeting principally the microwave downfalls of lack of crisping and browning, uneven heat distribution and compromised flavour development (Fraser and LeBlanc, 1989).

Foods cooked by conventional heating and microwave heating produce significantly different flavours, hence the need for improved ingredients for use in microwave products formulation. The success of new applications of microwave heating in foods depends on the understanding of the interactions between the microwave energy field and the material components. Any change in material properties will directly impact the heating pattern (Bows, 2000).

In microwaveable food product development, ingredient interaction is key to successful product development. Each material component possesses a different molecular makeup which gives it a unique heating property in the microwave oven. Water, the major constituent of most food products, is the main source for microwave interactions (Oliveira and Franca, 2002). Along with water, a food item is comprised of various components that each contribute their dielectric property to make a mass that has a unique and complex microwave heating potential (Hegenbart, 1992). The principal factors governing the way microwaves heat food are the component's dielectric properties, the specific heat, mass and shape.

### 4.6.1 Microwave browning

For many foods it is the browning during heating/cooking at temperatures above 140 °C which imparts distinctive and sought flavours. Without this browning, foods appear tasteless and dull. Two factors, time and temperature, involved in browning are absent in microwave heating. To compensate for that, browning formulations can be considered as an added ingredient to food formulations for acceptable quality in microwave processed foods (Decareau, 1992).

Browning formulations are essentially compounds (such as glucose, sodium carbonate, lecithin, salts, yeast extract, etc.) which can help give surface browning in a microwave oven or simply give a browned appearance (colour). It is the concentration of sugars with amino acids, peptides and proteins which results in the formation of key flavour profiles such as pyrazines, furans and thiazoles (Liao *et al.*, 2001).

Browning devices can also be considered to improve surface browning during microwave cooking of foods. The principle here lies in the conversion of microwave energy into heat in a supporting material in contact with the surface of the food to provide sufficient heat to brown the food (Decareau, 1992). The browning devices have been designed in a number of ways, dish, packaging material with susceptors, and ferro-magnetic compounds (see Chapter 11). The success of these devices depends on their capacity to heat faster than the food item.

Recently, a food ingredients manufacturer developed browning reaction accelerators. Derived from cellulose and dextrose, they take their colouring action from the Maillard reaction and develop an attractive brown colour when heated, including in microwave ovens. Caramelization of sugars occurs when a certain temperature is reached, which may be difficult to reach in a microwave oven (Davis, 1995). However, saturated sugar solutions can have two to three times higher microwave power absorption compared to pure water. Adding lactose to baked goods improves moisture retention, enhances crumb texture, increases volume and intensifies the Maillard reaction, especially at low temperatures, a handy trick for promoting microwave browning (Knehr, 2001). Size of the added sugar crystals can also play an important role. Indeed, in bakery products, sugar is very important for the development of the dough structure through starch gelatinization. If the sugar cannot go into solution fast enough (small crystals), the process of starch gelatinization will be much too long for the short microwave cooking period (Hegenbart, 1992).

### 4.6.2 Microwave popcorn

In a study by Singh and Singh (1999), coating systems were tested to improve popcorn popping. Coating systems studied consisted of hydrogenated oil, butter, sodium chloride and sodium bicarbonate. Effects on the bulk density, expansion index and percentage of popped kernels were significant for all ingredients tested and it was demonstrated that a given coating formulation can significantly reduce the bulk density while maximizing the percentage of popped kernels and expansion index. On the other hand, sodium bicarbonate was found to have no positive and even negative effects on microwave popping properties, while moderate levels of salt have a desirable effect on popping quality (Ceylan and Karababa, 2004).

### 4.6.3 Microwave baking (see also Chapter 7)

In the case of microwave-baked breads, considerable dough reformulation must be considered to achieve a minimum quality. Indeed microwave-baked breads traditionally have unacceptable texture and colour. Since the time of microwave heating is very fast, there is not enough time for proper starch gelatinization, enzymatic starch conversion or dough expansion (Sumnu, 2001). Trials have shown that the gluten content is an important factor affecting microwave baked breads. The lower the content of gluten in the flour (around 25%) the better the quality. Addition of a dough emulsifier (lecithin, soy protein, and gums) can also help increase the dough volume and reduce the bread firmness (Ozmutlu *et al.*, 2001). The addition of food-grade methylcellulose and hydroxypropyl methylcellulose in cake formulas has been demonstrated to increase final cake volume and improved crumb mouthfeel for microwave-baked cakes (Bell and Steinke, 1990). Clarke and Farrell (2000) obtained pizza dough improvements in microwave heating with the addition of a combined dough emulsifier and an oat fibre.

With the selection of proper ingredients to create the parameters needed to control moisture migration and by utilizing specially designed susceptors for browning and crisping, microwave bakery products have now reached unparalleled results (Mast, 2000; Ozmutlu *et al.*, 2001). The selected ingredients are used to control moisture migration, as well as enhance browning and crisping. A blend of cellulose powder, food starch, gums and vegetable oil can be designed to enhance moisture retention in dough products. A blend of alginate, cellulose powder, milk protein, gums and enzymes can be designed to control moisture migration and enhance volume and strength of cell structure in dough products (Keskin *et al.*, 2004). Whereas a blend of sugar powders, dextrin, shortening, browning agent and vegetable oil procures good dielectric properties that enhance browning and crisping of dough products when blended with other carrier agents (Seihun *et al.*, 2003).

Specialty starches are being formulated to perform a variety of functions in food matrices subjected to microwaves (National Starch and Chemical Co.). These include achieving optimum crispiness, improving texture and mouthfeel, controlling oil absorption and controlling expansion and product density. Starch can be physically modified with pre-gelatinization for quick viscosity development and swelling where process-tolerant products are needed such as in microwaves. Modified food starches such as amylose starch are less sensitive to water and hence can limit sogginess to provide a crisper coating.

In a frozen ready-prepared microwave meal, the starch properties are required to have a smooth short texture to maintain viscosity in case of overheating in the microwave.

### 4.6.4 Microwave cooking

Cooking fresh meat in a microwave can represent a challenge since the cool air surrounding the meat results in lack of browning. While the meat heats up inside, there is mass transfer from the interior to the outside, resulting in a tough, dry and flavourless product (Taki, 1991). Ingredient selection can target these problems, such as a salt-based coating to attract microwave energy to the surface of the meat along with a colouring agent, a water binding ingredient (starch) to reduce moisture loss and an enzyme to retain tenderness. Flavours can be added for overall improvements.

In general it is recommended to keep the salt concentration as low as possible to improve the penetration depth and slow the heating at the surface while providing more uniform heating and avoiding thermal runaway (Schiffmann, 1993). On the other hand, the addition of salt may be recommended in some cases as it can increase the heating rate at the surface for particular applications (Schiffmann, 1986).

### 4.6.5 Water migration

Water is probably the most important ingredient in any microwaveable food and care has to be given to its proper management in food systems. Usually, the higher the water content, the higher the dielectric loss factor and the better the heating. Many products can benefit from having higher than normal water content to provide tolerance to rapid heating and reduce uneven heating. In microwave baking, products that contain additional water with the help of water-binding ingredients yield better results (Miller and Hoseney, 1997).

In conventional cooking, the high temperature at the surface of the product leads to dehydration and crisping at the surface. The low temperature of the product surface in microwave heating and the internal temperature gradient forces the moisture to transfer to the surface, leading to sogginess. Special product formulations have been studied to address this problem in microwave processing (Fraser and LeBlanc, 1989). Food gums can be used to maintain consistent viscosities in microwaveable foods, to emulate the functional and sensory quality of fats and to provide a film barrier between the food item and the breading to preserve its crispness while preventing the escape of moisture from the food (The Dow Chemical Company).

Research has been conducted on non-meat ingredients as fat/moisture binders on sensory, cooking and compositional properties of microwave-cooked ground beef. With the addition of vegetable fiber (pea fiber), there is swelling of the fiber and fat absorption which interacts with the protein of the ground beef to form a complex matrix preventing fat and moisture release (Anderson and Berry, 2001).

Adjusting the meat composition in a microwave burger/bun combination can offer the food developer the flexibility to alter the temperature development during microwave heating (Lyng *et al.*, 2002). It is important to adjust the food with emulsifiers, gums, proteins, and sugars to manage the water content of the meat and the bun separately so that, when processed together in a microwave environment, the bun does not burn while the meat is cooking (Parker and Vollmer, 2004).

### 4.6.6 Flavours

The flavour industry has been working to meet the challenges of the microwave processing food developers with flavour systems specifically designed for microwaveable food formulations.

Full-flavoured taste and aromas are frequently absent in microwave-processed foods. To address this issue, food developers use ingredients that produce more complex and varied flavour precursors. Roasted flavour compounds have been formulated to ensure stability over wide ranges for processing conditions (Griffith Laboratories Co.).

Flavours added to microwave food formulations are very complex, since they must supply characteristic flavours such as lemon, butter or vanilla along with typical roasted, toasted and baked flavours not developed enough during microwave heating (Steinke *et al.*, 1989). The strong interaction of microwave energy with the water molecules of the food product can result in rapid loss of volatile fatty acids, leading to objectionable off-flavour developments. The presence of oil may help to limit the losses of volatile fatty acids, as was demonstrated by Steinke *et al.* (1989) for a variety of volatile acids in oil/water mixtures.

New encapsulated techniques are commercially being offered for controlling the release of active/functional food ingredients. One such product is hydrophobic nanospheres which are temperature designed to be utilized to release active ingredients and flavours at a certain temperature upon heating in a microwave oven, thus providing retention of volatile flavours (Shefer and Shefer, 2003).

## 4.7 Future trends

As materials undergo thermal microwave processing, they experience physical and structural transformations that, in turn, change their electrical properties and behaviour. The ability of microwaves to generate thermal energy thus varies during the process. Understanding the generation and interactions of microwaves with materials is thus critical to the development of any agri-food microwave application. The chemical composition of the material being processed, its size and shape, and the physics of the microwave/material interactions govern their success.

One of the most interesting areas of development in microwave baking is coming from what is called a 'micro-emulsion system' (Mast, 2000). The micro-emulsion system is designed to develop a coating for bakery products by creating interfacial tension sufficient to separate water and a surfactant coating to brown and crisp. The mix comprises a carrier agent – a water/food grade chemical, a special starch, a surfactant, a triglyceride vegetable oil, some dielectric ingredient and food stabilizer. This coating forms an edible susceptor capable of crisping and browning and has the ability to provide better, even heating of the product by focusing on the dielectric properties of the micro-emulsion system.

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# 5

# Microwave processing, nutritional and sensory quality

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## 5.1 Introduction

Electromagnetic energy (radiation) is emitted as particles or waves from atoms as they move from a higher to a lower energy state. Lower energy electromagnetic radiation (microwave (MW), radio, TV) occurs as very long waves with frequencies ranging from 300 MHz to 300 GHz. Unlike gamma and X-rays, 'non-ionizing' MW energy is sufficient to move the atoms of a molecule, but insufficient to change it chemically. MW travel at essentially the same speed as light waves. Metallic objects reflect them, some dielectric materials absorb them while others transmit them. Water, carbon, and foods which are high in water are good MW absorbers, while thermoplastics, glass and ceramics allow them to pass through, absorbing little or no energy (Decareau and Peterson, 1986).

When intercepted by dielectric materials, MW give up energy, and the temperature of the dielectric material increases due both to dipole rotation and ionic polarization. Polar molecules ($H_2O$) are generally oriented randomly but when placed in an electric field, line up with the field. If the field alternates, the polar molecules alternate at the MW frequency to maintain this alignment. As they rotate, they disrupt H-bonds between adjacent water molecules, generating heat. The rate of heat generation is partially dependent on the freedom of the polar molecules to rotate. Because the movement of water molecules in ice is restricted, it is a poor MW energy absorber. In an electric field kinetic energy accelerates the ions in solution ($Na^+$, $Cl^-$, $Ca^{++}$). They collide with other ions and give up heat. The more ions in solution, the more frequent the collisions, the higher the kinetic energy release, and ultimately the temperature of the dielectric material.

The electrical properties that affect energy absorption and transmission are the dielectric constant ($\epsilon'$), the ability of a material to store electromagnetic energy, and the dielectric loss factor ($\epsilon''$), the ability of a material to dissipate electrical energy as heat (Englander and Buffler, 1991). These properties depend primarily on the moisture and salt content, which varies among and within foods. Dielectric loss factor increases with salt content (Guan *et al.*, 2004). Under most circumstances, the greater the moisture and salt content, the shallower the depth of MW penetration. Heterogeneous foods containing distinct mixtures (weak salt solutions, solids with high salt concentrations and little water, layers of fat interspersed with solids, colloidal suspensions) heat differently due to the dielectric constant and loss factors of the various phases. MW heating of foods with substantially different phase properties (frozen vs. unfrozen regions) can result in substantial problems. When a mixed food system is subjected to MW, energy is transmitted to (absorbed by) the phase with the higher attenuation factor before reaching the phase with the lower attenuation factor (Mudgett, 1986). Differential heating often occurs in semi-solid heterogeneous foods, such as filled pastries, because the high sugar phase absorbs the energy before it reaches the dry pastry phase. The same is true for liquids with suspended solids (soups).

MW generate heat instantly, to different degrees in different phases and/or subsections of heterogeneous foods. If the expected changes in the food system are time-dependent, the instantaneous nature of MW heating may be problematic. Also, heat is transferred within foods via conduction at a rate that is dependent on geometry, homogeneity and composition (high water, aerated) of the food. Ultimately, the type of heat-generated effects required to produce the expected quality characteristics in a food will determine whether or not MW heating is likely to be an acceptable method. Some of the heat-generated effects that must occur in foods include:

- Production and expansion of gases by leavening agents that may require heating to allow leavening compounds to dissolve (cakes, dough systems).
- Texture generation due to gas expansion with temperature increase (yeast doughs, meringues).
- Texture generation due to starch gelatinization (breads, cakes, potatoes, corn, navy beans).
- Texture generation due to protein denaturation (meat, egg white).
- Texture fixation due to protein denaturation and/or starch gelatinization *after* production of leaving gases expansion due to heat (baked goods).
- Texture generation due to steam generation from water (popcorn).
- Browning (Maillard reaction) due to surface dehydration of protein/reducing sugar-containing systems (baked goods, meats) and caramelization due to sugar dehydration.
- Thickening due to water evaporation (jams, jellies, candy).
- Crisping due to high surface temperature and water evaporation (pizza, cookies).
- Enzyme inactivation due to protein denaturation (fruits and vegetables to be frozen).

These changes occur during several major unit operations which occur in food manufacture and home cooking (Mudgett, 1989): (1) blanching, (2) cooking, (3) dehydration, (4) pasteurization, (5) sterilization, and (6) tempering (thawing).

## 5.2 Microwave interactions with food components

The major food components – water, carbohydrates, lipids, proteins and salts (minerals) – interact differently with MW. Because the primary mechanisms of MW heating are dipole rotation and ion acceleration, MW interactions with foods depend heavily on salt and moisture content. Water selectively absorbs the energy (Mudgett, 1990). In intermediate and high moisture products, the water, not the solids, absorbs the MW energy (Mudgett, 1989; Karel, 1975). However, because of their high heat capacity, they tend to heat unevenly. In drier products, the dissolved salts are concentrated (in the remaining water); if the solids exceed saturation level and precipitate, their ionic conductivities are limited. However, the solids themselves do absorb energy (marshmallow ignition: Mudgett, 1989). Low moisture products generally heat more evenly due to their low heat capacity (Schiffman, 1986).

Alcohols and the hydroxyl groups on sugars and carbohydrates are capable of forming hydrogen bonds and undergo dipolar rotation in an electric field. Low levels of alcohols or sugars in solution in foods have little effect on the interaction of MW with water and dissolved ions. At higher concentrations (jellies, candies), sugars can alter the frequency response of water with MW (Mudgett, 1989).

Proteins have ionizable surface regions that may bind water (or salts), giving rise to various effects associated with free surface charge. Lipids, other than the charged carboxyl groups of the fatty acids, which are usually unavailable due to their participation in the ester linkages of triglycerides, are hydrophobic and interact little with MW if water is present. MW do appear to interact with lipids (and colloidal solids) in low moisture foods as evidenced by energy absorption that cannot be accounted for by either free water or ion activity.

Variations in electric fields, food constituents and the location of the food in a MW oven can lead to nonuniform heating, allowing for less-than-ideal interaction of food components and survival of microorganisms. A number of techniques to improve uniformity of MW heating, such as rotating and oscillating foods, providing an absorbing medium (water) around the product, cycling the power (pulsed power), and varying the frequency and phase, can improve the situation; however, dielectric properties of the food must be known in order to develop effective processes (Yang and Gunasekaran, 2001; Guan *et al.*, 2004). Using moisture, salt, and fat content, and temperature (<70 °C) at MW frequencies, Calay *et al.* (1995) developed polynomial equations to estimate dielectric properties of grains, fruits and vegetables, and meat products. However, they concluded that it was impossible to develop a generic composition-based equation. This may be, in part, because as cooking temperature increases, the dielectric constant may increase while the loss factor and depth of penetration decrease (Zheng *et al.*, 1998). The result is that changes in formulation usually require re-evaluation with regard to dielectric properties and behavior upon exposure to MW energy.

## 5.3 Drying and finishing fruits, vegetables and herbs

Drying occurs when water vapor pressure differences between the food interior and exterior drive moisture transfer into the surrounding air. MW drying occurs by both dielectric and conventional heating. When above 50% moisture, as moisture content decreases, dielectric constant and loss factor decrease, especially at higher temperatures. Below 30% moisture content, MW penetration depth increases sharply (Feng *et al.*, 2002). MW heating in a drying system may adversely affect product quality due to nonuniform temperature distribution and difficulty in controlling product final temperature at low moisture contents.

MW energy can improve quality of fried products. Potato chips can be fried then dried by MW and hot air (Decareau, 1985). MW finish drying to maintain the temperature below the Maillard browning point, of russet burbank potato slices containing <0.9% reducing sugar, allows production of chips of acceptable color and texture (Porter, 1971). Potatoes containing >0.9% reducing sugar must be removed from the oil at an intermediate moisture content >13% to obtain acceptable color of the MW-finished product. Oil content of MW-finished chips may be 90% that of conventional chips because the fat is absorbed at prefinish moisture levels.

Air dryer temperatures need to be in the 60 °C to 90 °C range to operate efficiently and require up to 15 h to dry fruits and vegetables. During the constant rate drying period, drying rate is controlled by energy transfer to the wet surface of the food (Karel, 1975). Because of evaporative cooling, product temperature is lower than it will be later in the drying period. Once the surface dries, the mass transfer rate from the interior to the surface is insufficient to keep the surface saturated with water. During the falling rate period, drying is controlled by diffusion rate and decreases with decreasing moisture content. This results in higher surface temperature because the evaporative cooling effect of water at the surfaces is reduced. At air dryer temperatures, volatile flavor compounds are lost, structural changes such as case hardening may inhibit later rehydration, and extended drying times allow chemical and enzymatic reactions to degrade vitamins, flavor and color compounds (Karel, 1975; Yousif *et al.*, 1999a; Lin *et al.*, 1998).

Osmotic dehydration prior to MW dehydration efficiently removes water from fruits and preserves volatile flavor compounds. Prothon *et al.* (2001) osmotically dried apple cubes in 50% (w/w) sucrose, then dried them in a MW-assisted drier. Osmotic dehydration reduced drying time required to reach 10% moisture, but also decreased drying rate and effective moisture diffusivity. Osmotic pretreatment increased cell wall thickness and increased firmness of rehydrated apple pieces, but reduced rehydration capacity. Drying is more efficient when strawberries and blueberries are pretreated with 2% ethyl oleate and 0.5% NaOH (osmotic drying: Venkatachalapathy and Raghavan, 1998, 1999). The osmotic dehydration step was necessary to produce MW-dried strawberries that had similar rehydration ratio, texture, color and sensory properties to freeze-dried berries. Dipping blueberries in 2.5% ethyl oleate and 0.2% NaOH followed by sucrose osmotic dehydration prior to MW drying treatment reduces drying (from >80% to 15% moisture) time to one-twentieth of that needed for tray drying (Feng *et al.*, 1999). MW-dried frozen berries had a higher rehydration ratio. MW drying generated three unique flavor compounds (2-butanone, 2-methyl butanal, and 3-methyl butanal) while freeze-dried berries lost several, including the typical blueberry aroma, 1,8-cineole. Compared with hot-air dried berries, MW-dried cranberries have better color, softer texture and similar storage stability at room temperature (Yongsawatdigul and Gunasekaran, 1996).

Vacuum permits water vaporization at a lower temperature and at a faster rate than at atmospheric pressure. Application of vacuum reduces the boiling point of water and the drying temperatures. Combining vacuum and MW drying (VMD) reduces or avoids the heat and rate limitations at atmospheric pressure (Durance and Wang, 2002). MW energy is an efficient mechanism of energy transfer through the vacuum and into the interior of the food. Drying time for carrots has been shown to be 30% less for a combination of VMD and hot air drying than that of a conventional hot air drying method (Baysal *et al.*, 2002). No constant rate period existed and drying occurred mainly during the falling rate period. No differences occurred in dry matter content, bulk density or porosity; however, $a_w$ and color ($L$, $a$, $b$ values) were higher and rehydration capacities were higher in carrots dried by the combination method.

Puffing of some dried products is desirable to increase rehydration rate, produce crisp texture or produce a product with a near-fresh appearance. VMD can expand the structure of some products, producing a puffy texture similar to that created by frying (Durance and Liu, 1996). With the rapid conversion of water to steam, a pressure differential is generated between the interior of the food and the vacuum chamber that allows rapid transfer of moisture out of the food. When steam is produced inside the tissues more rapidly than diffusion to the surface, puffing results (Lin *et al.*, 1998; Sham *et al.*, 2001). Reducing exposure of produce to air during drying helps reduce oxidative deterioration, and preserve color, flavor and nutrients (Sham *et al.*, 2001). During VMD, non-enzymatic browning is minimal due to low processing temperatures (Yousif *et al.*, 1999b). Apple chips, tomato, potato and carrot slices are more puffy when MW dried under vacuum (Durance and Liu, 1996; Sham *et al.*, 2001; Durance and Wang, 2002; Lefort *et al.*, 2003). Banana chips that have undergone VMD have lower levels of volatile compounds, probably due to decreased formation of an impermeable solute layer on the chip surface that traps volatiles during conventional drying (Mui *et al.*, 2002). Crisper chips with higher volatile levels and sensory ratings were produced using 90% AD/10% VMD. Increasing the vacuum during MW drying produces a less dense, more puffed apple chip with a crisper texture (Sham *et al.*, 2001). Air-dried chips shrink more and collapse with almost no open structure. Treating apple slices with $CaCl_2$ prior to VMD resulted in crisper chips. In addition, the puffing effect differed due to apple variety. The VMD rate of tomatoes is 18 times that of the AD rate (Durance and Wang, 2002). VMD tomatoes are more puffed and are less than half as dense as AD tomatoes. They rehydrate more completely and at twice the rate as AD tomatoes, absorb 1.6 times as much water, and more closely resemble fresh tomato sections in terms of shape, size and color.

Fruit and vegetable variety can have significant effects on the VMD process. After blanching potatoes prior to VMD to produce fat-free chips, Lefort *et al.* (2003) reported that yellow flesh cultivars had lower moisture content and higher specific gravity, starch content, and crispness scores than red flesh cultivars. The authors concluded that cultivars low in specific gravity and starch content produced chips with a crispy but less rigid texture, which are desirable characteristics for chips produced by VMD. Color was unaffected. A $CaCl_2$ pretreatment prior to MW-assisted AD increases the hardness of rehydrated apples and potatoes (Arhne *et al.*, 2003). Water loss rates are similar during drying at 50 °C, but at 70 °C rates in potatoes are slower.

Retention of volatiles makes VMD an attractive preservation method for herbs and spices. Parsley subjected to VMD is greener immediately and after 8 weeks than hot air-dried samples (Boehm *et al.*, 2002). VMD preserved more than 90% of the essential oils compared to 30% by hot air drying and resulting in higher parsley-like and green-grassy aroma and less hay/straw-like off-flavor. MW drying of a variety of herbs, requiring 10 to 16 min, affected color, appearance, aroma and relative reconstitution capacity (RRC; Fathima *et al.*, 2001). The RRC for dried coriander, mint, fenugreek, shepu and amaranthus was 10.3, 10.3, 31.7, 32.8, and 38.3 respectively. Herbs with the lowest RRC (mint, coriander), had the lowest scores for flavor and color scores, while dried amaranthus, with the highest RRC, had scores similar to that of the fresh herb. Storage (60 d) results in little change in sensory properties. Working with garlic, Sharma and Prasad (2001) reported that in comparison with hot air drying (70 °C) alone, VMD reduced drying time by 80–90% and dried garlic products had higher sensory quality scores. Yousif *et al.* (1999b) found that VMD basil yielded 2.5 times the linalool and 1.5 times methylchavicol (the major volatiles) as air-dried samples. VMD basil had more volatiles than fresh basil due to chemical reactions during drying. AD basil was darker and less green. VMD samples had a higher rehydration rate, while the potential of the plant material to rehydrate was hindered in AD samples possibly due to maintenance of structural integrity of the cells.

## 5.4 Blanching and cooling fruits, vegetables and herbs

Prior to freezing, most vegetables and some fruits are blanched to preserve quality characteristics including color, flavor, aroma and nutrient content. Many of the quality changes that occur during frozen storage are attributed to enzyme systems including peroxidase, lipoxygenase, cysteine lyase, pectin methyl esterase, polygalacturonase, lipase, proteases, ascorbic acid oxidase, and chlorophyllase (Katsaboxakis and Papanicolaou, 1984). Produce is typically blanched by subjecting it to steam or hot water (70–105 ºC) for a prescribed time. The advantages of MW blanching (MB) over conventional heat blanching methods (water or steam) include in-depth heating without a temperature gradient, and rapid inactivation of enzyme complexes that cause quality degradation coupled with minimal leaching of vitamins, flavors, pigments, carbohydrates, and other water-soluble components (de Ancos *et al.*, 1999).

While a number of enzymes catalyze reactions that reduce fresh produce quality, peroxidase, as the most heat resistant and durable, is generally used as an indicator enzyme to assess blanching adequacy (Gunes and Bayindirli, 1993; Barrett *et al.*, 2000). Peroxidase catalyzes reactions that cause undesirable changes including off-flavor, aroma and color, as well as loss of some nutrients (Adams, 1991; Brewer *et al.*, 1995; Hemeda and Klein, 1990). If peroxidase is inactivated, it is assumed that all other enzymes of concern have also been inactivated (Gunes and Bayindirli, 1993). Many blanching methods (boiling water, steam, MW) inactivate peroxidase in a variety of vegetables (Brewer *et al.*, 1994, 1995; Begum and Brewer, 1997, 2001a, b; Klein, 1992). However, the amount of energy required to inactivate 100% of the peroxidase is often detrimental to other product characteristics. Kidmose and Kaack (1999) reported that MW blanching asparagus sufficiently to inactivate peroxidase resulted in a similar or higher shear force value but a lower vitamin C content than steam or immersion blanching. Gunes and Bayandirli (1993) showed that a less severe heat treatment is required to inactivate indicator enzymes using MB, resulting in better product flavor, color, texture, and nutritional value. Brewer and Begum (2003) reported that broccoli blanched at the lowest power level (30%) had >27% of the original peroxidase activity remaining after 4 min. That subjected to 70% power was reduced to <7% of original activity. The lowest peroxidase activity (<6%) occurred in that heated at high power (100%) for 2 min followed by that heated at medium high and medium low powers (70% and 55%) for 3 or 4 min. At 30% or 55% power, 3 min or 1 min, respectively, were required to reduce peroxidase activity of asparagus by 90%. Glasscock *et al.* (1982) reported that, after 6 months of frozen storage, MB broccoli and zucchini retained high levels of peroxidase activity. In green beans, a 30-second blanch treatment inactivated 93% of the original peroxidase; 1 min was required for complete inactivation (Katsaboxakis and Papanicolaou, 1984). Ramesh *et al.* (2002) reported that peroxidase inactivation (90% reduction of original) by MB varied substantially: spinach 190 s, bell peppers 290 s, carrot 120 s. MB was comparable to water blanching when the ratio of surface area to volume of vegetable was lower (carrot, pepper), but not for those with higher ratios (leafy vegetables like spinach). Significant variation in peroxidase inactivation occurs from the end to the middle of ear of MB corn on the cob (Dietrich *et al.*, 1970). Samples stored at −20, 0 and 20 ºF had better flavor retention when microwave-blended for 4 min than did those steam-blanched for 12 min. A combination of water and MB gave good peroxidase inactivation without noticeable dehydration.

Blanching to inactivate enzymes responsible for quality deterioration and nutrient destruction can reduce content of heat-labile and water-soluble vitamins. Reducing time of heat exposure, regardless of the mechanism, reduces nutrient losses. Early work by Proctor and Goldblith (1948) demonstrated that MB of broccoli, spinach, carrots, green peas, and green beans, prior to freezing, resulted in higher vitamin C retention than did boiling water blanching. In general, MB and cooking of vegetables, because it is more rapid, allows them to retain more heat-labile nutrients (Mudgett, 1989). Whether leaching occurs depends on the exposed surface area that is in contact with cooking liquid.

Ascorbic acid (AA), one of the most labile nutrients in fruits and vegetables, is water soluble, pH-, light-, and heat-sensitive, readily oxidized, and affected by the naturally occurring enzyme system, ascorbic acid oxidase (Klein, 1992; Ihl *et al.*, 1998). Preservation of AA in vegetables, particularly those that are good sources of it (e.g. broccoli), is important in preserving food quality. Retention of AA during blanching depends on the type of energy used, time of exposure, presence of water and cut surface area of the fruit or vegetable. MW heating may cause significant AA losses (Drake *et al.*, 1981). Brewer and Begum (2003) reported that as MB time of broccoli increased, AA content decreased regardless of power level. Higher power levels (70% and 100%) produced broccoli with less AA at all blanching times than did lower power levels (30% and 55%). Brewer *et al.* (1995) reported ~20% decrease in AA content of broccoli MW-blended for 5 min in water at 100% power. Microwave blanching of green beans for 4 min at 70% or 100% power decreased AA content by nearly 50% (Brewer and Begum, 2003). Compared to traditional blanching, MB reduced AA losses by 18% for spinach, 8.5% for bell peppers and 33.5% for carrots (Ramesh *et al.*, 2002). Banana puree prepared from MB bananas had higher AA content, total soluble solids, total sugars, tannins, acidity and sensory scores but lower pH than that prepared from water bath blanched bananas (Premakumar and Khurdiya, 2002). MW inactivation of polyphenol oxidase, peroxidase and pectin methyl esterase was comparable to traditional blanching methods.

Glasscock *et al.* (1982) reported that, after 6 months of frozen storage, MB broccoli and cauliflower retained less chlorophyll, had higher shear force values and lower sensory evaluation scores than the water blanched vegetables for quality factors of importance to consumers. Larger sized samples of carrots and sweet potatoes had better peroxidase inactivation when blanched (30–180 s) in the MW than in boiling water for mass-equivalent times (Ramaswamy and Fakhouri, 1998). All blanched, frozen stored samples were acceptable after 7 months of storage; however, samples blanched for intermediate periods were superior. Lane *et al.* (1984) reported that no differences existed for flavor of green beans and mustard greens due to blanching method. In beans and mustard greens, steam blanching produced a texture equal to MB vegetables but chlorophyll degradation was greater.

The principal enzyme responsible for the browning reaction in mushrooms (and other light colored fruits and vegetables) is polyphenoloxidase (PPO). Direct application of MW energy to whole pieces of fruits or vegetables is limited by temperature gradients that can vaporize internal water and damage mushroom texture. Combining MW and hot-water bath treatment of whole mushrooms can completely inactivate PPO in a short time with minimal anti-oxidant loss, weight loss and shrinkage (Devece *et al.*, 1999). MW inactivation of polyphenol oxidase in bananas has been shown to be comparable to traditional blanching methods (Premakumar and Khurdiya, 2002).

Heating of legumes to destroy anti-nutritional factors is required in order for them to support nutrient needs. Otherwise, their digestibility and PER value are poor. MW heating destroys haemagglutinins and trypsin inhibitors without affecting the protein quality of most legume seeds. MW treatment in combination with hot air drying can decrease trypsin inhibitor activity and soluble carbohydrate (raffinose, stachyose) contents (Kadlec *et al.*, 2003). Heat-soaking soybeans prior to MB produces more trypsin inhibitor destruction and a higher PER than does MW-heating dry soybeans (Hernandez-Infante *et al.*, 1998). Yoshida *et al.* (2002) reported that MW roasting sunflower seeds (12 min) resulted in no significant loss or change in the content of tocopherols or PUFA in the kernels and only minor increases in oxidation indicators (carbonyl value, *p*-anisidine value).

Preservation of color of produce is an important quality consideration. MB of strawberry juice and concentrate has been shown to improve color stability and protect anthocyanin pigments, reactive phenolics, and AA during 8 weeks of storage (Wrolstad *et al.*, 1980). MB of kiwi fruit puree has been shown to inactivate peroxidase and PPO, with minimal loss of bright green color and only moderate degradation of chlorophylls (de Ancos *et al.*, 1999). While boiling water blanched artichokes have the best color, MB has been shown to produce the best AA retention and peroxidase inactivation (Ihl *et al.*, 1998). Color retention was also better in MB brussels sprouts (Dietrich *et al.*, 1970). Kidmose and Martens (1999) found that MB produced carrot slices with higher carotene, AA, and sucrose levels than other blanching methods both immediately following blanching and also after 3 months of frozen storage. Carotenoid loss in carrots was reduced by more than 35% compared with traditional blanching (Ramesh *et al.*, 2002). Brewer and Begum (2004) reported that the $L^*$ value of broccoli subjected to higher power levels (70% and 100%) for $\geq$2 min decreased, indicating that it became darker; however, that subjected to lower power (30% and 55%) was as light as or lighter than raw broccoli. Significant darkening occurred in both stems and florets of broccoli MB at 100% power for 5 min (Brewer *et al.*, 1995). After MW heating, the hue angle of green beans increased, indicating that color was less true green. Longer times and/or lower power levels produced green beans with hue angles equal to those subjected to shorter times and/or higher power levels (Brewer and Begum, 2003; Brewer *et al.*, 1994). Hue angles of asparagus subjected to 100%, 70% and 55% power did not differ over the 4 min treatment period. Similar results have been reported for instrumental color evaluations ($L^*$, $a^*$, $b^*$, hue angle) of MB asparagus (Begum and Brewer, 1997; Brewer and Begum, 2003).

### 5.4.1 Cooking

Vegetables are often cooked to increase palatability and digestibility. Mabesa (1978) found that while AA content of MW-cooked, frozen peas was lower, retention of chlorophyll and organic acids (lactic, succinic, malic, citric) was higher for peas cooked without water. Effects were smaller for carrots. Those cooked without water had higher flavor scores and carotene retention than those cooked with water. While MW cooking of vegetables generally results in better nutrient retention, there is no one method that produces overall superior sensory characteristics when considering color, flavor, texture, and moistness (Schnepf and Driskell, 1993).

Cooking starchy tubers gelatinizes the starch softening the texture. Wilson *et al.* (2002) reported that, after a lag of 4 min, water loss during MW cooking of potatoes was rapid and linear. Starch gelatinization began at the surface and in the center, then spread throughout the tuber cross-section after 1 min. Results suggest that the MW cooking process is divided into two phases: (1) the MW energy input raises the internal temperature to about 100 °C, then (2) water is vaporized at a constant temperature. Immersing potatoes in boiling water after the first phase prolonged cooking time compared to MW heating, suggesting that MW treatment affects texture by a mechanism independent of the thermal profile induced by cooking.

MW heating of peas has been shown to result in greater AA retention than conventional cooking in water. Cooking without added water increases AA retention compared to cooking with water added (Mabesa and Baldwin, 1979). These results may be a function of leaching during conventional cooking in water. Hudson *et al.* (1985) compared the effects of steaming, MW heating and boiling of frozen and fresh broccoli on nutrient content. Steaming was least detrimental and boiling most detrimental to thiamine and riboflavin content, although MW and steam heating produced products with equivalent AA content. MW-cooked broccoli has been shown to reduce concentrations of glucosinolate breakdown products, probably because of inactivation of myrosinase that normally breaks down glucosinolates (Howard *et al.*, 1997).

## 5.5 Dough systems

Conventional baking occurs in four stages: (1) formation of white crust (eliminated in MW baking), (2) heat transmission from crust to interior (instantaneous in MW baking which results in reduction of time to reach stage 3), (3) gelatinization/cooking (rapid, potentially incomplete in MW baking), and (4) browning (absent in MW baking) (Pei, 1982).

MW-baked dough products are often of lower quality than conventionally baked products (Moraru and Kokini, 2003). Differences in heat and mass transfer patterns, insufficient starch gelatinization due to very short MW baking times, MW-induced changes in gluten, and rapid generation of gas and steam result in crustless products which are tougher and coarser and have less firm textures than conventionally baked products (Yin and Walker, 1995). They often have reduced height, gummy texture, hard crumb, and an undesirable moisture gradient along the vertical axis of the product (Bell and Steinke, 1991). During baking, two simultaneous processes occur: (1) energy (heat) is transferred to the food and (2) this causes changes (starch gelatinization, protein denaturation) within and at the surface of the product. In conventional baking, the pattern of temperature rise in the interior differs substantially from that near its surface. During MW heating, the dough near the surface is heated instantaneously but heat must be transferred to the interior via conduction (Pyler, 1988). This instantaneous surface heating promotes nearly instantaneous water evaporation as well. In addition, the cellular structure of dough makes it a poor heat conductor.

Free liquid- and protein-bound water move into the starch component at about 60 ºC, enabling gelatinization to occur. This forms the initial dough structure that will trap evolving gases. MW drive moisture from the interior to the surface of the dough. Because the rate of heat loss at the dough surface, due to water evaporation, may exceed the rate of heat absorption by the dough, sufficient temperatures may not be achieved in some portions of the dough to cause required changes and adequate structure may not form (Pyler, 1988). Consumer acceptability requires that the bread crumb has a distinct resilience. This resilience develops above 80 ºC (Yin and Walker, 1995). Firmness appears to be related to starch gelatinization. In model starch systems, the gelatinization sequence is similar for MW and conductive heating; however, it occurs more rapidly in a MW system than in a conventional system (Goebel *et al.*, 1984). Lowering the temperature of or promoting starch gelatinization by changing ingredients or chemically modifying starch can benefit MW-baked bread temperature-dependent effects. When subjected to MW energy, both corn and rice starch gelatinize more slowly and at a lower temperature than wheat starch (Ndife *et al.*, 1998). Using starches that are pregelatinized, have high dielectric properties and low gelatinization enthalpy can alter the temperature at which gelatinization occurs, enhancing final texture. Increasing fat content and adding emulsifiers to inhibit gelatinization can reduce starch granule size and improve texture (Sumnu, 2001).

Rogers *et al.* (1990) suggested that the toughness observed in MW-baked bread is associated with changes occurring in the gluten fraction that may not be due to disulfide bond formation. MW-heated gluten balls exhibit a different pattern of water loss than those heated by conventional methods (LePage *et al.*, 1989). Water loss rate in conventionally heated gluten balls increases to ~50 g/min, then stabilizes when the surface temperature approaches 100 ºC. This period of stable water loss rate does not occur in MW-heated systems. The rate of water loss increases rapidly when interior temperatures reach 60–70 °C. The conventionally heated system expands in volume during this latter stage. In general, water loss occurs at a much higher and more constant rate in MW-heated dough systems than in those baked conventionally (Umbach *et al.*, 1992). Changes in water loss rates result in altered time-temperature patterns which may change both starch gelatinization and protein denaturation rates (Rogers *et al.*, 1990). In MW-heated dough systems, while the water loss rate is high, the time over which it is experienced by the dough is dramatically reduced. Therefore, because of evaporation at the surface, cooling is more important in MW than in conventionally heated materials (Datta, 1990). Reducing the toughening effects of MW baking may require reduction of gluten protein size by breaking the disulfide bonds. Increasing or adding agents such as L-cysteine, glutathione, yeast autolysate and bisulphites by a factor of two to three compared with formulations for conventionally baked products is one way to break disulfide bonds and reduce gluten toughness (Sumnu, 2001).

Based on the US patent literature, Shukla (1993) described strategies for development of new microwaveable dough systems. He recommended developing low $a_w$ dough incorporating salts and dextrose, increasing the amount of shortening and emulsifiers to prevent starch granule gelatinization and swelling, reducing gluten protein size, and using texturizing agents to produce uniform texture and minimize moisture redistribution. To aid cake volume and texture, LaBell (1992) described a dry cake mix system that used a mixture of granulated and powdered sugar to increase sugar availability and to slow down starch gelatinization, increased amounts of leavening agent and water, used double-acting baking powder, and incorporated xanthan gum into the formulation.

MW proofing and baking of yeast-leavened dough systems can be successful with modifications of both the formulation and the process. During yeast fermentation, enzymes (amylases, proteases) are produced which have substantial effects on water absorption capacity, consistency, stickiness, and gluten softening, all of which affect dough texture and ultimately, performance. Early work by Lorenz *et al.* (1973) suggested that MW baking required no formulation change for breads or rolls, but fermentation and proofing times had to be decreased. MW baking can produce loaves of good volume and texture, and normal weight loss, but they often lack a normal crust, have an unnatural appearance and lack mechanical stability (Chamberlain, 1973). Water-soluble dextrins (the end products of amylase action) are reduced by rapid baking, but the outer layer becomes excessively dry. A combined MW-thermal baking process using biscuit flour (about 9% protein) and added malt has been shown to give a better crumb structure than a conventionally baked loaf made from the same flour. Increasing yeast level and proof time can improve the quality, particularly volume, of yeast-leavened products (Willyard, 1998). MW proofing followed by conventional oven browning (Dungan and Fox, 1969) or baking at low enough frequencies (915 MHz) to allow sufficient penetration can allow baking to be complete (Martin and Tran, 1981).

Lack of crust browning commonly occurs in MW-baked dough products. There is no caramelization and Maillard browning because the product surface never reaches a high enough temperature (150 ºC) for these reactions to occur (Sumnu, 2001). In addition, during MW baking, flavor compounds may be lost due to distillation, and they may be chemically degraded or bound by starches and proteins. Flavors may be added to MW systems to supply the typical baked taste produced by Maillard reactions and caramelization in addition to the characteristic attribute (Osnabrugge, 1989).

While refreshing of stale bread, accomplished at 80 ºC in a conventional oven, returns the elastic modulus to a point similar to that of freshly baked bread, MW reheating does not completely reverse the effects of ageing and often causes toughening (Persaud *et al.*, 1990). Although the mechanisms of toughening are not understood, modifying the formula by adding emulsifiers (Huang *et al.*, 1991), using pregelatinized starch (Saari *et al.*, 1991), adding fiber and increasing shortening (Engelbrecht and Spies, 1992) can reduce the toughening effect induced by MW reheating. Adding 1% hydrated and ethoxylated monoglycerides, glycerol mono rizinolat, monooleate, castor oil, or castor oil + shortening can produce bread which allows MW refreshening without noticeable toughening (Miller and Hoseney, 1997). Fiber can also decrease MW-induced toughening when additional water is included. While 8% fiber is most effective, it is not practical as the dough becomes highly elastic and unmachinable (Engelbrecht and Spies, 1992). MW proofing of chemically leavened dough products can be accomplished in less than 5 min (compared with 40–60 min under conventional conditions) if special flours and dough conditioners are used to control dough rheology and integrity (Schiffman *et al.*, 1971).

MW-baked batters develop center-to-edge temperature gradients early in the baking period which ultimately converge at about 100 ºC (Lambert *et al.*, 1992). Temperature gradients are generally smaller in unleavened systems than in leavened systems. Edge temperatures rise more rapidly in fluid batters subjected to MW energy than in those subjected to conventional heating. Water loss rates are higher for MW than for conventionally heated systems, increasing slowly during the first several minutes of heating until the batter temperature reaches 60–70 ºC. In MW-heated systems, it continues to increase over the baking period, while that of conventionally heated systems exhibits an increase followed by a stable rate period and a subsequent rate increase; the latter may reflect pressure gradients due to expansion of leavening gases (Lambert *et al.*, 1992).

MW-heated products exhibit distinct porous and gelled regions that may reflect nonuniform heating. The structure in these regions develops much less uniformly in MW heated than in conventionally heated cake batters (Lambert *et al.*, 1992). Given the shorter heating time required for MW than for conventional heating of batters, having $CO_2$ available early in the baking period (tartrate vs SAS-P) might enhance development and stabilize the porous solid foam system (Lambert *et al.*, 1992). Timing of leavening gas release in chemically leavened products is critical. Dorko and Penfield (1993a, b) found that encapsulated melt point (EMP: 43, 52 and 60 ºC) of sodium bicarbonate increased batter pH from 0 to 1 week. Specific volume of MW-baked muffins containing EMP 43 ºC or

60 ºC increased with storage and were higher than those of other muffins, while EMP 52 ºC MW-baked muffins had the lowest specific volume. MW-baked muffins appeared flatter than conventionally baked muffins and had lower $L^*$ values. Powdered sodium bicarbonate produced muffins with greater specific volume than those containing the granular form.

After evaluating the time history of temperature and moisture profiles in a wheat-based biscuit during MW baking at various power levels, Naikar and Castell-Perez (1995) reported that, based on drying characteristics of dough, raise and baking time, texture and color, heating at 50% power produced a biscuit of acceptable texture and raise quality, although color remained a problem. During MW and conventional baking of canned biscuit dough, Pan and Castell-Perez (1997) found drastic increases in specific volume and modulus of elasticity at the beginning and the ending periods of both processes. Weight loss was linearly related to baking time, but the weight loss rate constant for MW baking was higher than for conventional baking. MW baking for 50 s best resembled the textural characteristics of wheat dough under conventional baking for 10 min. MW baking produced higher viscosity and modulus of elasticity which translates into baked biscuits with undesirable, tougher texture.

The quality of cakes (high sugar, high fat) is often adversely affected by MW baking compared to conventionally baked cakes in terms of appearance, tenderness, mouthfeel, flavor, and texture (Hill and Reagan, 1982). Addition of emulsifiers (glycerol monostearate, saturated and unsaturated monoglycerides), water-binding agents (methyl cellulose) or modified starches (instant, pregelatinized) improves moistness and reduce gumminess of MW-baked cakes (Bell and Steinke, 1991; Baker *et al.*, 1990), and use of crystalline sugars improves air cell uniformity (Baker *et al.*, 1990). The texture of high sugar, low moisture, flour-based products (brownies) baked in a MW oven can be controlled by regulating the steam retention capabilities of the batter by using an emulsifier (diacetyl tartaric esters: Yasosky *et al.*, 1990). Jackson and Roufs (1989) describe a patented process for bakery product dry mixes. These mixes, especially those for MW layer cakes, use high levels (0.1–5 wt%) of nucleating agent(s), that are water-insoluble materials with a particle size of 20–200 $\mu$m, preferably microcrystalline cellulose particles. These nucleating agents used in MW-baked cake mixes produce cakes of comparable quality, structure, volume and texture to those baked in conventional ovens.

Stinson (1986) found that in devil's food cake baked in a MW/convection oven, the most important factors affecting quality were the number of layers baked at a time, baking pan characteristics, and initial oven temperature. Crust color, moistness, and cake symmetry were affected by these conditions. Cakes baked in single layers received lower sensory scores and had sticky, less red crusts than double layers. Cakes baked in aluminum pans were flat. MW baking of sponge cake batters results in an almost linear evolution of $CO_2$ and volume increase until the batter reaches ~100 ºC after which volume remains constant (Grau *et al.*, 1999). Baking to a core temperature just sufficient to produce a stable crumb that prevents volume loss after baking in a conventional oven allows cakes to be MW reheated without producing gummy, tough products and enhances browning. Unsaturated monoglycerides increase cake volume (Baker *et al.*, 1990). It may be that monoglycerides with straight-chain fatty acids complex more easily with amylose, altering starch behavior during baking (Sumnu, 2001). Depending on the product, emulsifiers can double the range of acceptable MW heating time. This is probably due to their ability to complex with starch and emulsified water, reducing water loss rate and preventing premature crust toughening. However, because they are polar molecules themselves, they may affect the dielectric properties of the food (Schiffman, 1997).

MW baking of cookies can result in rapid surface drying and differential shrinkage near the surface that produces mechanical stress. Sufficient mechanical stress results in cracking. MW-baked cookies may not brown and may lack crunchiness (Mudgett, 1989). Conventional baking followed by MW heating results in a more uniform moisture distribution than does conventional baking alone. A moisture gradient >1.5%/cm in cookies produces significant cracking (Bernussi *et al.*, 1998). Cookies baked in MW ovens often expand less, apparently due to shrinkage. While conventional baking followed by MW baking can produce cookies with less cracking, color may be darker (Bernussi *et al.*, 1998). This process can reduce the moisture gradient from >2%/cm to <1%/cm, and cracking from >40% to zero (highest power level for 29 s).

Crisping and browning are often a problem when baked products have relatively low surface temperatures. The surface must reach at least 150 °C for browning and crisping to occur. Heat susceptors, metallized plastic film laminated to paperboard, absorb MW energy and convert it to heat (200–250 °C) which is transferred to the product by conduction heat, creating areas hot enough to evaporate water, crisp and brown the food (Zuckerman and Miltz, 1992). Additional salt, which increases energy absorption near the surface, raises surface temperature and enhances browning of dough products (Nott *et al.*, 1999). Coloring agents have been used to produce crust browning (Sumnu, 2001). Combining MW baking with convection or impingement cooking can also increase browning and crisping, and develop flavors.

## 5.6 Meat

### 5.6.1 Cooking

Cooking meat requires denaturation of the contractile proteins (myosin and actin) and solubilization of the connective tissue (collagen). MW heating can solubilize more collagen (percentage of hydroxyproline) than does boiling (Zayas and Naewbanij, 1986). In general, MW-cooked meat and poultry have higher cooking losses than those cooked by conventional methods (Riffero and Holmes, 1983; Moody *et al.*, 1978); however, losses and changes in palatability depend on both species (beef, pork, poultry) and cut. Payton and Baldwin (1985) reported that total cooking losses, evaporation and drip losses were greater for steaks cooked in MW convection ovens than for those cooked in forced air convection or conventional ovens, though they found no difference in juiciness, tenderness, beef flavor, or external color of the steaks. Howat *et al.* (1987) found that evaporative losses were higher for oven dry-roasted beef than for MW-convection roasts, which were higher than MW roasted samples. Drip losses were highest for MW, followed by oven roasted, then by MW–convection roasted samples. Although Instron shear values did not differ, oven dry-roasted samples were rated more tender by taste panelists.

Fulton and Davis (1983) reported that lean meat cook yield was the same for round and chuck roasts, whether cooked conventionally or in the MW, while it was lower for MW-cooked rib eye roasts than for conventionally cooked roasts. Tenderness, softness, natural flavor and tenderness (shear force) were unaffected. MW-cooked rib eye roasts were browner and less juicy. Hines *et al.* (1980) found no differences in drip loss of MW-cooked chops, though evaporative and total losses were lower than for broiling. Flavor scores were highest for broiled chops and did not differ due to MW power level. Chops cooked at low MW power were juiciest and tenderness varied inversely with cooking rate. Overall acceptability was lowest for chops cooked at high MW power level. Hammernick-Oltrogge and Prusa (1987) found that cooking time of chicken breasts increased with decreasing power level, but cooking losses were not affected. Both sensory and instrumental tenderness (Instron compression) were best at 60% power level, while juiciness, mealiness and flavor were unaffected by power level. Barbeau and Schnepf (1989) reported that convection–MW-cooked chicken was more tender, juicy and acceptable than MW-cooked chicken. Flavor intensity was similar. Thiamin retention ranged from 77% in conventionally cooked chicken breasts to 98% in MW-cooked chicken legs. Dunn and Heath (1979) determined that exposure of pre-rigor broiler muscle to MW energy decreased glycogen metabolism but had no effect on ATP retention and did not improve tenderness.

Addition of fluids and other ingredients, and cooking from the frozen state, appear to improve the overall outcome when meat is cooked in the MW. Hoda *et al.* (2002) reported that curing buffalo meat using a polyphosphate solution increased pH from 5.70 to 6.12 and reduced cooking loss from 17.5 to 10.3%. Visual color and tenderness improved for meat products cooked in the MW oven. Textural analysis showed greater peak forces for hot air oven-cooked products compared to MW-cooked products. MW cooking time was shorter and produced more uniform heating, though flavor was better in hot air oven-cooked products. Drew *et al.* (1980) reported that when cooking started from the frozen state, roasts cooked by MW on low power were comparable to those conventionally cooked in sensory quality. Roasts cooked from the frozen state by MW on high power had lower palatability scores (except flavor) and higher shear values.

Manufacturers' cooking instructions for raw foods are designed to produce organoleptically acceptable end products, and may not address the safety of the cooked food. This is a potential problem for meat products. Farber *et al.* (1998) reported that of 93 *Listeria*-positive roasting chickens MW-cooked to 87 °C as a uniform target, 9.7% remained listeria positive. The authors concluded that MW ovens were generally unable to heat chickens uniformly, resulting in microbial survival. Unda *et al.* (1991) reported that *Clostridium sporogenes* and *Listeria monocytogenes* inoculated onto the surface and via injection into the interior of beef roasts survived MW cooking in a bag to 62.8 ºC. Both species survived one cook cycle when inoculated onto the surface and two cycles (reheated) when inoculated into the interior. Mendiratta *et al.* (1998) found that while MW cooking resulted in lower fat contents, and higher water-holding capacity, TBA value and cook yield than conventional oven cooking, MW-cooked samples had higher total bacterial counts. However, cooking method had no effect on psychrotroph counts, *S. aureus*, yeasts and filamentous fungi or sensory characteristics.

Visually, MW-heated beef may appear to be unevenly cooked. MW-thawed and cooked roasts and steaks may be redder in the interior, and lighter and more yellow on the exterior, than their broiled counterparts (Riffero and Holmes, 1983; Moody *et al.*, 1978). Color variation and microbial survival are due to uneven heating rates. The irregular shape of many whole meat cuts results in significantly non-uniform heating. In addition, bone reflects MW, causing overheating in the regions adjacent to the bone (Van Zante, 1973). MW distribution based on physical parameters derived from beef has been modeled by Fleischman (1999). The temperatures experienced by a MW-heated beef slab can vary by as much as 50 ºC. This variation is a function of slab thickness (between 1 and 3 cm) and time, or a function of time alone for slabs >4 cm thick. Thermal insulation at the faces of the slab increases this variation.

MW are used primarily for reheating precooked meat products, making cook loss even more problematic. Because fluid losses appear to be the primary roadblock in producing precooked, reheatable meat products, adding fluid (enhancement) has been evaluated in an effort to produce a juicy product. Pumping fresh meat to 10% over original weight to produce 1% salt and 0.3% phosphate in the final product can produce an acceptably palatable, value-added, precooked product (boneless pork roast) designed for MW reheating (Boles and Parrish, 1990). However, flavor may suffer during MW reheating. Cipra and Bowers (1971) reheated precooked frozen turkey in MW and conventional ovens and found more stale, aldehyde-like aroma in conventionally reheated light turkey meat. Meaty-brothy flavor and aroma were more intense in MW-reheated meat. MW-reheated light meat was flat or bland flavored, less juicy and higher in moisture content than conventionally reheated meat. Steiner *et al.* (1985) found that MW cooking had no effect on chicken flavor or aroma, though MW reheating resulted in less warmed-over flavor than conventional reheating. King and Bosch (1990) reported that TBA analyses showed that multiple reheating of dark turkey meat using MW energy retarded lipid oxidation, including that caused by NaCl (2.0%) which was a pro-oxidant compared to KCl (2.0%). Hsieh and Baldwin (1984) reported that MW reheating did not influence warmed-over aroma or flavor or TBA values of cooked stored roast beef. Development of off-flavors may be somewhat species-specific.

### 5.6.2 Tempering

Tempering of frozen food, wherein it is heated to just below the freezing point (−2 to −4 °C) then allowed to thaw fully at refrigeration temperature, can make food easier to slice and reduce drip loss. Frozen meat can be tempered by MW energy. At temperatures slightly below 0 °C, the outer layer of the meat can absorb significant amounts of energy, resulting in overheating near the surface. Frozen foods thawed in the MW may experience 'runaway heating' due to selective heating of the liquid phase (opposed to the crystalline phase of the ice). MW power penetration is greater at 915 MHz than at 2450 MHz so it is more suitable for heating thick masses of materials (Decareau and Peterson, 1986). Tempering frozen food has been more successful at 915 MHz than at 2450 MHz, partly because of surface overheating at the latter frequency. This can be offset, to some degree, by circulating cold air around the product; however, this may increase drip losses by up to 10%. MW tempering requires less time and space, produces little or no weight loss, increases juice retention, and reduces bacterial growth (Rosenberg and Bögl, 1987).

## 5.7 Flavor and browning

Flavor may be a problem in MW-cooked foods because flavor volatiles distill off, bind to proteins and other molecules or fail to develop at all. A number of methods have been developed to prevent or offset these flavor problems. Burns (1996) described a patented extraction process wherein substrates are mixed with MW-transparent solvent and exposed to MW which liberates target compounds from natural materials (e.g. spices). Selectivity can be varied by altering solvents/conditions. MW extraction in combination with liquid $CO_2$ can be used as an alternative to supercritical fluid extraction (decaffeination of coffee, defatting of cocoa powder). Parliment *et al.* (1991) patented a process to generate desirable aromas when a food and/or package is subjected to MW radiation. The aroma-generating material, consisting of a sugar alone or in combination with an amino acid source, and an effective amount of a MW susceptible material for conductive heat transfer sufficient to catalyze the desired chemical reactions.

Peterson *et al.* (1994) investigated propylene glycol as a potential browning/flavoring agent for microwaved foods using a proline/xylose model system for the Maillard reaction at 0, 2.5 or 5% moisture. Good browning and flavor development were attained when no water was added to the system. The characteristic baked/roasted aroma produced decreased as moisture content increased. Flavor development was still apparent in the 5% moisture system (GC/MS analysis of flavor compounds) despite very little browning. Yeo and Shibamoto (1991) found that electrolytes (0–0.5M NaCl, $CaCl_2$, $FeCl_2$, or $NaSO_3$) enhanced both flavor production and browning intensity in an L-cysteine/D-glucose model system. NaCl promoted the development of the greatest amount of volatiles (seven times the control) and $FeCl_2$ the least (three times the control). NaCl produced the most browning while $FeCl_2$ produced the least. Sahin *et al.* (2002) evaluated browning treatments for breads. When susceptors were used with MW baking, desired browning and hardness were obtained on the bottom surfaces of the breads but did not affect surface color significantly. Breads coated with the solution containing sodium bicarbonate (10.5%), glucose (31.6%) and glycine (5.3%) did not have the desired crust color or hardness, while conventional browning at 200 °C achieved browning on top and bottom surfaces and crust formation on the bottom surface in 8 min.

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# Part II

# Applications

# 6

# Microwave technology for food processing: an overview

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## 6.1 Introduction

This chapter presents an introduction to the field of industrial microwaves and introduces various processing applications of microwaves for food and biological materials.

Over 60% of homes in the UK and over 90% of homes in the US and Canada possess a microwave oven and an ever-increasing range of processed foods is produced with microwave reheating instructions. The uptake of microwave processing by industry has been far less dramatic (Giese, 1992; James, 2000). Areas that have shown promise and where systems have been developed are drying, pre-cooking of bacon/meat, pasteurization of ready meals and the tempering of meat and fish. There is, however, a growing experimentation on various new applications such as blanching (Begum and Brewer, 2001), baking (Sumnu, 2001) and microwave phyto-extraction (Hong *et al.*, 2001; Williams *et al.*, 2004).

Microwave heating applications have been researched since the late 1940s with various levels of success. For the past 40 years, there have been investigations on the development of microwave heating applications in agriculture, with target applications in grain drying (Bhartia *et al.*, 1973; Shivhare *et al.*, 1994) and insect control (Nelson, 1973). Since then, numerous food applications have been studied with some successful industrial developments. Process applications were studied for food drying (Maurer *et al.*, 1971; Sobiech, 1980; Tulasidas *et al.*, 1995; Beaudry *et al.*, 2003), for blanching (Chen *et al.*, 1971; Avisse and Varaquaux, 1977; Ramesh *et al.*, 2002; Severini *et al.*, 2004), for pasteurization (Lin and Li, 1971; Jaynes, 1975; Zhang *et al.*, 2004) and for cooking (Nykvist and Decareau, 1976).

## 6.2 Industrial microwave applicators

Practical applications of microwave heating did not start until after World War II following the development of the cavity magnetron during the war by two British physicists Henry A. Boot and John T. Randall (Brittain, 1985; Osepchuk, 1984). The discovery of microwave heating was triggered by observations from many individuals during research conducted at Raytheon on microwave waveguides with observations of warmth and popping corn near radiating tubes. The appreciation of the heating powers of microwaves and their potential application is attributed to Percy Spencer at Raytheon, who went on to patent many microwave heating applications. During many years, scientists at Raytheon, GE Westinghouse, among many others, worked on equipment and applications development for industrial and microwave oven heating. Raytheon first launched the Radarange™, a free-standing water-cooled unit which was upgraded during the early 1950s to air-cooled floor and countertop models. Most units were adopted by restaurants and food service kitchens. By the 1960s Raytheon started to get competition from other manufacturers such as Litton, Tappan and GE. At that time Raytheon did not pursue the consumer microwave oven market, preferring to license to other companies such as Westinghouse and Whirlpool (Osepchuk, 1984). By the mid-1960s, Raytheon purchased the Amana company to acquire expertise in manufacturing and marketing for the consumer market. By the early 1970s considerable competition was actively developing countertop microwave ovens, including Tappan, GE, Amana, Toshiba, Hitachi and Sharp. Technical improvements were made over the years with better door seals, solid-state power control, microprocessors, etc.

Today's microwave ovens come in a variety of designs. However their underlying principles are very much the same. Microwaves are generated inside an oven by stepping up the alternating current from domestic power lines at frequency of 60 Hz to 2450 MHz. A device called a magnetron, which operates at 4000 volts inside microwave ovens, accomplishes this. The step-up transformer that powers the magnetron accounts for more than half the weight of domestic microwave ovens! A waveguide channels the microwaves into the cavity that holds samples for heating. Domestic ovens have reflecting cavity walls that produce several modes of microwaves, maximizing the efficiency of heating. However, in research where temperature is closely controlled, it is desirable to use single mode ovens that homogeneously distribute the microwaves into the reactor/cavity in a definite way.

The basic requirements in microwave power applications are efficiency of power transfer, low cost and reliability of system operation. The most successful device for power application is the magnetron (Osepchuk, 2002). Magnetrons operate in microwave ovens from 300 to 3000 W and in high power applications in the 5–100 kW range. Today's magnetrons are produced in millions annually at an amazingly low price and a high conversion efficiency of 70% (Brown, 1989). The supplied power is fed into a cavity known as the applicator. The most common applicators include the Multi-Mode Cavity, the Single Mode Cavity, and the Travelling Wave Device.

In addition to these fairly standard devices, there is a whole raft of special purpose applicators, many of which are described in Metaxas and Meredith (1983). Of particular interest in composite manufacture is a device that will supply a high and fairly constant field over a length of a meter or more so that, for example, layered product such as a laminated sheet can be heated uniformly across its width. One device that shows considerable promise in this area is a double L-septa waveguide combination (Guha and Saha, 1995; Saha and Guha, 1999). For complex shapes the prospect of using mode-switching to obtain uniform temperature development has shown promise.

### 6.2.1 Multi-mode applicator

The simplest applicator is a rectangular metal (conductive) box that can accommodate the target load. When microwaves are launched into such a device via a waveguide, the waves undergo multiple reflections from the walls. The reflected waves interfere and, in so doing, establish a distribution of electrical field strengths within the internal space (including the load), that correspond to many different stable modes of propagation. It is, for this reason, called a multi-mode applicator. The most common example of this device is a domestic microwave oven.

The field distribution with a load contained in a multi-mode applicator depends not only on its dielectric loss, but also on its size and its location within the applicator. In this respect a multi-mode device is best suited to a load that is very lossy and that occupies a large volume (more than 50%) of the applicator. For low to medium loss materials occupying less than about 20% of the volume of the applicator, the temperature rise in the material at best will be non-uniform and, at worst, will contain potentially damaging ‘hotspots’ that correspond with high local fields.

By incorporating a mode stirrer (a rotating reflector) or continuously rotating the load on a turntable, temperature uniformity can be improved, albeit to a limited extent, by effectively smearing the electrical field distribution within the load. A major criticism of the use of a multi-mode oven for scientific study is that since the spatial distribution of field strength is unknown, the facility to generalize the results from a particular investigation is compromised, making it very difficult to effect a reliable scale-up.

It is worth stressing that with all applicators, the important criterion is the electrical field within the sample. While it is possible to map the field distribution within an oven by moving, for example, a water load around it and recording the rate of rise of temperature, the results of such an exercise apply only to water. Once the target material is placed in the oven, the field distribution is changed completely.

It is possible to calculate the field distribution within a loaded multi-mode cavity using Finite Difference Time Domain (FDTD) procedures (see Chapter

16) and, once such codes are established and more generally available, the reservations over the use of such applicators may disappear.

Over the past few years, interest in multi-mode ovens for low loss materials has increased as a result of the availability of multi-frequency sources. These allow a range of frequencies (typically, 2–6 GHz) to be swept continuously so that the time average field pattern (and the resulting temperature rise in a load) is relatively uniform. At present the main disadvantage of such devices is that they are limited to relatively low power (100 W) and are expensive (usually reserved for telecommunication applications).

### 6.2.2 Single mode applicator

The single mode resonant cavity is by far the most efficient applicator, particularly for filamentary materials. Within such a cavity only one mode of propagation is permitted and hence the field pattern is defined in space, and the target load can be positioned accordingly. A single mode cavity may be cylindrical or rectangular.

The simplest (and physically smallest) single mode cavity operates in the $TM_{010}$ mode in which the electrical field strength is constant along length and varies with radius according to a combination of Bessel functions, such that the field is greatest at the axis ($r = 0$). The radii of the cavity and load are determined by solving the electric and magnetic field equations within the cavity for the particular boundary conditions and mode of propagation (see also Chapter 3). The resonance condition so derived defines these radii in terms of the dielectric constants of each of the components.

A rectangular single mode cavity consists of a length of waveguide which houses a non-contacting plunger that determines the effective cavity length. The mode of operation of such a device is, typically, $TE_{10n}$ with the target load positioned in a region of high field strength. The major limitation of this device is that the width of the load must be less than half a wavelength, otherwise the periodicity of the device will be reflected in a periodic heating pattern across the target. This can be overcome by moving the plunger in a reciprocating fashion so that the time-average field seen by the load is smeared.

### 6.2.3 Travelling wave applicator

A travelling wave applicator consists of a length of waveguide arranged in such a way that the target load passes through it from one end, and from the other end is launched a microwave source. As microwaves pass along the waveguide they are absorbed by the load exponentially with distance, according to the dielectric properties and size of the load. As a precaution, a dummy water load is attached to the load-end of the waveguide to absorb any microwave energy that is not absorbed by the load. Providing the load moves at a constant speed through the waveguide, each part of it experiences the same total field strength, once steady state has been established – i.e. after at least one length of material has passed through the waveguide.

## 6.3 Applications

Industrial applications of microwaves are numerous in the processing of food, rubber, textiles, wood products, ceramics, waste, etc. Cloth drying and garbage treatment are innovative microwave applications (Chan and Reader, 2000). Microwave in food technology is often a target of research and development. Applications are increasingly being perfected in tempering, vacuum drying, freeze drying, dehydration, cooking, blanching, baking, roasting, rendering, pasteurization, sterilization and extraction (Lew *et al.*, 2002; Lidstrom *et al.*, 2001; Venkatesh and Raghavan, 2004).

In recent years, industrial microwave processing in the food industry has firmly established itself in tempering, bacon cooking and pasta drying. Other industrial applications do exist to a smaller extent in vacuum microwave drying (EnWave Corp. vacuum microwave dehydrators, BC, Canada) (see Chapter 8) and in pasteurizing/sterilizing for ready-made meals (Tops' Foods, Belgium).

There are several reasons for the slow success of a greater development of microwave applications in the food industry. They are principally economic, technological and safety issues (Buffler, 1993). Microwave processing equipment has a considerable capital cost which is detrimental to equipment selection. Processing equipment needs to be designed precisely around an application and requires additional technical skills for proper maintenance and operation. Microwave energy use is also feared for safety reasons associated with radiation leakage and contaminants transferring to foods from susceptors and containers. For most successfully adopted industrial applications of microwave processing, the process produces a product with unique features not otherwise obtained by conventional processing.

### 6.3.1 Cooking

Cooking can cause partial or total loss of valuable nutrients depending on the process parameters. Research has demonstrated that many food vitamins are thermolabile and leach out during thermal processing. Over the years, microwave processing has demonstrated an advantage over traditional processing with reduced nutrient losses (Uherova *et al.*, 1993; Finot, 1996; Villanueva *et al.*, 2000; Begum and Brewer, 2001; Brewer and Begum, 2003) (see also Chapter 5).

A success story in industrial application lies in microwave cooking of bacon which yields rapid output and high quality rendered fat collection for reuse/resale (Edgar, 1986). The microwave rendered fat presents greater stability and higher quality. Microwave processing of sliced bacon yields great product appearance and convenience and diminishes the risk of nitrosamine formation (Ohlsson and Bengtsson, 2001). Industrial microwave bacon cookers are available from Microdry Incorporated (KY, USA), and Defreeze Corp. (MA, USA). Combination ovens are now being marketed for commercial use (restaurant and food services) to offer a competitive edge with innovative combination of convection, radiant and microwave technology (Amana Veloci High Speed oven).

### 6.3.2 Tempering (Chapter 10)

Frozen food often needs to be thawed or tempered ahead of processing. This is achieved at home by leaving the product in air at ambient temperature. In the past, similar methods were used in industry – immersing in water for extended periods. These inefficient methods are rapidly being replaced by microwave and radio frequency processes (Meisel, 1972). Microwave tempering of frozen food products aims to raise the temperature of the product as uniformly as possible to allow further mechanical handling/processing (slicing, cutting, molding, etc.), while maintaining the quality of the product under refrigerated temperature. With rapid microwave tempering, there is no temperature abuse of the product and there are reduced drip losses and reduced space and inventory requirements. Conveyorized microwave tempering tunnels (Fig. 6.1) are commercially available from various suppliers (Microdry Incorporated, Sairem, Defreeze Corporation, Amtek Inc., etc.).

### 6.3.3 Drying (Chapter 8)

Drying of agricultural and food products is an important method for preservation and production of a wide variety of products. The aim is to prolong storage life. Unfortunately, changes in the physical and biological structures are inevitable. In convective drying, dry air is used to take away surface water from the

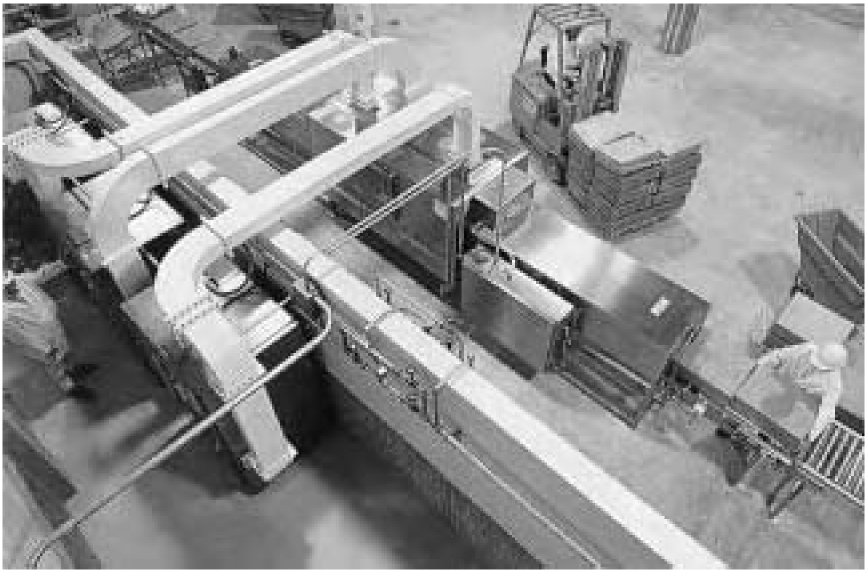

**Fig. 6.1** Tempering tunnel (Defreeze Corporation).

commodity, therefore creating a pressure gradient between the surface and inner part which causes water migration from inside the commodity to the surface. In this process, the increased temperature will enhance the ability of dry air to remove water from the surface and increase the water migration rate within the commodity. The conventional means of energy supply is mainly through conduction in the material. The process takes time to reach equilibrium, with potential overheating of the product surface. On the other hand, with microwave heating the commodity is heated throughout (volumetrically). This mechanism pushes water out of the product with great efficiency, as the moisture content of the product decreases.

An advantage of using microwave energy is the possibility of combining multiple drying methods. Combination of convection hot air drying with microwaves offers reduced drying times and improved food quality. In addition to hot air, microwaves can also be combined with freeze drying or vacuum drying. A significant industrial application is in microwave/air tunnel drying used principally as a finish drying process to level-off moisture content in pasta, cracker or chip drying (Osepchuk, 2002). Use of microwave energy in drying offers some advantages as it complements well conventional drying in later stages by targeting specifically the internal moisture of the product. However, when the heat generation within the product is too rapid, it can cause the generation of great internal steam pressure, resulting in expansion which can lead to product collapse or material explosion, as was experienced by Venkatachalapathy and Raghavan (2000) during the microwave drying of whole strawberries.

Microwave/hot air tunnel dryers are commercially available from various sources (Microdry Incorporated, USA; Sairem, France; Püschner, Germany), all of which will adjust the equipment design to meet specific product requirements (Fig. 6.2).

Research conducted by Altan and Maskan (2004), on microwave assisted hot air drying of macaroni pasta, concluded that combined microwave/hot air drying shortened the drying time and improved the physical, textural and cooking properties of dried macaroni compared to hot air dried ones.

Microwave vacuum dryers (Fig. 6.3) are commercially available custom-made to specific product requirements (EnWave Corporation, Püschner). The

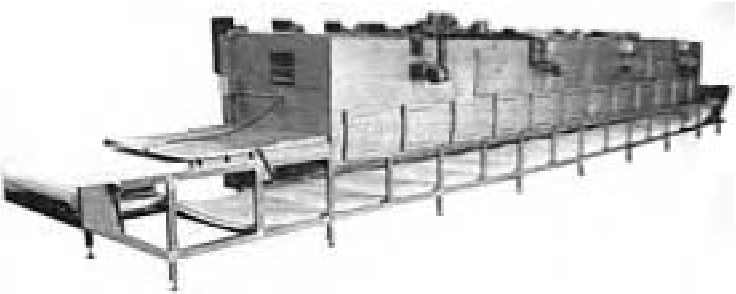

**Fig. 6.2** Microdry microwave/air tunnel dryer (Microdry Incorporated, KY, USA).

**Fig. 6.3** EnWave VM Model 15, 15 kW, 2450 MHz, fully variable microwave power with vacuum to 30 torr (Enwave Corporation, BC, Canada).

main purpose of vacuum drying is to enable the removal of moisture at much lower temperature than the boiling point under ambient conditions. For example, the boiling point of water will reduce to 29 °C at 40 mbar. The low temperature is important for many products that are heat sensitive. Furthermore, the absence of air, especially oxygen, helps preserve many of the components sensitive to oxidation (Regier *et al.*, 2004).

### 6.3.4 Pasteurization

Microwave heating can offer high temperature and short time processing, resulting in quality advantages. Recent focus has been in the microwave pasteurization of packaged foods. In a study by Lau and Tang (2002), pickled asparagus in glass jars was pasteurized using 915 MHz microwaves. The process produced uniform heating while reducing the process time by at least one-half compared to water-bath heating. Furthermore, the microwave pasteurization significantly reduced thermal degradation of asparagus. When using microwave heating for pasteurization, care must be taken to ensure the homogeneity of the thermal process within the product and that the target lethal temperature is maintained for a sufficient period of time to provide a safe product (Finot, 1996).

### 6.3.5 Blanching (Chapter 9)

Microwave blanching/steaming is gaining considerable interest for the greater nutritional quality of its products. Microwave blanching of tomatoes was investigated by Begum and Brewer (2001) and compared to boiling water and steam blanching. Steam blanched tomatoes were the lightest while boiled water tomatoes generally had the best appearance scores. Microwave blanched tomatoes retained the best nutritive value with acceptable colour and flavour scores.

Devece *et al.* (1999) studied the industrial microwave blanching of mushrooms to inactivate polyphenoloxidase activity which causes browning. Their results demonstrated that with proper applicator design, the microwave treatment can achieve complete enzymatic inactivation in a short time, ensuring minimal loss of antioxidant and moisture with minimal browning.

Amana (the commercial line of microwave oven from Raytheon) offers a commercial Amana microwave steamer. The high wattage microwave input (3 kW) provides a rapid steaming process to bring out more of the foods' succulent flavour, colour, texture and nutrients than conventional steam cooking.

### 6.3.6 Baking (Chapter 7)

Microwave baking has been the focus of much research and development since the 1950s, with variable success. All results point to the general rule that to achieve success, considerable product reformulation must be considered (Decareau, 1992). Baking with various emulsifiers, gums, starches, fat contents and enzymes has been widely investigated (Ozmutlu *et al.*, 2001; Sumnu, 2001; Seyhun *et al.*, 2003; Keskin *et al.*, 2004). With adequate product formulation, microwave baking can offer good quality products with high convenience. Pillsbury® has a new line of frozen biscuits and dinner rolls specifically designed for the microwave to deliver warm, soft, ready-to-eat bread rolls in 25 s.

### 6.3.7 Packaging (Chapter 11)

Microwave interactive packaging and cooking aids called susceptors are used to modify the impact of food processing. There are several designs of packaging susceptors, heating pads and crisping sleeves that add surface effects such as browning and roasting during microwave processing (Turpin and Hoese, 1978; Andreasen, 1988; Babbitt, 1992).

Lack of browning in microwaved food is, after all, desirable from a health point of view, with reduced levels of acrylamine, a probable carcinogen. But few consumers combine functional aspects and emotional satiation in their food intake. Browning is still 'red flag' for microwave technology. There are packaging methods that have been used to develop browning. There are also hybrid methods combining infrared, convection and microwaves (Brastad, 1980, 1981; Turpin, 1989).

### 6.3.8 Microwave-assisted extraction (MAE)

Solvent extraction is a process using solvent to separate components that contains the target components from the solid matrix. The extraction rate and the quality of the extract depend on many factors, among which the most important are the characteristic of the matrix, the distribution of the target components in the matrix, the solubility of the solvent to the target components and the interfering components, and temperature. Breakdown of the membrane system will drastically accelerate the extraction process. The most desired solvents are those with high solubility to the target components and low solubility to the interfering ones, but this is normally not the case. Temperature is important in the extraction process, because the higher the temperature, the higher is the diffusion rate and consequently the higher is the extraction rate. In some extraction processes, high temperatures over long extraction times are not desired, owing to the decomposition of heat-sensitive components.

The reduction of extraction time is one of the most attractive results attributable to the introduction of microwaves into the extraction system. In 1986, Ganzler *et al.* first introduced microwave energy in the extraction system for crude fat, vicine, convicine, and gossypol from seeds, foods and feeds using organic solvents. With only 3.5 minutes of microwave irradiation, the yields of these compounds were comparable to those obtained with a 3-hour Soxhlet extraction. Paré *et al.* (1991) compared microwave-assisted extraction with steam distillation for producing essential oil from fresh peppermint. The extraction was carried out with hexane as solvent. With a 40 s microwave irradiation (2450 MHz) at 625 W, the yield was 0.371%, compared to 0.227% for a 2-hour steam distillation. Williams *et al.* (2004) reported the extraction of pungent principles capsaicin and dihydrocapsaicin from capsicum species, showing that with 15 minutes of microwave extraction the yields of both capsaicin and dihydrocapsaicin more than doubled compared to the results of reflux extraction for 2 hours, and were 50% higher than shaken flask extraction for 24 hours. Besides the great acceleration effect, microwave-assisted extraction can also improve the product quality as a result of short processing time or due to the special characteristics of microwaves in the extraction method. For example, when a system of fresh mint leaf and a non-polar solvent is exposed to microwave radiation, microwaves will travel freely through the solvent, which is transparent to microwave energy, and reach the sample. A significant fraction of microwaves is absorbed by the sample, mainly the water in the glandular and vascular systems, which results in a sudden temperature rise inside the sample, with a dramatic expansion in volume leading to explosion at the cellular level. The substances located in the cells are then free to flow out of the cell to the surrounding solvent.

Solvent-free microwave extraction is being developed as a green alternative method. Results obtained by Lucchesi *et al.* (2004) demonstrated rapidity, efficiency and cleanliness (no solvent) of the process.

## 6.4 Future trends

Due to their selective and volumetric heating effect, microwaves bring a lot of new avenues to various bioprocessing techniques, such as the increasing rate of drying, improved final product quality, increasing yield and extract quality in an extraction process. These advantages are to be considered in choosing an alternative to conventional processing methods.

For successful industrial applications of microwave energy, there needs to be the understanding that any microwave operation will require thorough operator and maintenance staff training. Furthermore, for initializing production, the food company will have to fine tune the operating parameters in close collaboration with the microwave manufacturer to ensure that all production staff have acquired the confidence to operate the equipment in the small window of maneuverability to achieve product quality (Gerling, 1986).

In the field of microwave baking, halogen lamp–microwave combination baking is a promising new technology, offering the speed of microwave heating and the browning and crisping benefits of halogen lamps (Keskin *et al.*, 2004). Research and development is underway to produce new magnetrons for widespread applications at 5.8 GHz. This will offer great new horizons for product and applications development. Developments are also underway for scaling up microwave-assisted extraction processes, which will have great benefits for functional and nutraceutical food product development.

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# 7

# Baking using microwave processing

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## 7.1 Introduction

Microwave baking has the advantages of saving time, energy, space and nutrients. However, microwave baked products have not yet been fully accepted by consumers, owing to quality problems. Firm and tough texture, rapid staling, dryness and lack of colour, flavour and crust formation are the common quality problems observed in microwave baked products. Mechanism and speed of microwave heating are the major reasons for the inferior quality of microwave baked products. Additional product development is necessary to obtain microwave baked products that have the same quality as conventionally baked ones. Studies in recent years have been aimed at improving the product quality by changing the product formulation and oven design. This chapter first concentrates on the basic principles of microwave heating. Secondly, it discusses the advantages and disadvantages of microwave heating. Then, it gives information about the interaction of microwaves with major baking ingredients. Finally, it summarizes information about recent trends to improve the quality of specific baked products such as breads, cakes and biscuits.

## 7.2 Principles of microwave baking

Baking is a complex process which involves simultaneous heat and mass transfer. There are many physical, chemical and biochemical changes in food during baking, which are gelatinization of starch, denaturation of protein, liberation of carbon dioxide from leavening agents, volume expansion, evaporation of water, crust formation and browning reactions.

In conventional baking, heat is transferred to the product mainly by convection from the heating media and by radiation from oven walls to the product surface followed by conduction to the centre. Rate and amount of heat application, humidity level in a baking oven and baking time are important baking conditions which affect final product quality (Therdthai and Zhou, 2003). In microwave baking, in contrast to conventional baking, food is surrounded by air at ambient temperature which is not heated by microwaves. There is heat generation inside the food due to the interaction of microwaves with charged particles and polar molecules. The generated heat is conducted through the food material. The time of heating is very fast in a microwave oven due to the rapid heat generation inside the food. For this reason, there may not be enough time for completion of baking reactions such as starch gelatinization, starch conversion by enzymes, enough expansion of dough/batter, crust formation, browning and final setting of the dough/batter into a rigid crumb structure during microwave baking. Kinetic reactions such as starch gelatinization and browning reactions depend not only on temperature but also on baking time. Therefore, it is necessary to be sure that gelatinization and browning reactions are completed when baking time is reduced, otherwise the quality of the product can be degraded (Therdthai *et al.*, 2002).

For microwave heating the energy equation can be expressed as follows:

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T + \frac{Q}{\rho C_\mathrm{p}} \qquad [7.1]$$

where $T$ is temperature, $t$ is time, $\alpha$ is thermal diffusivity, $\rho$ is density, $C_\mathrm{p}$ is the specific heat capacity of the material, and $Q$ is the heat generated per unit volume of material, which represents the conversion of electromagnetic energy.

The relationship between $Q$ and electric field intensity ($E$) at that location can be derived from Maxwell's equations of electromagnetic waves as shown by Metaxas and Meredith (1983):

$$Q = 2\pi \epsilon_0 \epsilon'' f E^2 \qquad [7.2]$$

where $\epsilon_0$ is the dielectric constant of free space, $\epsilon''$ is the dielectric loss factor of the food, $f$ is frequency of the oven, and $E$ is the root-mean-squared (rms) value of the electric field intensity.

For microwave heating of dough, a one-dimensional mathematical model of heat and mass transfer with variable thermal and moisture transfer properties and internal heat generation was proposed (Tong and Lund, 1993).

Mass transfer mechanism during conventional baking involves diffusion together with evaporation and condensation (Tong and Lund, 1993). Moisture movement in crumb and crust can be described by Fick's Law (Sablani *et al.*, 1998; Thorvaldsson and Janestad, 1999).

The driving forces for moisture transfer during microwave baking are pressure and concentration gradients. The high pressures developed during microwave heating of high moisture foods have been studied by various researchers (Ni *et al.*, 1999; Feng *et al.*, 2001).

The biggest difference between microwave and conventional baking is the inability of microwave ovens to induce browning and crust formation. This is related to the fact that the air inside the microwave oven is at ambient temperature and not heated as in conventional baking ovens. Therefore, the surface of foods baked in a microwave oven does not reach temperatures required for browning reactions.

Dielectric and thermal properties are the physical properties of food that affect microwave heating. Dielectric properties are the dielectric constant and loss factor, while thermal properties are thermal conductivity and specific heat capacity. The dielectric constant is a meaure of the ability of a material to store microwave energy, while the dielectric loss factor is a measure of the ability of a material to dissipate microwave energy into heat. Dielectric properties of foods depend on food composition, temperature and frequency (Calay *et al.*, 1995). Studies on dielectric and thermal properties of baked products and of the main baking ingredients will be helpful in understanding the heating patterns during microwave baking of foods.

## 7.3 Technologies and equipment for microwave baking

Usage of microwave baking in industry is limited. DCA Food Industries developed a commercial proofing procedure (Schiffmann, 2001). In this procedure conventional proofers were replaced with a straight line microwave conveyor. The advantages of this proofing system were reduction of proofing time, high process control, high product quality, uniformity of proofing and equipment sanitation. These systems operated at 2450 MHz and were in operation in the US, the UK and continental Europe. However, today none of the proofers remain.

In the early 1990s, a microwave–conventional baking oven for post-baking was developed by APV Baker (UK) as an alternative to radiofrequency (RF) heating (Bengtsson, 2001). While RF heating has the advantage of moisture levelling activity, microwave equipment is more compact, flexible and advanced technology. Therefore, there is a tendency towards microwave and conventional combination heating instead of RF in baking and post-baking processes. Microwave ovens working at 896 MHz have been reported in Britain for bread baking for production of bread crumbs (Bengtsson, 2001).

APV uses a multimedia oven, including a microwave option, as a heating medium to bake biscuits (www.apvbaker.com). Multimedia baking involves simultaneous application of conventional heat and microwaves inside the baking chamber. This helps to attain high product quality by conventional baking while taking advantage of the reduced baking times and improved process control obtained by microwave technology. Application of microwaves in the early stages of baking sets the biscuit structure accurately and allows immediate adjustment of the final stack height for packaging. The advantages of this technology are retention of the distinctive flavour, colour and texture through

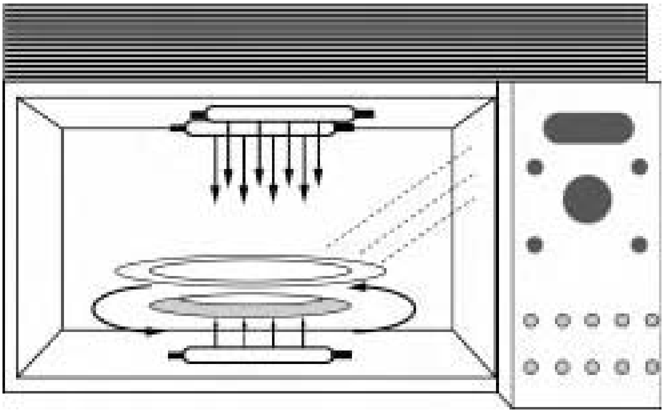

**Fig. 7.1** Illustration of halogen lamp–microwave combination oven.

the baking process, increased throughput, virtual elimination of checking, and instantaneous response to changes in control settings.

Microwave heating was combined with halogen lamp heating in the Advantium$^{TM}$ oven which was produced by General Electric (Louisville, KT, USA) in 1999. Halogen lamps are placed on the top and bottom of the oven (Fig. 7.1). The halogen lamp–microwave combination oven combines the browning and crisping advantages of halogen lamp heating with the time-saving advantage of microwave heating. A halogen lamp which provides near-infrared radiation is used to achieve surface browning and to prevent a soggy surface.

## 7.4 Strengths and weaknesses of microwave baking

The temperature of a microwave baked product rises more rapidly as compared to the conventional baking process. Therefore, the overall baking time is shortened. This in turn saves energy. Another advantage of microwave baking is that the final product has higher nutritive value than in conventional baking. In addition, microwaves penetrate into the dough and inactivate $\alpha$-amylase, which causes the crumb to be sticky (Chamberlain, 1973). Finally, microwave equipment requires less space.

However, there are many quality problems in microwave baked products. Short baking time is responsible for most of these problems, since completion of baking reactions requires a long time. Physicochemical changes which would normally occur over a lengthy baking period in conventional baking could not always be completed during the short period of microwave baking (Hegenbert, 1992). Other reasons for inferior quality of microwave baked products are the differences between microwave and conventional heating mechanisms and specific interactions of each component in the product with microwave energy (Goebel *et al.*, 1984). The reasons for quality changes in microwave baked breads were stated to be insufficient starch gelatinization, microwave induced gluten changes and rapidly generated gas and steam (Yin and Walker, 1995).

The quality defects observed in microwave baked products are firm and tough texture, rapid staling, lack of colour and crust formation and a dry product (Sumnu, 2001). Firm and tough texture are related to microwave induced gluten changes, high amylose leached out during baking and insufficient starch gelatinization. In microwave heating, especially in intermediate to low moisture foods such as baked goods, dramatically different patterns of starch transformation as compared to conventional heating are observed due to non-uniform heating. As a result, poor textures such as tough and leathery crumbs are obtained (Zallie, 1988). The reason for the rapid staling in microwave baked products is not clear yet. High amylose leached during microwave baking as compared to conventional baking may be the reason for rapid staling of microwave reheated breads (Higo and Noguchi, 1987) and microwave baked cakes (Seyhun, 2002). The high moisture loss during microwave baking results in drier baked products than conventionally baked ones. Cakes and breads baked in a microwave oven were shown to lose more moisture than those baked by conventional heating (Sumnu *et al.*, 1999; Seyhun *et al.*, 2003; Keskin *et al.*, 2004a). Interior heating creates significant internal pressure concentration gradients which increase the flow of moisture through the food to the boundary (Datta, 1990).

The browning reactions in baked products are the result of heating of reducing sugars with proteins or nitrogen-containing substances to form compounds like melanoidins, and start at around 160 ºC (Matz, 1960). When sugars such as fructose, maltose and dextrose are heated to around 171 ºC, molecules are combined to form coloured substances called caramels. A relatively low food surface and low surrounding temperatures in microwave baking do not enable the browning reactions to occur. Moreover, in microwave ovens, evaporated water molecules from the food system directly interact with cold air around the product and condense, which prevents browning and crisping reactions (Schiffmann, 1994). Dough products which are expected to be crisp and brown become soggy after baking. When heated for a longer period, they become dry and brittle but never brown. Brown surfaces achieved by Maillard reactions and caramelization of sugars are a result of high temperature accompanied by dehydration (Burea *et al.*, 1987). In addition, time is necessary for completion of these browning reactions. The kinetic rate constant of browning reaction increases with increased temperature (Ibarz *et al.*, 2000) and decreased moisture content (Moyano *et al.*, 2002).

Flavours generated as a result of browning reactions are also absent in microwave baked products. The aroma profile of a microwave baked cake was shown to be similar to that of batter. Many of the nutty, brown and caramel-type aromas observed in the conventional cake were lacking in microwave baked cakes (Whorton and Reineccius, 1990). Individual flavour components are subjected to losses through distillation, flavour binding by starches and proteins and chemical degradation during microwave baking. Crust also provides a barrier against the loss of flavours (Eliasson and Larsson, 1993). Flavours can easily be released from microwave baked product due to the absence of crust. Changing the food formulation to reduce compound volatility minimizes loss of flavour compounds during microwave baking. This can be done by adding an oil phase or increasing the oil content (Yaylayan and Roberts, 2001). Flavouring agents may be encapsulated to reduce the volatility of aroma compounds (Whorton and Reineccius, 1990). Unwanted flavours such as flour or egg-like flavours develop during microwave baking of cakes. Flavouring agents may be added to mask these unwanted flavours and obtain a similar flavour profile to conventionally baked cakes.

Since products baked in microwave ovens have inferior quality, improving this quality represents a challenge to food technologists. Therefore, a thorough understanding of the effects of microwaves on the major ingredients in baked products such as starch and gluten will play an important role in improving the quality of these products.

## 7.5 Interaction of microwaves with major baking ingredients

The interaction of microwaves with a material is highly dependent on the dielectric properties of the material. It is necessary to know the dielectric properties of food materials for proper understanding of the heating pattern during microwave baking. Water is the most important dipole component but salt, fat and protein also act as dielectric components (Decereau and Petersen, 1986; Mudgett, 1986).

### 7.5.1 Dielectric properties of baked products

Studies of the dielectric properties of baked products are limited in the literature. The dielectric properties of bread dough and yeast were studied under different conditions (Zuercher *et al.*, 1990). Both the dielectric constant and loss factor decreased with increasing flour content in the dough sample and also during baking. When yeast was heated in a microwave oven, both dielectric constant and loss factor decreased with temperature until a sharp peak around 64 ºC appeared, due to the death of yeast cells.

The effects of temperature and mixing time on dielectric properties of wheat dough were studied by Kim and Cornillon (2001). As mixing time increased, the dielectric constant of wheat dough decreased, due to the low amount of mobile water in the sample after mixing (Fig. 7.2). The loss factor also decreased during mixing, since mixing resulted in a decrease in the amount and mobility of dissolved ions and water. Increased mobility of water molecules with temperature resulted in an increase in the amount of dissolved ions and thus an increase in the dielectric loss factor. The increase in dielectric loss factor with temperature was less pronounced above the gelatinization temperature.

Salt addition did not affect the dielectric constant of bread (Goedeken *et al.*, 1997). The dielectric constant of samples with and without salt increased up to

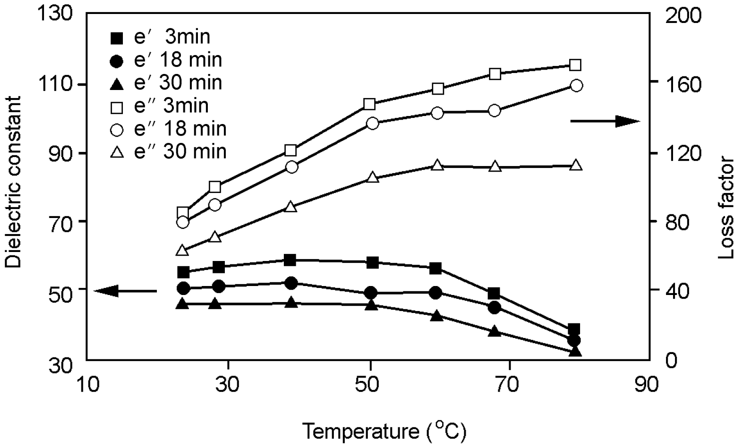

**Fig. 7.2** Dielectric constant and loss factor of dough samples at different mixing time and temperatures at 10 MHz. (Reprinted from *Lebensm Wiss u Technol*, Vol. 34, Kim YR and Cornillon P, Effects of temperature and mixing time on molecular mobility in wheat dough, 417–423, Copyright © (2001) with permission from Elsevier.)

60 °C, then remained constant. As expected, the dielectric loss factor increased with temperature in salt-containing samples, while the opposite trend was observed in samples without salt.

### 7.5.2 Dielectric properties of starch and gluten solutions

The major components in baked products are starch and gluten. Investigating the dielectric properties of these components is essential for the proper understanding of the heating pattern during microwave baking. The dielectric properties of food polymers depend on their interactions with water and charged food constituents such as salt ions, leavening agents and free amino acids (Shukla and Anantheswaran, 2001). Nelson *et al.* (1991) showed that dielectric properties of potato starch changed with moisture content and temperature. The loss factor of gelatinized potato starch was higher than that of its granular form (Roebuck and Goldblith, 1972). Gelatinized or swollen starch binds less water to its structure, therefore more water is free to respond to the alternating microwave field, resulting in heat build-up. Ryynänen *et al.* (1996) observed that both dielectric constant and loss factor decreased with increase in temperature for potato, wheat, corn and waxy corn starch suspensions. The higher dielectric constant values were obtained with more dilute suspensions while the loss factor did not change with concentration. Ndife *et al.* (1998a) studied the effects of temperature on dielectric properties of tapioca, corn, wheat, rice, waxy maize and amylo-maize starches in granular and suspension forms at different starch/water ratios. The dielectric constant and loss factor of granular starches increased while those of starch solutions decreased with temperature. It was concluded that corn, wheat and rice starches could be used in microwave baked products where incomplete gelatinization is a problem since they had higher loss factors than tapioca, waxy maize and amylo-maize starches.

The effects of temperature, concentration, frequency and salt addition on dielectric properties of starch solutions were studied and correlations were developed for estimation of dielectric properties of starch solutions (Piyasena *et al.*, 2003). The dielectric loss factor increased with increasing temperature and salt concentration. The dielectric constant decreased with temperature for starch solutions without salt. Penetration depth was lowered with salt addition. Salt ions affect the dielectric properties, especially the dielectric loss factor, significantly. The dielectric constants of the salt solutions are known to decrease, whereas the dielectric loss factor is known to increase with an increase in salt concentration.

When the effects of microwave and conventional heating on dielectric properties of starch–gluten–water mixtures at different proportions were studied, the increase in moisture content increased the dielectric constant of both heated and unheated sample (Umbach *et al.*, 1992). Dielectric constant decreased as starch/gluten ratio decreased and also during heating. Composition played a major role in microwave heated samples. Water appeared to interact more strongly with the denatured gluten than with the gelatinized starch, as the high protein containing samples had lower dielectric properties than high starch containing samples.

### 7.5.3 Effects of microwave heating on physicochemical properties and heating profiles of major baking ingredients

A thorough understanding of the effects of microwaves on physicochemical properties and heating profiles of starch and gluten will play an important role in improving the quality of microwave baked products. Goebel *et al.* (1984) and Zylema *et al.* (1985) studied gelatinization of wheat starch suspensions with different starch/water ratios in a microwave oven. Wheat starch samples heated conventionally were found to be structurally more uniform than those heated by microwaves (Goebel *et al.*, 1984). However, no differences in gelatinization pattern or gel structure were found in samples heated by microwave and conventional heating by other researchers (Zylema *et al.*, 1985). Increased starch concentration increases the viscosity of the food system. As a result, the mobility of water decreases, resulting in conductive heating taking place in addition to internal microwave heat generation. Therefore, starch thickened pastes increase in temperature more quickly than an equivalent amount of water in a microwave oven (Zallie, 1988). Gelatinization of corn starch in a microwave oven was significantly lower and slower than that of wheat and rice starch (Ndife *et al.*, 1998b). This may be explained by its low dielectric loss factor and high thermal properties (specific heat capacity and gelatinization enthalpy).

Sakonidou *et al.* (2003) studied microwave and conventional heating of maize starch suspensions at different starch/water ratios. Although the required temperature is achieved, gelatinization is not completed in microwave-heated samples due to limited starch–water interaction during the short microwave heating period. In microwave heating, temperature rises faster in dispersions with higher starch content, as previously observed by Goebel *et al.* (1984) and Zylema *et al.* (1985). This is in contrast to conventional heating where temperature rises faster in dispersion with lower starch content. In conventional heating, heating rate was not dependent on concentration below 70 ºC. However, above 70 ºC, the rate of temperature rise was higher in more dilute starch dispersions. In conventional heating, heat diffuses faster in the dilute suspensions which have low viscosity due to the effects of convective currents provided by agitation. However, in microwave heating, since heat is internally generated the heat transfer problem is overcome without agitation.

The effect of microwave heating on physicochemical properties and structure of tuber (potato and tapioca) (Lewandowicz *et al.*, 1997) and cereal starches (wheat, normal and waxy corn) (Lewandowicz *et al.*, 2000) has been studied. The time–temperature profiles of starch samples were significantly affected by their moisture contents (Lewandowicz *et al.*, 1997). Temperature increased sharply in samples containing low moisture (1–5%), while a plateau was observed for high moisture containing samples (above 20%), due to isothermal transformation occurring in starch samples. Rheological properties of starch samples were also affected by microwave heating. Susceptibility of different starches to changes due to microwave irradiation was shown to depend not only on their crystal structure but also on their amylose contents. Microwave heating reduced crystallinity, solubility and swelling characteristics of wheat and corn starches (Lewandowicz *et al.*, 2000). However, in waxy corn starch subjected to microwave processing, these properties remained almost constant.

Microwave irradiation seems applicable to starch processing but it has not been used on a commercial scale (Lewandowicz *et al.*, 1997). When lentil starch was exposed to microwave irradiation, moisture, crude protein and crude fibre contents, water absorption, solubility, swelling power and retrogradation tendency decreased but absolute density, ash and reducing sugar contents increased (Gonzalez and Pérez, 2002).

The heating profile of starch solutions was significantly changed by the addition of salt, since salts within the product are known to interact with microwaves to generate additional heat (Rozzi and Singh, 2000). Initially salt-containing samples had lower temperatures but then they heated faster than the samples without salt. The control samples heated more slowly than the salt-containing samples due to the lack of ionic conductivity imparted into the starch solution by the salt. When salt is added, the dielectric constant decreases as a result of binding of dissolved salts by free water molecules. The dielectric loss factor, on the other hand, increases due to the addition of the ions from the dissolved salts to the solution. Therefore, the heating pattern of samples containing salt changes. No significant effect of salt type on heating profile was determined.

When the effects of microwave and conventional heating on water mobility (self-diffusion coefficient) of starch–gluten–water mixtures at different proportions were studied, higher diffusion coefficient values were obtained when more water was present in dough samples in both of the heating methods (Umbach *et al.*, 1992). Different heating rates were obtained in microwave and conventional heating but diffusivity values were close to each other. Self-diffusion coefficient values decreased with heating, indicating an increased binding and redistribution of water between starch and gluten.

The effects of conventional and microwave heating methods on moisture loss rates and temperature profiles of isolated gluten model systems were investigated (Lepage *et al.*, 1989). In a conventional oven, moisture loss rates increased to a local maximum in the early heating period followed by a relatively long period of decreasing moisture loss rates before a second period of rapidly increasing rates began. At the local maximum, the surface temperature was above 100 ºC and the dough relaxed. An initial local maximum was not observed in microwave heating and the rate of moisture loss increased slowly. Surface and inner temperatures were close to each other. The gluten ball relaxed but no expansion occurred in microwave-heated gluten balls. Expansion was asymmetrical initially but as heating progressed the gluten balls became more symmetrical.

## 7.6 Application of microwave baking to particular foods

As discussed before, there are various quality problems in microwave baked products. There are various studies in the literature to reduce quality problems in these products. Most of the researches are on improving the quality of microwave baked breads and cakes. There are limited studies on biscuits and other baked products.

### 7.6.1 Microwave baked bread

When conventional bread formulations are baked in the microwave oven, unacceptable textures are obtained (Lorenz *et al.*, 1973; Ovadia and Walker, 1996; Keskin *et al.*, 2004a). The exterior parts are rubbery and tough and interior parts are firm and difficult to chew (Shukla, 1993). Firmness and toughness are two different properties. Firmness is expressed by the force required to compress a given area by 25% of its thickness (Ovadia and Walker, 1996). Toughness can be characterized by the exertion required to pull a slice of bread apart. Miller and Hoseney (1997) measured microwave-induced toughness by cutting bread slices with a wire cutter attached to a texture analyser. The peak force required to cut the bread was taken as a measure of toughness. The developed method is able to differentiate bread toughness from bread firming.

Toughness is related to gluten protein while firmness is related to starch granules. It is possible to improve the texture of microwave baked products by manipulating the gluten protein network, the size and swelling of starch granules and the moisture level (Shukla, 1993). The firmness problem of the interior of the bread is associated with the large-diameter and reswollen starch granules. Incorporating fat and emulsifiers can reduce the firmness problem in baked products. Toughness of breads can be decreased by breaking the disulphide bonds, resulting in reduced size of the gluten proteins. Sulfhydryl-containing agents such as L-cysteine, glutathione, yeast autolysate and potassium or sodium bisulphite used in conventional formulations for this purpose can also be added in microwave baked products but at higher levels (Shukla, 1993). Conventional formulations can be improved or a new formulation can be designed to solve the problem of toughness or firmness in microwave baked breads.

Breads baked from hard wheat flour were found to have a more rubbery and tough internal texture than those baked from soft wheat flour (Ovadia, 1983). Gluten content was found to be the significant factor in affecting the crumb firmness of microwave baked breads (Ozmutlu *et al.*, 2001a). Microwave breads formulated with low gluten flour were softer and had higher volume than those formulated with high gluten flour. For breads formulated with low gluten, the firmness decreased and the specific volume of breads increased as fat and emulsifier contents increased. In the same study, increasing fat, emulsifier and dextrose contents were shown to reduce the weight loss of microwave baked breads. Addition of low levels of gliadin, mildly hydrolyzed wheat gluten or wheat protein isolate to the bread formula effectively reduced the microwave induced toughness of pup loaf bread but was not effective in reducing microwave induced toughness of laboratory-scale hoagie buns (Miller *et al.*, 2003).

Processing conditions can be adjusted to decrease the toughness or firmness in microwave baked breads. Ovadia and Walker (1996) showed that bread toughness was a function of microwave power and was increased by pressure when microwave baking was combined with high pressures. Buns baked by microwave–conventional combination heating were equal in quality to conventionally baked buns when yeast level and proofing time were increased, while fermentation time had little effect on bun quality (Willyard, 1998). When proofing was performed in the microwave oven before microwave baking, proofing time was shown to affect the volume and firmness of microwave baked breads (Ozmutlu *et al.*, 2001b). The increase in proofing time increased the firmness of breads significantly for longer proofing times (Fig. 7.3). Firmness was expressed by the force required to compress bread crumb by 25% of its thickness. Addition of emulsifier, Purawave, reduced the firmness of breads since mono-di glycerides and lecithin found in the emulsifier are known to make a complex with amylose and have a softening effect on bread.

There are various patents concerning bread baking in microwave ovens (Schiffmann *et al.*, 1982, 1983; Jahnke, 2003). A method of baking firm bread in metal pans using microwave energy was described in US Patent 4,318,931 (Schiffmann *et al.*, 1982). The baking process involved two stages. In the first stage, conventional heating was used in covered standard baking pans but for a reduced period of time in about 10–12 min. The second stage with the cover removed from the metal pan involved simultaneous conventional and microwave heating. The second stage can be completed in 10–12 min. There was a

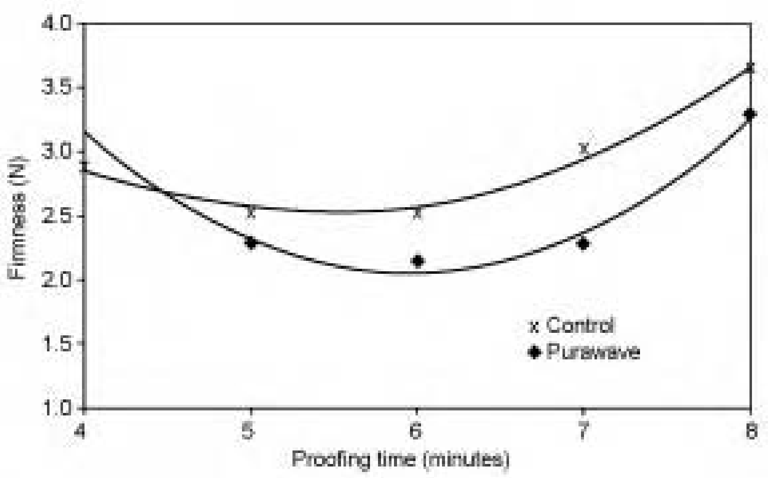

**Fig. 7.3** Effects of microwave proofing time on firmness of microwave baked breads. (Reprinted from *Eur Food Res Technol*, Vol. 213, Ozmuthu O, Sumnu G and Sahin S, Effects of different formulations on the quality of microwave baked bread, 38–42, Copyright © (2001) with permission from Springer.)

reduction of about 50% of conventional baking time. Overall baking time of breads was reduced by using low levels of microwave energy and metal pans in a simultaneous microwave and conventional oven (Schiffmann *et al.*, 1983). More uniform baking was achieved if microwave energy was applied at 915 MHz and 2450 MHz simultaneously. Using a gelling component, gum and enzyme in frozen dough was shown to control moisture migration and starch recrystallization and a fresh microwave baked leavened bakery product was obtained (Jahnke, 2003).

In order to achieve browning and crust formation in breads one commercial approach is to use susceptors. Susceptors consist of metallized, generally aluminized, biaxially oriented polyester film laminated to paperboard on top of which, or within which, the product is placed (Zuckerman and Miltz, 1997). Susceptors have the property of absorbing the microwave energy and converting it to heat, which is transferred to the product by conduction and radiation. The temperature of the susceptor may reach 200–260 °C. The temperature of the dough at the dough–susceptor interface heated in a microwave oven was shown to be a function of the weight and dimensions of the product (Zuckerman and Miltz, 1995). When bread dough was placed on top of the susceptor, desired browning and hardness values were obtained on the bottom surfaces of the breads (Sahin *et al.*, 2002). However, they did not affect top surface colour significantly. Microwave power was a significant factor in enhancing hardness development. The variation of hardness of the bottom surface of breads with time was found to be significantly higher than that of the top surface. The significant increase in the hardness of the bottom surface of breads in the

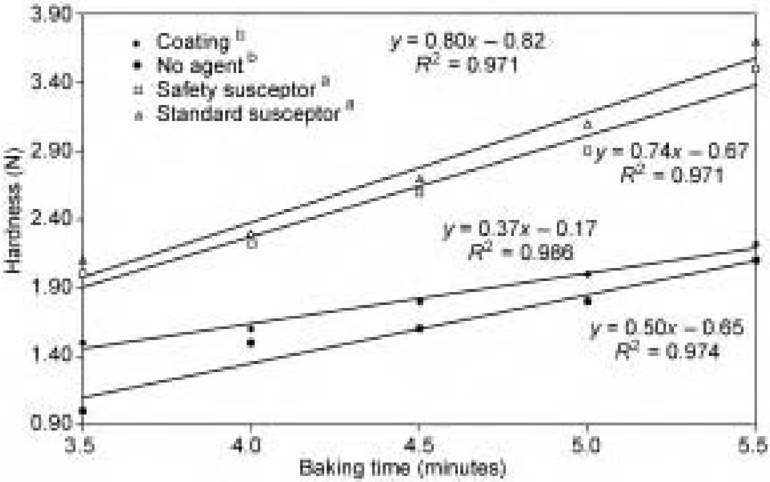

**Fig. 7.4** Effects of different treatments on the bottom surface texture of breads during microwave baking at 20% power. Treatments with different letters (a and b) are significantly different ($p \leq 0.05$); $y$ represents hardness in N and $x$ represents time in minutes in regression equations. (Reprinted from *Journal of Microwave Power & Electromagnetic Energy*, Vol. 37, Sahin S, Sumnu G and Zincirkıran, Effects of susceptor, coating and conventional browning applications on colour and crust formation during microwave baking, 223–236, Copyright © (2002) with permission from International Microwave Power Institute.)

presence of susceptors is shown in Fig. 7.4 (Sahin *et al.*, 2002). The hardness of the bottom surfaces of breads was determined by using a penetrometer which measures the force required for the conical tip (diameter 12 mm, height 9 mm) to penetrate into 35% of the bread thickness. There was no significant difference between the coated and untreated breads in terms of bottom hardness.

A microwave baking pan was developed to allow baking of bread by using both conventional heating and microwave or RF energy (Ovadia, 1994). Metallic pan walls provided rapid and uniform browning with crust formation. Properly sized and oriented apertures in the baking pan permitted entrance of microwave or RF radiation so that the interior of the product could be completely baked.

Hybrid or multimedia ovens combining impingement with microwaves have been introduced so as to produce a brown and crisp crust in microwave baked products (Walker and Li, 1993). Impingement is the process of directing jets of fluid at the surface to accelerate the surface heating (Ovadia and Walker, 1998). Rapid microwave baking of the product interior can be matched by the rapid impingement baking of the crust. Moreover, it is possible to reduce the higher evaporative moisture loss related to microwave baking by the crust formed by impingement baking.

Combining microwave heating with halogen lamp heating is a recent development in microwave baking. The halogen lamp–microwave combination oven combines the browning and crisping advantages of halogen lamp heating with the time-saving advantage of microwave heating. Halogen lamp–microwave combination baking has been recently used in bread baking and has reduced the conventional baking time of breads by about 75% (Keskin *et al.*, 2004a). Breads baked in a halogen lamp–microwave combination oven had specific volume and colour values comparable with the conventionally baked breads but their weight loss and firmness values were still higher. Microwave heating was found to be the dominant mechanism in halogen lamp–microwave combination heating in affecting firmness and weight loss. Halogen lamp–microwave combination ovens can be recommended for use in bread baking to reduce the problem of lack of browning and crust formation.

In order to reduce the firmness of breads baked in microwave and halogen lamp–microwave combination ovens, enzymes (protease, $\alpha$-amylase, xylanase and lipase) were added to the bread formulation (Keskin *et al.*, 2004b). Enzymes are commonly used in conventional baking to reduce the firmness and staling and to increase the volume of breads. Table 7.1 shows the percentage of reduction in firmness of breads baked in different ovens when enzymes were used as compared to breads containing no enzymes. As can be seen in this table, in microwave and halogen lamp–microwave combination baking, all of the enzymes were effective in reducing both initial crumb firmness and firmness during storage.

The initial firmness problem of the interior of bread due to the high amount of amylose leaching might have been reduced by the addition of $\alpha$-amylase and lipase enzymes (Keskin *et al.*, 2004b). The firmness problem due to the microwave-induced gluten changes might be reduced by the use of proteases which break down gluten protein, resulting in softer breads. Xylanases could have a specific action on the rate of gluten development and quality of gluten (Hamer, 1995). This may explain the beneficial effects of xylanase on the crumb

**Table 7.1** Percentage reduction in firmness of breads baked in different ovens[a]

| Baking method | Time of analysis | Amylase | Xylanase | Lipase | Protease |
|---|---|---|---|---|---|
| Conventional | Just after baking | 0 | 0 | 0 | 11.94 |
| | After 2 days' storage | 3.96 | 18.47 | 14.51 | 18.21 |
| Microwave | Just after baking | 33.33 | 29.17 | 17.71 | 23.96 |
| | After 2 days' storage | 15.59 | 19.72 | 21.79 | 22.90 |
| Halogen lamp–microwave combination | Just after baking | 49.84 | 47.87 | 41.97 | 61.31 |
| | After 2 days' storage | 13.69 | 5.22 | 13.43 | 20.60 |

[a] Reprinted from *Nahrung-Food*, Vol. 48, Keskin S O, Sumnu G, Sahin S, Usage of enzymes in novel baking process, 156–160, Copyright © (2004) with permission from Wiley.

structure of breads baked in microwave ovens. Since microwave heating was observed to be more dominant in affecting firmness than halogen lamp heating, the effects of enzymes on reducing the firmness of breads during halogen lamp–microwave combination baking or storage were found to be similar to those resulting from microwave baking.

It was possible to reduce the firmness of breads baked in a halogen lamp–microwave combination oven by providing the required humidity within the oven during baking (Demirekler *et al.*, 2004). Breads baked for 5 min at 70% upper, 50% lower halogen lamp power and 20% microwave power in a halogen lamp–microwave combination oven had comparable quality with conventionally baked ones in terms of colour, textural characteristics, specific volume and porosity.

After baking, all bakery products undergo a series of chemical and physical changes which is broadly referred to as staling (Cauvain, 1998). It is known that starch retrogradation implies hardening of the starch gel, therefore it is supposed to be responsible for the increased firmness of the stale product. The most important change associated with staling is the gradual increase in the firmness of the baked product. The mechanism of rapid staling in breads baked in a microwave oven is not clear yet. The probable cause may be the same as the hypothesis about the staling of microwave-reheated breads which states that more amylose is leached out of starch granules during heating (Higo and Noguchi, 1987).

### 7.6.2 Microwave baked cakes

Baker *et al.* (1990a) compared the effects of different types of emulsifiers and sucrose on temperature profiles of cake formulations baked in microwave and conventional ovens. They reported that the mode of heating was the primary factor accounting for observed differences in temperature profiles rather than the variations in cake formulation. Cake structure appeared to be more variable for conventionally baked cakes than for the microwave baked ones as a function of formulation change. The material of the baking pan was shown to affect the direction of temperature gradients in cakes baked in a microwave oven (Baker *et al.*, 1990b). It was found that cakes baked in glass pans had higher edge temperatures than centre temperatures (Baker *et al.*, 1990b; Sumnu *et al.*, 1999). The increase in moisture content of the batter and oven power increased the temperature of the cake batter significantly during microwave baking of cakes (Sumnu *et al.*, 1999). Starch type did not affect the change of temperature but affected the final cake quality.

A patented microwaveable cake mix can be found in US Patent 4,396,635 (Roudebush and Palumbo, 1983). Cake mixes containing a sugar to flour ratio of 1.4:1 to 2:1, 1% to 5% leavening, 0% to 16% shortening and about 2% to 10% emulsifier were found to be moist and tender when baked in a microwave oven. Sponge cakes when heated in a microwave oven were shown to rise in a similar way to conventionally baked sponge cakes (McPherson *et al.*, 2002). The addition of mesophase gel to the other sponge cake components resulted in a leavening action and contributed to the palatability and lightness of the sponge cake. The mesophase gels were formed using two emulsifiers and an aqueous phase. Composition of the mesophase-containing sponge cakes and methods for making such mesophase-stabilized sponge cakes were described in detail in the patent.

One of the common problems in microwave baked cakes is the dryness of the products. Moisture loss of cakes baked in microwave ovens was found to be greater than that of cakes baked in convection ovens by most researchers (Lambert *et al.*, 1992; Sumnu *et al.*, 1999; Seyhun *et al.*, 2003). In order to reduce moisture loss in microwave baked cakes, hydrocolloids having a high water-holding capacity can be used to increase moisture retention during microwave baking. Methyl cellulose was shown to be an effective hydrocolloid to improve moisture retention of microwave cakes as well as their height and texture (Bell and Steinke, 1991). Seyhun *et al.* (2003) showed that addition of emulsifier and/or gum to the formulation and changing the fat content in the cake formulation were significant factors affecting the moisture loss in microwave baked cakes. Using gums in combination with emulsifiers provided better moisture retention and softer cakes than using gums alone due to the synergistic effects of the two ingredients.

Differences in cell structure between microwave and conventionally baked cakes were reported, and crumb of microwave baked cakes was found to be coarser (Martin and Tsen, 1981). When the effects of starches on the quality of model microwave cakes were investigated, wheat starch cakes had superior quality than rice and corn starch cakes (Sumnu *et al.*, 2000). Oven power was found to be the most significant factor in affecting cake volume, tenderness and uniformity. Tenderness of microwave cakes was affected by baking time, power of the oven and moisture content.

It was possible to achieve browning in microwave baked cakes by the help of air impingement. Combining air impingement with microwaves reduced the baking time significantly and produced cakes with acceptable colour but the lowest volume and the firmest texture (Li and Walker, 1996).

Studies on the staling of microwave baked cakes are limited in the literature. In order to reduce the staling rate of microwave baked cakes, different types of emulsifiers and gums and different amounts of fat were added to the cake formulation (Seyhun *et al.*, 2003). Use of emulsifiers and gums retarded the staling of microwave baked cakes. Fat content was found to be a significant factor in affecting the firmness and weight loss of microwave baked cakes during storage.

### 7.6.3 Microwave baked biscuits

In conventional ovens non-uniform moisture distribution is the main problem in baking cookies. Use of microwaves for the final baking of cookies resulted in more uniform moisture distribution and so reduced the incidence of cracking significantly (Schiffman, 1992; Bernussi *et al.*, 1998). Microwave heating resulted in shrinkage of the product. However, volume and density of the product were not significantly affected. Checking was reduced and mechanical strength was increased, since uniform distribution of moisture within the product was provided in microwave baked biscuits (Ahmad *et al.*, 2001). In this study, the predicted heat and mass transfer model confirmed the higher drying rate and more uniform internal moisture distribution in microwave baked biscuits.

The effects of microwave and conventional baking of canned biscuit wheat dough on its textural and viscoelastic properties were studied by Pan and Castell-Perez (1997). The range of acceptable firmness value was exceeded in the microwave baked product. The rate of weight loss was higher in microwave baked biscuit dough. Microwave baking of biscuit dough resulted in product with tough and leathery texture associated with high modulus of elasticity and high ratio of elasticity to viscosity (Pan and Castell-Perez, 1997).

### 7.6.4 Other microwave baked products

There is little research in the area of microwave baking of bagels, cookies, muffins and doughnuts. Although total baking time was considerably shorter in microwave baking, temperature profiles of bagels were found to be similar during conventional and microwave baking (Umbach *et al.*, 1990). The rate of temperature rise increased in microwave baking but decreased slightly in conventional baking. The conventionally baked bagels lost more moisture during baking than did the microwave baked ones. However, moisture loss after removal of sample from the oven was higher in microwave baked bagels due to the lack of crust (Umbach *et al.*, 1990). The bagel structure, examined by scanning electron microscope, showed differences in cell structure matrix development and starch swelling as a function of location and heating method.

Conventionally baked muffins were darker in colour than microwave baked muffins (Dorko and Penfield, 1993). Panellists evaluated microwave baked muffins as flatter than conventionally baked ones.

In microwave frying of doughnuts, the interior heating properties of microwaves were able to overcome the heat transfer resistances normally found in frying doughnuts (Schiffmann, 2001). Microwave doughnuts reach higher volumes in a shorter frying time. Fat absorption can be 25% lower in microwave doughnuts than in conventional ones. They had longer shelf life, better sugar stability and excellent eating quality. Doughnut proofing with microwave energy can be accomplished in 4 min compared with 40–60 min in conventional proofing (Russo, 1971). Microwave baking of cake-doughnuts after initial frying in hot fat lowered the processing time (Rosenberg and Bögl, 1987). Browning of the dough was achieved by deep-frying on both sides. The interior of the doughnuts was lighter in colour with a non-uniform structure of low density. There were at least 12 commercial microwave doughnut fryers in the USA in the late 1960s and early 1970s (Schiffmann, 2001). However, after several years they disappeared from the industry in spite of high consumer satisfaction.

## 7.7 Future trends

Microwave baking when used alone results in products with inferior quality. Future trends are towards combining microwave heating with other heating methods such as hot air, impingement and halogen lamp. As discussed in Section 7.5.1, when halogen lamp was combined with microwave heating it was possible to obtain breads having similar colour to conventionally baked breads (Keskin *et al.*, 2004a). Further research is required to study the effects of this oven on qualities of different baked products. Phase control, which is a novel method of microwave heating, can be used to control heating rates and temperature distribution in the product (Bows *et al.*, 1999). Since this method offers opportunities for direct control of microwave field and the consequent temperature distribution, it may be used during baking of foods to achieve browning.

It is necessary to investigate the interaction of different ingredients with microwave energy, which will provide insights in improving the quality of microwave baked products. Modelling the changes of dielectric, thermal and functional properties of batter or dough during microwave baking can reduce the quality defects in microwave baked products. Improving the quality of microwave baked products will remain a challenging topic in the future. If success is achieved there will be great savings in time and energy, and products with high nutritive quality will be obtained.

## 7.8 Sources of further information and advice

Reviews in the recent literature on microwave baking include those by Schiffmann (2001) and Sumnu (2001). Information about the Advantium$^{TM}$ oven can be found on the website of GE Consumer & Industrial Appliances at http://www.geappliances.com. Detailed information about susceptors can be found in the chapter written by Bohrer and Brown (2001).

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# 8

# Drying using microwave processing

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## 8.1 Introduction

To understand the particular benefits of microwave drying we should first have a quick look at the much more conventional method of air drying. As idealised in Fig. 8.1, a typical drying curve of a foodstuff can be subdivided into three phases. The first period is one of constant drying rate per unit of surface area. During this period the surface is kept wet by the constant capillary-driven flow of water from within the particle. The factors that determine and limit the rate of drying in the so-called 'constant rate period' all describe the state of the air: temperature and relative humidity as well as air velocity. By changing any of these parameters we can speed up the process considerably.

The situation changes drastically in the next phase. Here we are dealing with two simultaneous transport problems. While the water (vapour) has to get to the surface of the particle in order to be removed by the flowing air, the heat for the evaporation of the water has to travel into the particle. During the process, the surface where evaporation takes place is receding more and more to the centre of the object, so the distance for both types of transport gets longer and longer. Moreover, the surface area for evaporation decreases constantly. As a result, the rate of dehydration drops dramatically, and we call this phase the 'first falling rate period'. It is not easy to increase the rate of drying in this situation. If we want to transfer more energy, we have to apply a higher temperature gradient, which means that the product surface may suffer from overheating or simply dry out too early, causing a phenomenon called 'case hardening'. In the second falling rate period there is no free water any more. There is only a slow diffusion of water to the inner surface (if existing), a desorption from there and the diffusion through pores to the surface of the particle.

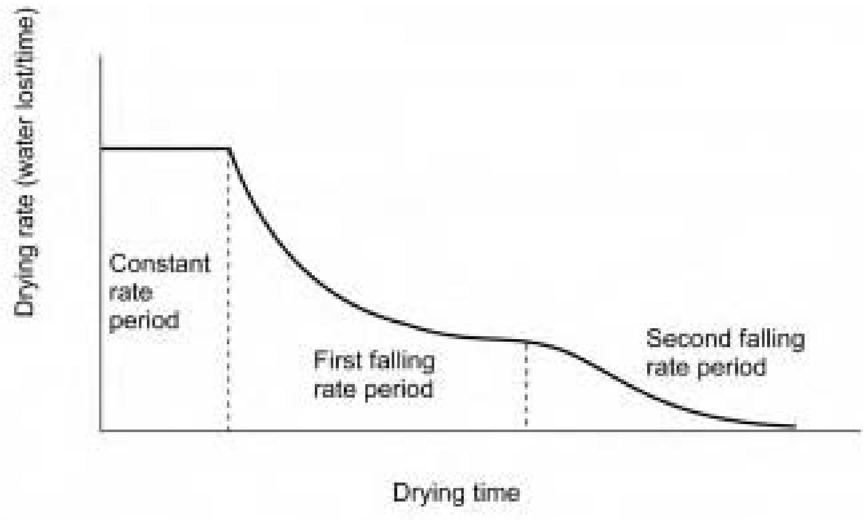

**Fig. 8.1** Typical drying curve for air drying.

It is mainly the falling rate period in which the use of microwaves can make a huge difference. As described in Chapter 1, microwaves can transmit energy in a different way. They travel through the food and provide volumetric heating. They are even absorbed more in the wet than in the dry regions of the product. Consequently, the usual temperature gradient in the particle can be reversed so that the centre is warmer than the surroundings. This effect accelerates the mass transfer. If a vacuum is applied in addition, the mechanism of mass transfer changes completely. In a vacuum, the boiling point of the water can be lowered so much that the product temperature is practically determined solely by pressure. At the boiling point, any additional energy is directly transferred to the evaporation of water. This means that a lot of steam may be created within the product. This steam flows through the particle not just based on a difference in partial water vapour pressure, but as a result of an overall pressure gradient. Thus it is no longer diffusion but convection.

Figure 8.2 shows simplified experimental curves from a microwave vacuum drier. In this example, carrot slices were dried at 60 mbar. As explained before, the temperature stays at about 40 °C until more than half of the water has been removed (the boiling point of pure water would be 36.2 °C). It then starts to rise slowly and later quickly to reach up to 100 °C. Most foods can withstand the final increase of temperature, because with only a little moisture left in the product it is less harmful.

Figure 8.3 shows three curves of the drying rate of carrots at different microwave power levels. Again a vacuum of 60 mbar has been applied. The basic shape appears similar to normal drying curves, but the underlying physical principles are not. Reading them from right to left – as the process takes place – the curves have a slight initial increase, because some energy is needed to reach

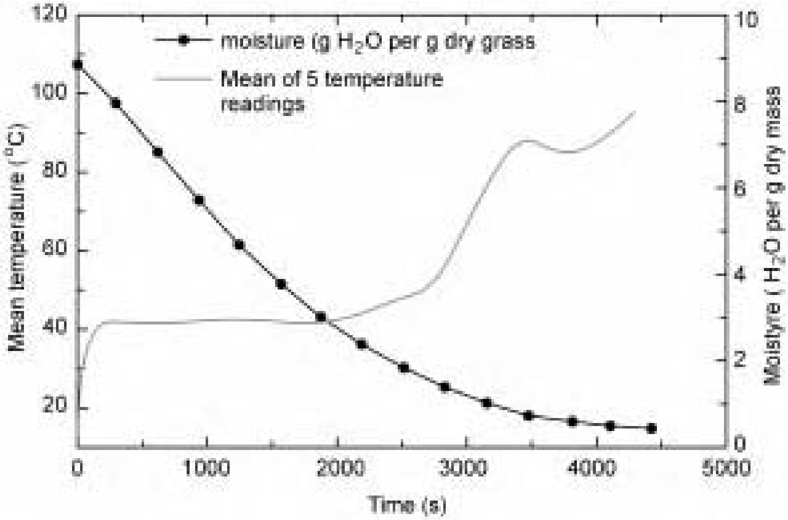

**Fig. 8.2** Moisture and temperature in MW-vacuum drying.

the boiling point. This is followed by a long decline of the drying rate. The key difference from a set of air drying curves is that the drying rate in microwave drying is proportional to the applied microwave power in all phases of the process. Thus we can speed up the process even in the 'falling rate period' simply by using more microwave power. As long as there is enough water left,

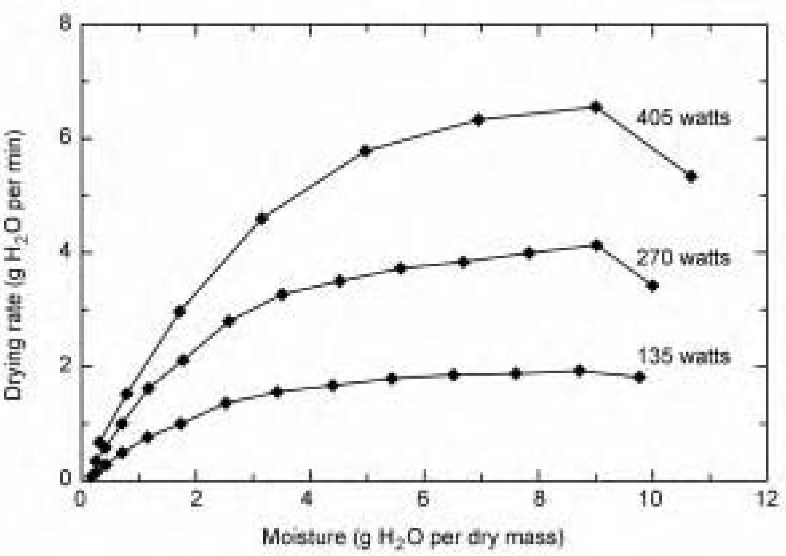

**Fig. 8.3** Drying curves at various microwave power levels.

the product temperature is controlled only by the pressure level. This is what makes microwave drying interesting: the bigger the particles, the more important become the differences in energy and mass transfer and the more obvious is the key advantage of microwaves.

But why are the curves falling at all? As described in Chapter 2, the extent to which microwaves are absorbed by a material depends on its dielectric properties. It is mainly the imaginary part of the dielectric constant, $\epsilon''$, that determines the heat generated by an electromagnetic field of a certain frequency. As the water – together with some dissolved ions – has the biggest influence on $\epsilon''$, it is no surprise that the microwave absorption decreases with decreasing water content of the material. The real part of the dielectric constant, $\epsilon'$, is also governed by the water. Figure 8.4 shows this trend for apple pieces, but the curves for foodstuffs all show more or less the same behaviour. Again reading from right to left, we can see a slight increase of $\epsilon''$, probably due to the rising concentration of dissolved ions. It seems strange that the samples lose a lot of water without a loss in $\epsilon''$. To understand this, we have to consider that the slices lose some volume, too, so that what we can measure by the 'open coaxial line' method used here (see Chapter 3) are the dielectric properties of a slightly compressed object. Later, at lower moisture levels, the absence of water causes $\epsilon''$ to drop considerably. The material is now much less inclined to absorb the offered energy, thereby causing the efficiency of the drier to drop as well. Connected to the falling efficiency is a rise in the electromagnetic field strength, because the less absorption there is in the drier, the higher the field strength becomes, which sometimes creates problems (see below).

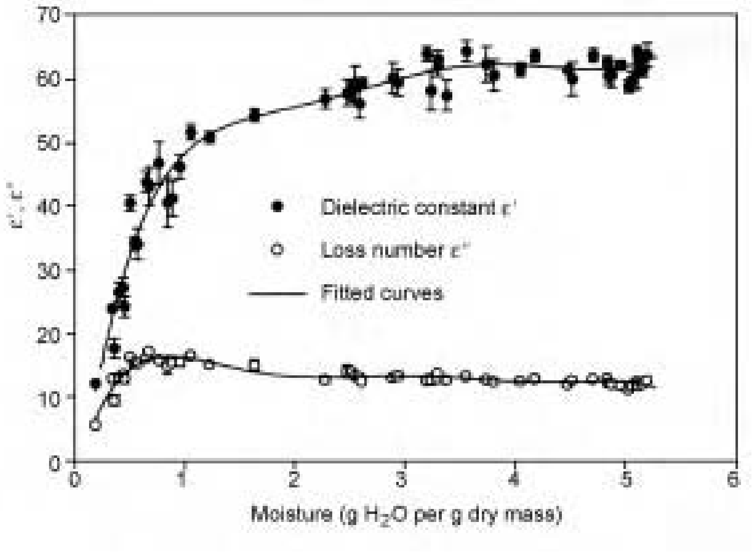

**Fig. 8.4** Dielectric properties of apples as a function of moisture.

The dielectric properties of the material are also responsible for another potential problem: like other polymers, the biopolymers in food show a steep increase in $\epsilon''$ when exceeding a critical temperature. As the substance gets soft, the molecules can move more freely and thereby absorb more microwaves. An unstable system which bears the risk of sudden overheating and burning of the product is created. Without vacuum it may even cause a fire. This phenomenon is known as 'thermal runaway'. As a consequence, we are limited with the microwave intensity towards the end of the process, because the evaporation of water may not cool the product enough to prevent thermal runaway.

Another reason to limit microwave power has to be considered, especially if a vacuum is applied: a breakdown, or discharge of the electrical field. This is basically a flow of electrons or air ions, which may even result in visible phenomena such as plasma or arcing. While effects like plasma are desired in some technological fields, they are usually unwanted in microwave drying. Not only do they consume energy, they may also damage the equipment as well as the product. For instance, Teflon® parts inside a microwave vacuum drier can turn black and erode due to plasma formation. Foods can get thin black crusts, making them unsuitable for consumption. Metaxas and Meredith (1983) have provided a quite detailed description of breakdown effects along with their causes. Important factors are electrical field strength, pressure, and the type of gas in the atmosphere. Local field strength is of course a function of microwave power setting, drier design, mass and dielectric properties of the product, etc. As poorly absorbing products lead to high field intensities, it is often necessary to reduce microwave power towards the end of the process. Once a plasma has been created, it requires much less electrical field strength to be maintained. This is why it is so important to prevent peaks in the microwave intensity. The use of 'low ripple' magnetrons, equipped with a very steady power supply, is recommended for microwave vacuum driers.

The last – and perhaps most important – reason not to exaggerate microwave power is the distribution thereof. Although considerable progress has been achieved in drier design, the microwave field is never completely even. The occurrence of 'hot' and 'cold' spots is described in Chapter 13. Some manufacturers use mode stirrers to distribute the waves, but it is always a good idea to move the product so that all parts of it get approximately the same dose of energy. This is why household microwave ovens usually have a turntable. Using microwaves in a 'modest' way means that there is more time for heat conduction to level out any unbalanced microwave absorption.

Figure 8.5 illustrates one more potential pitfall in microwave drying of particulate foods. This curve for Mie's absorption coefficient stems from a calculation based on spheres of various diameters, which have the dielectric properties of water. The absorption coefficient shows a steep decline towards the left-hand side of the diagram. A value of 1 for this coefficient means that 100% of the incident electromagnetic energy is being absorbed by the object. The calculation reveals that the absorption of electromagnetic waves is very poor when the object is much smaller than the wavelength. At the commonly used

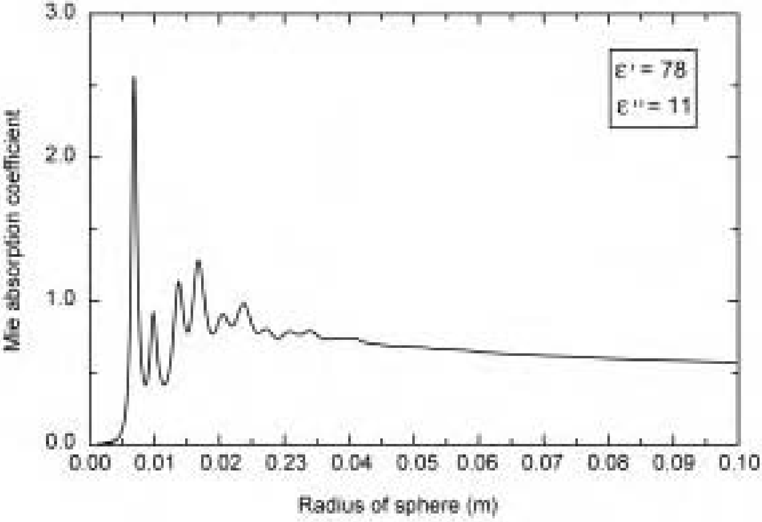

**Fig. 8.5** Mie's absorption coefficient – calculated for spheres of water.

frequency of 2.45 GHz, the corresponding wavelength is around 12.2 cm. A small, wet object may therefore not receive enough microwave power. This effect is of practical relevance if the design and operation of the drier allows for single particles. As long as the particles are in contact with each other and form a bulk, the effect is not significant. The occurrence of values higher than 1 is caused by resonant interaction between wave and object.

## 8.2 Quality of microwave-dried food products

In general, the quality is somewhere between air-dried and freeze-dried products. The reduction of drying times can be quite beneficial for the colour and the aroma. Raghavan and Koller (1995) dried rosemary in a household microwave oven with good aroma retention. Krokida and Maroulis (1999) measured colour and porosity of microwave-dried apples, bananas, and carrots. Khraisheh *et al.* (2004) compared air-dried and microwave-dried potatoes and found a reduction of shrinkage and improved rehydration for the latter. Akahoshi (1996) reported on chicken products, seafood, and vegetables of good quality. He used air at 10–20 °C to cool the product during microwave drying.

Quality can often be improved further by the use of vacuum. This reduces thermal as well as oxidative stress during processing. For instance, Yongsawatdigul and Gunasekaran (1996) showed that colour and texture of microwave-vacuum-dried cranberries were better than those of air-dried samples.

If we look specifically at the retention of aroma, it becomes necessary to distinguish between two basic cases. In most foods the aroma molecules are present in very small amounts, so that they are likely to be dissolved in the water phase. In this situation, the volatility of the aroma molecule in water is essential. Considering the fact that we perceive aroma – as opposed to taste – with our noses, it is quite clear that aroma molecules are normally volatile, otherwise they would stay in the food during eating and not contribute to the aroma. In other words, if there is an interface between a water phase (i.e. a food) and a gas phase, the aroma molecules tend to choose the gas phase. In air drying, the surface where the aroma molecules can escape is mainly the outer surface of the particles. This is also where the water molecules evaporate. So the surface of the food particle will be depleted of aroma, but the losses cannot be higher than those that come with the capillary water flow from within. As a result, the losses of water and aroma are coupled.

## 8.3 Combining microwave drying with other dehydration methods

Microwave–vacuum drying may be used only as one step in a chain of dehydration processes. When combined with an osmotic pre-treatment, much of the water can already be removed by keeping fruits or vegetables in a concentrated solution for a few hours. Meanwhile, some of the solutes, like sugar or calcium ions, may penetrate the tissue and have beneficial effects on the quality of the final product. For example, it has been found that sucrose and calcium chloride from an osmotic treatment reduce shrinkage of apples and strawberries during subsequent microwave–vacuum drying (Erle and Schubert, 2001).

The combination of microwave–vacuum drying and air drying is perhaps the most obvious option: as air drying is relatively cheap, the first unit in the process chain is preferably an air drier. When it becomes inefficient, as explained above, microwaves and vacuum can be used not only to continue the dehydration, but to create a huge volume of steam, enough to inflate the product and regain much of its original volume. This step, called ‘puffing’, gives the product a better appearance and also facilitates, by making it more porous, the final drying step. However, for successful puffing it is essential that the moisture distribution in the pre-dried material be very narrow. A few percent deviation from the ideal moisture – product-dependent from approximately 15 to 40% – will cause many unpuffed particles. This is a critical aspect, as air driers are normally not designed to deliver such pre-dried material. Since the efficiency of microwave drying drops towards the end, the final drying is again carried out in an air drier. This makes sure that no wet spots, possibly left after microwave puffing, remain.

Figure 8.6 compares carrot cubes from three different drying processes. Freeze drying is generally rated as the most gentle method, giving very porous but rather pale products. Microwave puffing yields a stronger colour, but the porous pieces look more like pillows, sometimes with only one gas bubble inside. The air-dried control samples exhibit the usual problem of extensive shrinkage.

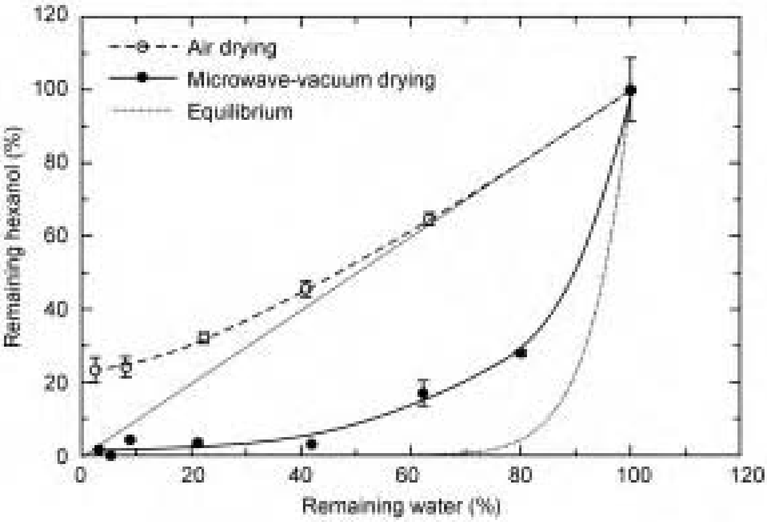

Fig. 8.6 Carrot cubes, dried in different processes.

The rate of rehydration is best for freeze-dried products. This is because they have an open pore structure and – due to capillary effects – draw up the water within seconds. Puffed particles, although quite porous, usually have a closed surface and cannot make use of the capillary effect. Still, they are superior to air-dried products, not necessarily for a higher rehydration rate but because they soften more rapidly in hot water.

## 8.4 Microwave drying applied in the food industry

Microwave drying is not common in the food industry. There are many reasons for its limited use: the technical problems described above were not well-understood in the past. This has led to some failures, which have surely discouraged other potential users. Schiffmann (2001) has listed a number of formerly successful applications that have been discontinued. Among these are the finish drying of potato chips, pasta drying, snack drying, and the finish drying of biscuits and crackers. It is apparently not always the microwave process itself but rather changes in the circumstances of production that make competing technologies more successful.

In spite of these difficulties, there are some current applications. Schiffmann (2001) mentions cereal cooking and drying with a production rate of nearly 1 ton/h. Pasta drying with microwaves is carried out in Italy. Microwave–vacuum drying is being used for meat extract and, at least for a number of years, for the production of a powder made from orange juice concentrate (Attiyate, 1979). The combination of air drying and microwave–vacuum puffing is being

**Table 8.1** Comparison of five different drying methods

| Type of drying process | Specific energy demand kWh/kg water | Specific investment costs For equal throughput |
|---|---|---|
| Air band drying | 1.9 | 100% |
| Spray drying | 1.6 | 120% |
| Vacuum contact drying | 1.3 | 150% |
| Microwave vacuum drying | 1.5 | 190% |
| Freeze drying | 2.0 | 230% |

used in Germany and Poland for fruits and vegetables. As the food industry does not disclose all its production processes, we cannot expect this list to be complete.

Hauri (1989) has provided values for the necessary investment and the specific energy requirements of five different drying methods (see Table 8.1). Based on the same throughput, the investment needed for microwave–vacuum drying is rather high, while the energy figures are more favourable than for air drying.

## 8.5 Modelling microwave drying

A simple way to model microwave-assisted air drying is to vary microwave power, air temperature and air velocity. Later, the influence of these factors on drying rate and product temperature can be assessed by multiple regression. This method has, for instance, been applied by Khraisheh *et al.* (1995), Tulasidas *et al.* (1995), and Ruíz Díaz *et al.* (2003). However, these empirical models are very limited in use, because the underlying physical principles are not included. Other authors have applied balances of heat and mass, in which the dissipated microwave energy shows as an extra source term. Lu *et al.* (1998, 1999), Jun et al. (1999), Torringa et al. (1996) and Bouraoui (1994) have taken this approach, only neglecting shrinkage in their calculations. The resulting diffusion coefficients are therefore somewhat distorted. Stammer (1991) used non-shrinking objects for his model. He proved the existence of resonance-based variations in the drying rate, similar to those derived from the theory of Mie (see above).

Microwave–vacuum drying has been modelled for apples, kiwi fruits, and pears by a statistical regression method in order to show the influence of microwave power and pressure on a drying constant (Kiranoudis *et al.*, 1997). A more physically based approach was taken by Lian *et al.* (1997) for the belt drying of a pasty substance with 65% solid content. Using numerical differential equations for heat and mass transfer as well as Lambert's (local field strength) and Fick's (diffusion of vapour) laws, the authors achieved good results, although shrinkage was neglected. Models on microwave–vacuum drying can be simplified by assuming that the absorbed energy is just used for the evaporation of water, which leaves the object as a convective flow of steam. This makes the calculations of mass transfer obsolete and has yielded a good correlation with measured drying curves of apple cuboids (Erle, 2000). Recently, the relatively new technique of Magnetic Resonance Imaging (MRI) has provided the opportunity to see the distribution of water and temperature inside the objects – even during the process. This is a valuable tool to verify more complete calculations, comprising three-dimensional heat capacity, thermal conductivity and diffusion coefficients (Knörzer *et al.*, 2004).

From a practical point of view, none of these modelling attempts has achieved much significance for the food industry. So far it has always been easier to use trial and error, based on former practical experience, than to collect all the necessary information on thermo-physical properties, dielectric properties, field distribution in the drier, etc. This may change in the future, when more physical data will be available and the application of such models becomes more of a routine.

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# 9

# Blanching using microwave processing

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## 9.1 Introduction

Blanching is an important step in the industrial processing of fruits and vegetables. It consists of a thermal process that can be performed by immersing vegetables in hot water (88–99 ºC, the most common method), hot and boiling solutions containing acids and/or salts, steam, or microwaves. Blanching is carried out before freezing, frying, drying and canning.

The main purpose of this process is to inactivate the enzyme systems that may cause color, flavor and textural changes, such as peroxidase, polyphenoloxidase, lipoxygenase and pectin enzymes. The efficiency of the blanching process is usually based on the inactivation of one of the heat resistant enzymes: peroxidase or polyphenoloxidase.

Blanching has additional benefits, such as the cleansing of the product, the decreasing of the initial microbial load, exhausting gas from the plant tissue, and the preheating before processing. A moderate heating process such as blanching may also release carotenoids and make them more extractable and bioavailable (De la Cruz-García *et al.*, 1997).

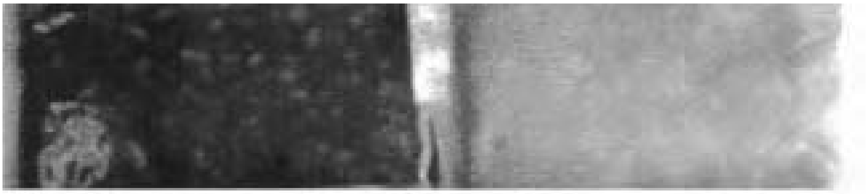
However, this operation has also some inconvenient effects such as losses in product quality (texture and turgor), environmental impact, and energy costs. Leaching and degradation of nutritive components, such as sugars, minerals and vitamins, may occur when blanching with water or steam. The blanching process should assure enzyme inactivation while minimizing the negative effects, taking into account the interdependence of every aspect (Gaiser *et al.*, 1996; Arroqui *et al.*, 2002).

The use of microwaves for food processing has increased through the last decades. Some of the advantages compared with conventional heating methods include speed of operation, energy savings, precise process controls and faster start-up and shut-down times (Kidmose and Martens, 1999). Microwave blanching of fruits and vegetables is still limited. Some of the advantages compared with conventional heating methods include speed of operation and no additional water required. Hence there is a lower leaching of vitamins and other soluble nutrients, and the generation of waste water is eliminated or greatly reduced.

## 9.2 Blanching and enzyme inactivation

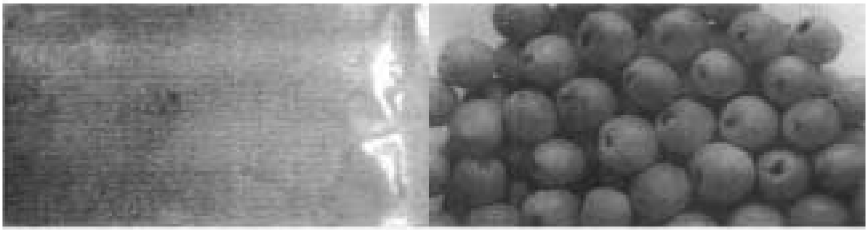
Enzymatic browning is a prominent deteriorative reaction in fruits. It causes discoloration associated with increased concentration of polymeric derivatives of *o*-quinones, which derive from phenolic substrates through oxidative reactions catalyzed by polyphenol oxidase (PPO) in the presence of atmospheric oxygen (del Valle *et al.*, 1998). Polyphenol oxidase is a generic term for a group of enzymes. The brown pigments they produce also lead to the development of off-flavors and losses in nutritional quality. These enzymes are relatively heat labile: temperatures of more than 50 ºC and proper time of treatment allow a decrease in activity, whereas they are inactivated at temperatures $\geq$80 ºC. An example of a fruit with a high browning potential is hawthorn (*Crataegus mexicana* Moc. & Sessé) (Ortiz-Moreno, 2004). Figure 9.1(d) depicts whole hawthorn fruits, Fig. 9.1(a) shows the enzymatic browning of hawthorn pulp, a hawthorn sample blanched using a traditional method (heating on a hot plate) can be observed in Fig. 9.1(b) and hawthorn pulp treated with microwaves to prevent browning is seen in Fig. 9.1(c).

Peroxidase is widely distributed in higher plants, with high concentrations in fig sap and horseradish. It is also found in some animal tissues and in microorganisms. This enzyme controls the level of peroxides in the tissue. However, its catalytic action produces a deteriorative effect in raw vegetable products, since it contributes to browning action and other oxidative reactions. In fact, peroxidase catalysis is associated with four types of activity: peroxidatic, oxidatic, catalatic, and hydroxylation. Under the usual assay conditions *in vitro* where a phenolic substrate is used, only the peroxidatic reaction is of importance (Whitaker, 1994). Peroxidatic activity on phenolic compounds, such as ferulic acid, can generate phenolic crosslinks that connect polymer chains; this action affects the mechanical properties of cell walls and therefore the texture of vegetables. This enzyme system has gained much attention due to its role in modulating the mechanical properties of cell walls during extension and cell adhesion, as related to the thermal stability of texture (Tijskens *et al.*, 1997). The assay most frequently used to detect peroxidatic activity is the peroxidatic reaction with guaiacol as the substrate. This assay is very simple and readily followed in a continuous fashion in a recording spectrophotometer. Complete inactivation of peroxidase assures that all other enzymes have been destroyed. Hence loss of peroxidase activity is generally used as an index of proper blanching of vegetables.



9.1a blank

9.1b microwaves



9.1c conventional

9.1d hawthorn fruit

**Fig. 9.1** Blanching of hawthorn (*Crataegus mexicana* Moc. & Sessé) pulp with a traditional method and with microwaves (a) blank; (b) microwaves; (c) conventional and (d) hawthorn fruit.

Lipoxygenase is found in a wide variety of plants, particularly the legumes. There are at least three detrimental effects of the action of lipoxygenase in foods: (a) destruction of the essential fatty acids (linoleic, linolenic and arachidonic); (b) production of free radicals, which damage other compounds including vitamins and proteins; and (c) development of off-flavor and odor. In beans and peas this is characterized as a hay-like flavor. This is a serious problem in unblanched frozen peas, beans and corn since lipoxygenase can continue its action even at low temperatures (Whitaker, 1994).

The pectic enzymes are a group of catalysts that degrade the pectin substances and have been found in higher plants and in microorganisms. They are useful for treatment of fruit juices and beverages to facilitate filtration and clarification, to increase juice yields, and in the production of low-methoxyl pectin and galacturonic acids. They are considered deteriorative enzymes since they cause excessive softening of many fruits and vegetables, as well as ‘cloud’ separation in such products as tomato and citrus juices. There are three types of pectic enzymes that catalyze three different types of reactions. The enzyme pectin methyl esterase (PME) demethylates the carboxymethyl groups of the pectic polysaccharide chains, which triggers different processes related to texture and firmness. These processes may comprise cross-linking by $Ca^{2+}$, increasing the hydration at the demethylated sites, enhancing shielding and repulsion forces by the electric charges within the biopolymer matrix of the cell wall, as well as decreasing the susceptibility to polygalacturonase activity (Tijskens *et al.*, 1999). This enzyme has been claimed to be activated by low-temperature long-time (LTLT) blanching treatments (del Valle *et al.*, 1998), hence to prevent changes in texture due to PME activity, a high temperature blanching process is recommended. Other pectic enzymes are the polygalacturonases and the pectate lyases that hydrolyze glycosidic linkages in pectic substances, causing viscosity reduction in fruit products.

### D, z *and TIT values*

The thermal inactivation curve for enzymes is generated by subjecting an enzyme extract or a food sample to a series of heat treatments at a specific temperature, and then testing for residual enzyme activity. The range of temperature tested is beyond the optimal temperature, where a rather steep decline in activity is observed, due to denaturation. In general, the shape of the decrease with temperature is exponential, indicating a first-order reaction. From the resulting plot of log of residual enzyme activity versus time, the *D* value of an enzyme may be calculated. It represents the heating time in minutes required to inactivate 90% of the total enzyme activity at a particular temperature (Ramaswamy and Abbatemarco, 1996).

The *z* value is a temperature sensitivity indicator, and it is obtained by plotting the logarithm of *D*-values against temperature. The *z*-value indicates the temperature range between which the *D*-value curve passes through one logarithmic cycle. Svensson (1977) reported the *z*-values for the thermal inactivation of potato enzymes, peroxidase being the enzyme most resistant to temperature with a value of 35 ºC, followed by polyphenoloxidase (7.8 ºC), lipoxygenase (3.6 ºC) and lipolytic acid hydrolase (3.1 ºC).

### *Thermal Inactivation Time (TIT)*

An enzyme is considered inactivated when there is no measurable residual activity, and then the corresponding heating time is taken. This is known as the thermal inactivation time. The calculation of blanching time for a specific product is based on the heating time of its most heat-resistant enzyme. Alternatively, the enzyme that causes commercial deterioration in a particular commodity may also be considered.

The thermal inactivation time of a particular enzyme is strongly dependent on the processing temperature: at higher temperatures, there are lower TIT values. The same applies for the thermal death time of microorganisms. However, at relatively low thermal processing temperatures, the destruction rate for enzymes is greater than that for microorganisms, but as process temperature increases, the destruction rate for microorganisms increases faster than that for enzymes. This is why the inactivation of some enzymes is used to verify the efficiency of a thermal process, e.g. pectin methyl esterase activity has been used to determine the adequacy of pasteurization of fruit juices, and alkaline phosphatase inactivation is used to verify the pasteurization of milk. Thermal inactivation times of enzymes are also affected by different blanching media, type of vegetable, weight and size of samples; and in general by all the factors that influence the energy transfer in the food or the stability of enzymes. Particular cases are presented in Table 9.1.

**Table 9.1** Different conditions for enzyme inactivation in some fruits and vegetables

| Enzyme/food | Thermal inactivation time | Temperature | Other conditions | Reference |
|---|---|---|---|---|
| Lipoxygenase/ tomato juice | 1–7 min | 80–95 ºC | Microwave oven Bauknecht MCG 1731, Germany | Servili *et al.*, 2000 |
| Peroxidase/ carrot slices | 1 min (250 g) | Temperature not specified | Continuous conveyer microwave oven, 0.5 m min$^{-1}$ | Kidmose and Martens, 1999 |
| Peroxidase/ carrot slices | 3 min (1000 g) | 90 ºC | Steam blanching | Kidmose and Martens, 1999 |
| Peroxidase/ carrot slices | 4 min (1500 g) | 90 ºC | Water blanching | Kidmose and Martens, 1999 |
| Polyphenoloxidase/ avocado purée | 5 s (20 g) | 103 ºC | Microwave heating, pH 6.5 | Dorantes-Alvarez *et al.*, 2000 |
| Polyphenoloxidase/ sliced potatoes | 2 min (100 g) | Boiling temperature | Boiling saline solutions | Severini *et al.*, 2003 |
| Peroxidase/spinach | 180 s | 90 ºC | Agitated water bath, 120:10 water:spinach w/w | Gaiser *et al.*, 1996 |
| Peroxidase/endive and spinach | 210 s | 90 ºC | Water blanching | Ponne *et al.*, 1994 |
| Peroxidase/potato cylinders | 10 min (4 cylinders, 7 cm long, 1.2 ∅) | 93 ºC | Recycled water blanching | Arroqui *et al.*, 2002 |
| Polyphenoloxidase/ apple cylinders | 60 s | 97.3 ºC | Boiling water | Del Valle *et al.*, 1998 |

High-temperature short-time (HTST) processes were developed upon the knowledge that enzymes and vegetative cells of pathogenic bacteria may be inactivated at high temperatures and short times. One of the advantages of HTST is that it results in greater nutrient retention (Lund, 1977). As HTST treatments may be accomplished in solid foods by the application of microwaves, a greater nutrient retention is expected.

## 9.3 Comparing traditional and microwave blanching

Even though reports on some applications may be contradictory, microwaves do have a more efficient transfer mode than traditional thermal techniques, thus allowing shorter heating times and minimizing food quality deterioration. For example, some research reports were reviewed by Rosenberg and Bögl (1987). They observed that the qualitative results given by microwave blanching on some vegetables are sometimes comparable to those obtained by conventional blanching methods. However, results can also be less satisfactory. The authors concluded that microwaves can be better than conventional methods for some applications (peaches, reduction of $\alpha$-amylase in dough), but not for others (whole corn cobs).

Ponne *et al.* (1994) compared the effects of different blanching methods on endive and spinach leaves: microwaves, a combination of microwaves and steam, steam, water, infrared and radio frequency energies. Texture, color, dry matter, vitamin C content, nitrate content, and sensory characteristics were evaluated on the blanched leaves after freezing and thawing. Microwave blanching was carried out in a microwave tunnel (6 kW, 2450 MHz) for 90 s. The leaves had better texture when blanched with microwaves or the microwave–steam combination, which correlated with the sensory attributes 'firm' and 'fibrous'. The retention of vitamin C was highest in those samples processed with steam, microwaves, and microwaves–steam. High vitamin C losses were observed in water-blanched samples. The vegetables processed with microwaves–steam scored highest on the sensory evaluation, and microwaves–steam and microwaves resulted in an improved quality of the final products when compared with water and steam blanching.

Another study that compared microwaves with traditional blanching methods was published by Kidmose and Martens (1999). Before freezing, carrots are blanched to avoid the development of off-taste due to fatty acids released by esterase. The blanching efficiency of this particular process is established by the inactivation of peroxidase. The study compared the effect of microwave (continuous conveyer microwave oven 10 kW, M25, with four magnetrons of 1.25 kW each), steam or water blanching and subsequent freezing on the texture, microstructure and nutritional quality of carrot slices. The authors found a tendency towards increased firmness after microwave blanching, with very few fissures and cracks observed in the carrot tissue. The microwave process also resulted in a higher nutritional quality of the product, with higher contents of dry matter, minerals, ascorbic acid and total sugars. Significantly higher carotene content was also obtained by microwave blanching. However, after freezing, the microwave treatment did not result in an improved texture when compared to conventional blanching methods.

Krokida *et al.* (2000) studied the effect of osmotic-, microwave-, sulfite-, water-, and steam-blanching on the color of dried potatoes. Untreated and microwave pre-treated materials showed extensive browning during drying. Osmotic, sulfite, water-, and steam-blanching suppressed browning during drying, as shown by the $L^*$, $a^*$ and $b^*$ parameters. On the other hand, van den Eide *et al.* (2000) studied the combination of microwave and boiling water treatment for fresh potato slices. They found that this combined process efficiently inactivated PPO and thus prevented oxidative browning.

A comparison of the effects of steam, microwave blanching (microwave oven, 400 W) and osmotic treatments on the quality of strawberries was carried out by Moreno *et al.* (2000). Traditional processing methods used for the conservation of strawberries seriously affect the sensory and nutritional values of the fresh fruit. Steam and microwave blanching lead to about 80% of residual enzyme activity, and greatly promote sucrose gain in the subsequent osmotic processes. The changes in the tissue induced by these two methods promote a cell decompartmentation, which results in a faster mass transfer rate.

Polyphenol oxidase (PPO) present in strawberry tissue causes loss of red color due to deterioration of anthocyanins and browning. Chrome is the color attribute that was subject to the greatest changes, and both blanching treatments caused loss of chrome color. However, this loss implies non-perceptible changes to the human eye.

With regard to texture, the microwave treatment resulted in a lower force decrease than steam. Microwaves also preserved cells better at the microstructural level. However, the steam treatment was more effective in sample preservation, possibly due to the reduction of the initial count of microorganisms in the sample surface by thermal effect and the slightly lower $a_w$ reached in the subsequent osmotic treatment.

Cano *et al.* (1990) compared the effects of microwaves (650 watts for 2 min) and boiling water (11 min) in the blanching of banana slices. Microwaves greatly decreased residual activities of both polyphenol oxidase and peroxidase (from 65 to 75%). However, blanching in boiling water produced almost a complete inactivation of both enzymatic systems (higher than 93% in all maturity levels), and an acceptable sensory quality. The rapid heat onset produced by microwaves in vegetable tissues may cause oxidation and degradative reactions in some cases. In this study, banana slices blanched with microwaves resulted in a poor quality product from the sensory point of view, and therefore the authors considered it an unsuitable process, even though it accomplished a great enzyme inactivation.

### 9.3.1 Evidence of enhanced thermal effects

The following studies, among others, suggest the possibility of some non-thermal enhanced effects associated with microwave heating. The mechanism by which microwaves contribute to additional microbial and enzyme destruction is still unclear. Tajchakavit *et al.* (1998) studied the kinetic parameters (*D*-values and *z*-value) for destruction of *S. cerevisiae* and *L. plantarum* in apple juice during continuous flow non-isothermal microwave heating, as compared to the values obtained from batch thermal treatments. Microwave heating resulted in characteristic first-order reaction kinetics.

The comparison of both methods on the survival of the microorganisms indicated that the *D*-values obtained for microwaves were considerably lower than those for the conventional treatment. In the case of *S. cerevisiae*, the *D*-value for thermal destruction (25.1 s) was higher by an order of magnitude than the one for microwave destruction (2.08 s). For *L. plantarum*, the *D*-values indicated that the destruction under microwaves was about six times faster than under batch thermal treatment. These results suggest that microwaves were more efficient in destroying microorganisms in apple juice than the thermal treatment.

Similar results were reported for enzyme inactivation studies (Tajchakavit and Ramaswamy, 1997). The authors studied the inactivation kinetics (*D*-value at different temperatures and *z*-value) of PME in orange juice, using a microwave oven (700 W) under full power operation, which was modified to accommodate a continuous flow of liquid. The authors defined clearly the temperature exposure of the samples during both heating and cooling.

The tube length and flow rate were adjusted to give selected exit temperatures (55, 60, 65 and 70 ºC). The authors considered the kinetic parameters to be a result of thermal and microwave effects. The calculated *D*-values ranged from 38.5 s at 55 ºC to 1.32 s at 70 ºC, while the values reported for conventional methods ranged from 10 to 390 s at 55 ºC, and from 6 to 36 s at 70 ºC. Hence, *D*-values obtained under microwave heating are smaller by an order of magnitude.

On the other hand, some authors are opposed to the concept of non-thermal effects given by microwave processing (Welt *et al.*, 1994; Fujikawa *et al.*, 1992; Goldblith and Wang, 1967).

After reviewing various studies on microwave inactivation of enzymes, Anantheswaran and Ramaswamy (2001) concluded that the results obtained with this technique appear to be predominantly due to the thermal effects generated by microwaves, even though some enhanced effects may exist. Therefore, these authors recommend that the design of processing conditions would be based on the well-documented thermal effects and take as safety the additive enhanced effects.

## 9.4 Applications of microwave blanching to particular foods

Some patents on blanching by microwaves are presented in Table 9.2. This selection does not pretend to be comprehensive, but rather illustrative of relevant development in this area.

Blanching with hot water after the microwave treatment compensates for any lack of heating uniformity that may have taken place, and also prevents desiccation or shriveling of delicate vegetables. And while microwave blanching alone provides a fresh vegetable flavor, the combination with initial water or steam blanching provides an economic advantage. This is because low-cost hot water or steam power is used to first partially raise the temperature, while microwave power, which costs more, does the more difficult task of internally blanching the food product.

A still further advantage is that microwave blanching enables a finish blanching of the center sections more quickly and without being affected by thick or non-uniform sections. Uniformity is also more rapidly accomplished in microwave ovens of the continuous tunnel types in contrast to the customary non-uniformity in institutional or domestic ovens (Smith and Williams, 1971).

**Table 9.2** Summary of microwave blanching applications to particular foods based on patents

| Commodity | Equipment | Comments or remarks | Author, patent and publication date |
|---|---|---|---|
| Diced vegetables | Waveguide coated with an epoxide resin | Vegetables can be blanched or cooked by microwave radiation transmitted along the waveguide without resonance | Taylor and Wilson (1968),<br>UK Patent GB1105088<br>6 March 1968 |
| Fruits and vegetables | N.S.[a] | Partially dried foods are blanched by microwaves and then dehydration is completed at subatmospheric pressure | Godson (1968),<br>UK Patent GB1112438<br>8 May 1968 |
| Food in partially sealed plastic pouches | Microwave oven, vacuum chamber for cooling | Used for cooking or sterilizing foods, or to blanch before a freezing process | Jeppson (1968),<br>UK Patent GB1135239<br>4 Dec. 1968 |
| Vegetables (specially fragile ones such as asparagus, broccoli and cauliflower) | Vat of hot water, steam chest, microwave chamber of the continuous tunnel type, endless conveyor | The product is blanched with water above or atmospheric pressure steam at 185 ºF, then microwaved preferably while the product is blanched with steam. Finish with a hot water blanch (at least for 2 min) and water cooling at 45–65 ºF | Smith and Williams (1971), US Patent 3,578,463, 11 May 1971 |
| Vegetable materials | Combined apparatus for saturated steam and microwave application, transporter under spraying device | Pressurized steam and microwaves are applied at intervals, thereafter quickly cooling with water at 0 to −10 ºC. The conveyor band retains vegetable juices during blanching | Bailey (1992),<br>EPA[b] EP 0498972<br>19 Aug 1992 |

**Table 9.2** Summary of microwave blanching applications to particular foods based on patents

| Commodity | Equipment | Comments or remarks | Author, patent and publication date |
|---|---|---|---|
| Fresh fruits and vegetables | N.S.[a] | Whole or cut pieces are treated with microwaves not exceeding 45C and then freezing. Upon thawing the product has organoleptic characteristics of the corresponding fresh product. | Tishel (1997),<br>EPA[b] EP 0 706 762 A3,<br>4 Jun 1997.<br>Int. Class. A32B7/04,<br>A23B7/01, A23B7/02,<br>17 Apr 1996.<br>US Patent 5,595,775,<br>21 Jan 1997 |
| Pieces and juice of a cruciferous plant | N.S.[a] | By performing a microwave treatment, blanching and drying, a $\alpha$-aminobutyric acid enriched vegetable product is obtained, keeping its original green colour. | Hattori (2001),<br>EPA[b] EP 1 082 911 A3,<br>25 Apr 2001.<br>US Patent 6,632,458,<br>14 Oct 2002 |
| Vegetables | N.S.[a] | The drying comprises exposure to microwave radiation at subatmospheric pressure | Subramaniam (2001),<br>TW438576<br>7 Jun 2001 |
| Leguminous plants and cereals | N.S.[a] | Clean fruits are microwaved (2450 MHz, 750 W, > 100 ºC) for 10–25 min, dipped in water at 40–60 ºC and frozen at a temperature below $-18$ ºC | Kepka (2002),<br>EPA[b] EP 1 217 903 A1,<br>3 Jul 2002 |
| Foods | N.S.[a] | Reduced time and power for drying process with microwave blanching and drying | Sapunov and Ivanov (2003),<br>RU2195824<br>10 Jan 2003 |

[a] N.S.: Not specified in the patent.

[b] EPA: European Patent Application.

The spraying of cold water at the end of the blanching process allows a better nutrient retention than the immersion of the food in cold water. Sub-atmospheric pressure, when applied to the steam blanching process, reduces the amount of oxygen and therefore results in a lower degradation of vegetable pigments and nutrients. Pressurized steam reduces blanching time. Optimal conditions of time, temperature, vapor pressure and microwave power depend on the particular vegetable that is being processed and must be empirically determined.

The knowledge of precise microwave power per weight of food that is needed to inactivate a particular enzyme should be sufficient to achieve a successful blanching and to avoid adverse effects. When the process temperature is not adequate, the enzymatic deteriorative action may prevail or even increase in some cases. Figure 9.2 shows the activity of mushroom polyphenol oxidase in a phosphate buffer 0.05M solution. The samples were previously treated in a microwave oven at specific times, using different potency levels: high, medium and low, which correspond to 770, 560 and 240 watts, respectively. After the thermal process, the samples were cooled to room temperature and their browning potential was tested by mixing with a specific substrate and immediately reading the change in absorbance at 420 nm with a spectrophotometer. The sample processed at 770 watts reached an internal temperature of 80 ºC, showed no visible browning and the absorbance change rate was very low: 0.02 $\Delta \mathrm{Abs}_{420}\mathrm{mL}^{-1}\mathrm{min}^{-1}$. The sample processed at 560 watts had an initial rate of 0.10 $\Delta \mathrm{Abs}_{420}\mathrm{mL}^{-1}\mathrm{min}^{-1}$. The sample treated with a potency of 240 watts showed a slightly higher initial rate than the blank (0.22 > 0.20), due to its internal temperature of 47 ºC that accelerated the browning reaction. The maximum degree of browning was 0.84, the same for both the last sample and the blank (Dorantes-Alvarez, L., unpublished results).

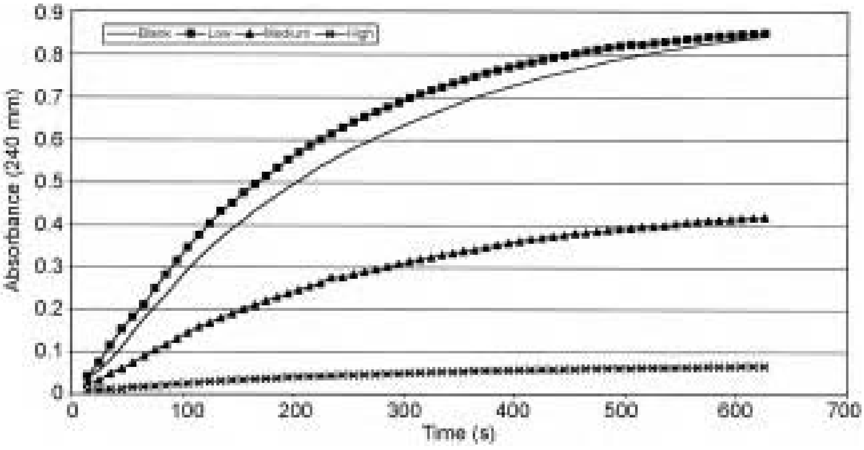


**Fig. 9.2** Mushroom tyrosinase as affected by microwaves (Dorantes, L., unpublished results).

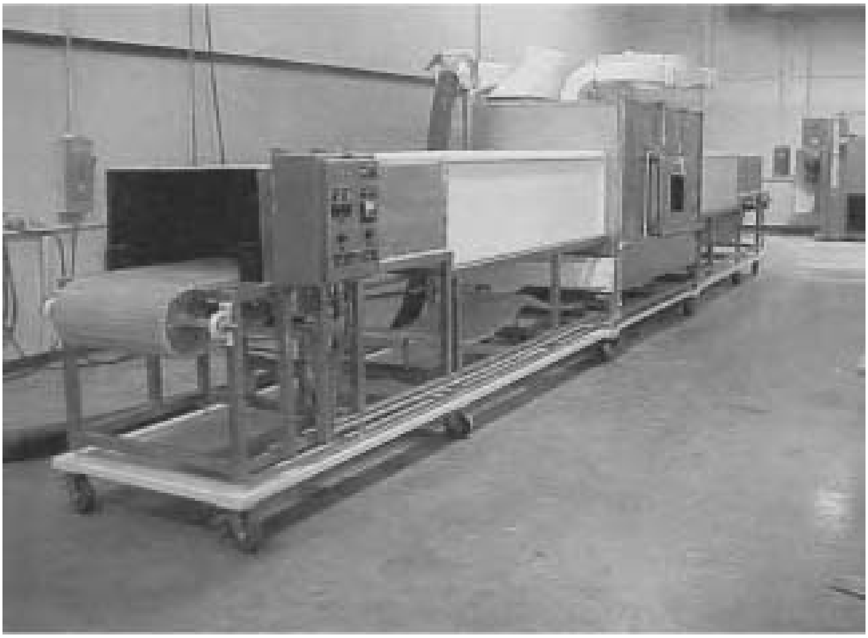


**Fig. 9.3** Microwave blanching equipment (courtesy of Microdry Inc., Crestwood, Kentucky, USA).

### 9.4.1 Microwave blanching equipment design

Planar or cylindrical microwave heating systems may be used for blanching, tempering, partial drying or conditioning food materials. These microwave systems are scalable depending on the particular application, and the microwave power output required, its frequency and design are determined by the volume per hour of material to process, its microwave properties and processing specifications (Industrial Microwave Systems, 2004).

In blanching applications, initial moisture content and temperature, as well as processing parameters and physical properties of the material, such as maximum permissible temperature, minimum bed depth, density and specific heat, must be known to develop and tailor a suitable system for specific needs.

Microdry Incorporated (Crestwood, Kentucky, USA) offers a planar oven (tunnel) with a 60 kW, 915 MHz power generator, fitted to a multi-mode conveyor, the size of which may vary with the volume of food to be blanched per hour (see Fig. 9.3). In this system, adjustable microwave power for industrial applications may be incorporated. Output power may be varied from 0 to 60 kW at FCC assigned frequency of 915 MHz. Power generator may be controlled by an electro-mechanical logic relay.

## 9.5 Strengths of microwave blanching

Microwave heating involves conversion of electromagnetic energy into heat by selective absorption and dissipation. Microwave heating is attractive for heating of foods due to its origin within the material, fast temperature rise, controllable heat deposition, and easy clean-up. The very high frequencies used in microwave heating allow for rapid energy transfers and, thus, high rates of heating. These rates are a main advantage of this technique. Also, because microwaves penetrate the sample, heating is accomplished in the interior of the food. When heating rapidly, the quality of fruits and vegetables such as flavor, texture, color and vitamin content is better kept (Dorantes-Alvarez *et al.*, 2000). However, rapid heating can also lead to problems of non-uniform heating when excessively high energy transfer rates are used (Ohlsson, 2000). It has been observed that microwave processing of chicken, beef, bacon, trout, and peanut oil does not change the fatty acid composition of these products, nor produces *trans* isomers (Mai *et al.*, 1980).

Other advantages of microwave blanching are as follows.

*Minor times of enzyme inactivation – reduction of process times*

Blanching time can be significantly shortened with the use of microwaves. A study by Collins and McCarthy (1969) reported that in potato tubers with a mean radius of 2.27 cm, peroxidase was inactivated in 13 min by boiling water and in 4.7 min by microwaves. Polyphenol oxidase (PPO) was destroyed in 6 to 7.5 min and in 3 to 3.5 min by hot water and microwaves respectively. The authors concluded that microwave energy could be used to shorten the blanching period of this product.

Inactivation of PPO in samples of avocado purée (pH 6.6) required a microwave treatment at 103 ºC for 5 s, which was achieved by heating 20 g of purée for 23 s at medium/low power of a domestic oven. Since the optimum pH for avocado PPO is 6 to 7, when the pH was lowered to 4.3 with citric acid the treatment time was lowered to 2 s at 103 ºC, and when the pH was 3.9 to 1 s at 103 ºC (Dorantes-Alvarez *et al.*, 2000).

*Lower leaching of soluble nutrients, better retention*

Muftugil (1986) blanched green beans by four methods: water, steam, microwave, and convection oven. Ascorbic acid and chlorophyll were found to be significantly higher in the microwave blanched sample (microwave oven, 650 W, 2450 MHz). The slow penetration of heat to the centers of the vegetable pieces could explain slow enzyme inactivation by water. The author also reported that the minimum blanching time for complete peroxidase inactivation was less in the microwave method.

Microwave blanching has the advantage of retaining a higher content of soluble protein in soy beans, which is a fundamental property for producing an acceptable soymilk. A 98% inactivation of lipoxygenase in beans with 8.7% moisture content was achieved after 240 s of exposure to microwave heating in a domestic oven at 2450 MHz (Wang and Toledo, 1987).

A study by De la Cruz-García *et al.* (1997) also illustrates the higher nutrient retention that can be achieved by microwaves. The authors examined the effect of four culinary treatments (steaming and boiling in a covered pot, a pressure cooker or a microwave oven) on the chlorophyll and carotenoid contents of fresh green vegetables. The least tender product was obtained by microwave cooking. However, all the treatments, except for microwave cooking, reduced the total amount of chlorophyll *a* and *b*, lutein, phaeophytin *a* and *b*, and carotene. The large losses of total pigments are attributable to thermal degradation of chlorophylls into phaeophytins that occur along the treatment time. On the other hand, the carotenoid content was increased by all the culinary treatments. The method that caused the highest losses on pigments extracted was steam cooking. Microwave blanching also reduces the amount of waste waters produced in the process.

### *Prevention of surface fouling on the walls of heat exchangers*

The walls of plate or tubular heat exchangers foul as a result of the contact of fluids, such as juices or milk, with high-temperature surfaces in continuous HTST processes. This can be prevented by microwave heating, since this form of radiation has the capability to heat the fluid internally, without significantly increasing the surface temperature of the product (Tajchakavit and Ramaswamy, 1997).

### *Texture of vegetable tissues*

Quenzer and Burns (1981) compared the effects of water, steam and microwave blanching on the texture of freeze-dried spinach. The spinach was blanched for a period sufficient to inactivate enzymes, which was confirmed by a negative catalase-peroxidase end point. Microwave blanching was carried out in a domestic oven (650 watts, 95 s), and the samples never came in direct contact with water, which accounted for a superior retention in ascorbic acid. However, microwave samples had a significantly lower content of carotene. Intense heat and high energy radiation are known factors in carotene degradation.

The microstructure of blanched spinach was studied with a scanning electron microscope. It was observed that microwave blanching induced coagulation of protoplasmic material surrounding the cell walls, keeping the cellular structure intact. After freeze-drying, the microwave blanched samples resulted in significantly higher dehydration ratios and acceptable textural characteristics. This process yielded a superior freeze-dried product as compared to water and steam blanching.

### *Sensory quality*

A sensory evaluation between blanched avocado purées with microwaves or conventional heating showed preference toward the former (significant difference $P < 0.05$). This was probably due to a shorter treatment time, and therefore better flavor retention. Considering that a rapid increase in temperature can be achieved in a microwave oven that not only inhibits enzymatic browning, but also preserves flavor, microwave blanching offers a good alternative for the inactivation of PPO in avocados (Dorantes-Alvarez *et al.*, 2000). Also, Guzmán *et al.* (2002) pointed out that it was possible to form zinc–chlorophyll complexes when avocado purée was blanched with microwaves, giving a better green color on the samples over a storage period of 10 days.

Another method that can be sensorily improved with the use of microwaves is tomato processing. This processing includes thermal treatments to inactivate enzymes (blanching) or to stabilize the product (sterilization) that cause changes in sensory and nutritional characteristics of tomato derivatives due to co-oxidation reactions of carotenoids and Maillard reaction. Since consumers are demanding products that would preserve the characteristics of the fresh tomato fruit, Servili *et al.* (2000) optimized the blanching conditions of tomato juice using microwave energy, at two different conditions corresponding to the industrial processes *hot* and *cold break*. For the *cold break*, times ranged between 10 and 40 min and temperatures between 60 and 75 °C, while for the *hot break*, times ranged between 1 and 7 min and temperatures between 80 and 95 °C. The thermal treatments were performed using a microwave oven (Bauknecht MCG 1731, Germany). The authors recommended 67 °C for a time of 24 min as optimal conditions for the *cold break* treatment. The recommended conditions for the *hot break* treatment were 86 °C for 3.5 min, both using microwave energy. These methods showed better preservation of the flavor characteristics of the fresh product.

*Improvement of current processes*

Kadlec *et al.* (2001) applied microwave energy to germinated yellow peas before drying them in an oven at 80 °C. They reported that this treatment is useful for wet germinated seeds (moisture content 31–50%) first of all because moist heat is more effective than dry heat. The higher temperature in the sample after the microwave treatment represents greater economy than convective drying alone. The content of rafinose family oligosaccharides (FOS), sucrose and monosaccharides in dried germinated peas decreased after the microwave treatment and hot air drying, due to hydrolysis, thermal decomposition and Maillard reaction. The authors concluded that the combined effect of germination, microwave treatment and hot air drying to a final moisture content of 12–14% and to a highest temperature of 80 °C can be recommended as a method of decreasing the high content of $\alpha$-galacto-oligosaccharides and improving the nutritional quality of yellow peas.

## 9.6 Weaknesses of microwave blanching

The uneven temperature distribution in the microwaved samples is a problem discussed by several authors. This non-uniformity is due to many factors: localized microwave adsorption due to heterogeneity of dielectric properties and heat capacity among food components, variations in field intensity, and differences in shape, size, and placement of the food. Also, the limited penetration depth of microwaves (1 to 2 cm at 2450 MHz, from one side) implies that the distribution of energy within the food can vary. The control of microwave heating uniformity is difficult, as the objects to be heated are of the same size as the wavelength of the material. The difficulties in controlling heating uniformity must be seen as the major limitation of the industrial application of microwave heating. Thus, an important requirement for microwave equipment and microwave energy application in the food industry is the ability to properly control heating uniformity (Ringle and Donaldson, 1975; Ohlsson, 1983; Rodríguez *et al.*, 2003). The cost of microwave processing can be another limitation on its use on an industrial scale (Rodríguez *et al.*, 2003).

We think that specific equipment for microwave processing will be developed in the future, as well as adaptations of present equipment, when advances in research result in important or value-added products. The authors encourage researchers to use such parameters as microwave energy applied by kilogram or gram of foods, in order to be able to compare results obtained in different studies.

## 9.7 Future trends

With continuing progress in nutrition, food technology and biotechnology, it is reasonable to expect the design of specific processes that would result in food products with special characteristics. Consumers are very interested in healthy eating, and are more concerned with consuming safe and high-quality foods than in the past. With the development of genetically modified commodities, food processes will have to adapt to these new raw materials. This may be the case with modified tomatoes with no expression of pectic enzymes; blanching will not be needed to inactivate those enzymes, but will still be required for other purposes, such as enhancing lycopene bioavailability and/or conditioning of tomatoes before canning or freezing. In this context, the use of microwaves for the conditioning or pretreatment of raw materials will have, in our opinion, a very important role for two reasons: (1) the better preservation of nutrients and nutraceuticals achieved by waterless microwave blanching, and (2) the efficiency of microwave heating in solid foods that gives the characteristics of a high-temperature short-time blanching process.

### 9.7.1 Non-thermal effects, enhanced thermal effects and specific effects

Even when evidence points to thermal effects as sufficient explanation for most, if not all, of the actions of microwaves on living cells, some authors such as Anantheswaran and Ramaswamy (2001) have considered microwave effects as non-thermal when they are observed independently of the sample temperature; when they depend on temperature, they are considered enhanced thermal effects.

Microwaves have the capacity to penetrate the food and create heat by friction of dipole molecules of water, which will try to orient and align with the field. This is the macroscopic thermal effect of increasing temperature within the material. On the other hand, non-thermal effects refer to lethal effects without involving a significant rise in temperature, as in the case of ionizing radiation, which is an electromagnetic radiation above $2500 \times 10^6$ MHz (X-rays, gamma rays, etc.). The chemical changes that take place when ionizing radiation is absorbed by organic materials are the result of breakage of chemical bonds and the formation of ions or free radicals which react and form secondary products. The radiation known as non-ionizing is of a longer wavelength and a lower frequency (such as 2450 MHz), and it does not have the capability to break chemical bonds. Microwaves belong to this group, and it has been demonstrated that microwaves cannot influence any type of chemical bond.

On the other hand, it is known that some structures in biological materials may be affected by very low energies, such as hydrogen-bonded structures, in which protons may be displaced at very low energy expense. Chromosomes are also susceptible to microwave disturbances. Another effect is the orientation of subcellular particles, which line up (pearl chain formation) under the influence of microwaves. Most likely no chemical change is involved, but this effect may be nevertheless of biological significance. More research at cellular and subcellular levels may give more evidence on this matter.

A specific effect of microwave blanching in avocado purée is the release of oil by the disruption of membranes of the idioblastic cells (Ortiz-Moreno *et al.*, 2003). This was confirmed with a microstructural study. We suggest talking about specific effects, even if they involve the effect of fast temperature rises, enhanced thermal effects and/or non-thermal effects. At this moment, we are still not able to discern between them.

### 9.7.2 Behavior of nutraceuticals and other high-value components

Nutraceuticals are substances that are present in food and have additional beneficial effects on human health. These substances are claimed to have anticancer, antioxidant, and cholesterol-lowering properties, among others. Hence, preservation of these compounds is important in food technology. Wrolstad *et al.* (1980) observed a better retention of anthocyanins when using microwave blanching. Ortiz-Moreno *et al.* (2003) reported that avocado oil obtained using microwave blanching had a high content of chlorophylls and vitamin E.

When preserving nutraceuticals and other high-value components, the thermal stability of the material must be considered, as well as the generation of undesirable compounds such as *trans* fatty acids and the proper inactivation of deteriorative enzymes. Examples of this have been given in Section 9.3. Research on an adequate combination of factors that may influence the thermal inactivation times of enzymes while preserving sensory characteristics, nutrients, nutraceuticals and their bioavailability is expected to continue in the near future. Again, it is likely that microwave blanching will be considered a powerful tool to shorten heating times and minimize food quality deterioration.

### 9.7.3 Development of unique-single systems for microwave blanching

The most likely future for microwave food processing is in the continued development of unique single systems that overcome the limitations discussed previously. Compared to the development of traditional blanching systems, it is still a challenge to design appropriate equipment for microwave blanching. This is due mainly to the following factors:

- Better control of the process is required due to the shorter heating times that microwave heating requires.
- The temperature distribution within the food product is affected by additional factors. A better distribution can be achieved by the use of standing and hold times at the end of the process.

More research is needed in order to develop a method that would assure better repeatability of the process and equilibration of temperatures. The last objective can also be helped by a careful control of the food composition (Anantheswaran and Ramaswamy, 2001).

Since the heating migration in microwave processing occurs from the initial and hottest locations in the interior of the food, it is difficult to locate and assess the cold point, as in traditional thermal methods. Therefore, the use of specific software to calculate the parameters of the process will help to achieve a higher efficiency (Rodríguez *et al.*, 2003).

In the near future, it is expected that researchers interested in this matter will discover more specific effects that may be advantageous in the processing of food by microwave blanching. This would give an additional value to food products and would overcome the cost of microwave energy for this particular application.

## 9.8 Sources of further information and advice

The authors encourage readers to consult specific journals on microwaves such as *Journal of Microwave Power*. Consulting patents and reviews on this matter may also be useful, as well as specific papers in food journals that deal with particular commodities.

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# 10

# Thawing and tempering using microwave processing

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## 10.1 Introduction

Thawing and tempering have received much less attention in the literature than most other food processing operations. In commercial practice there are relatively few controlled thawing systems.

Frozen meat, fish, vegetables, fruit, butter and juice concentrate are common raw materials for many food-manufacturing operations. Frozen meat, as supplied to the industry, ranges in size and shape from complete hindquarters of beef to small breasts of lamb and poultry portions, although the majority of the material is 'boned-out' and packed in boxes approximately 15 cm thick weighing between 20 and 40 kg. Fish is normally in plate frozen slabs; fruit and vegetables in boxes, bags or tubs; and juice in large barrels. Few processes can handle the frozen material and it is usually either thawed or tempered before further processing.

Thawing is usually regarded as complete when all the material has reached 0 ºC and no free ice is present. This is the minimum temperature at which the meat can be boned or other products cut or separated by hand. Lower temperatures (e.g. $-5$ to $-2$ ºC) are acceptable for product that is destined for mechanical chopping, but such material is 'tempered' rather than thawed. The two processes should not be confused because tempering only constitutes the initial phase of a complete thawing process.

Thawing is often considered as simply the reversal of the freezing process. However, inherent in thawing is a major problem that does not occur in the freezing operation. The majority of the bacteria that cause spoilage or food poisoning are found on the surfaces of food. During the freezing operation, surface temperatures are reduced rapidly and bacterial multiplication is severely limited, with bacteria becoming completely dormant below −10 °C. In the thawing operation these same surface areas are the first to rise in temperature and bacterial multiplication can recommence. On large objects subjected to long uncontrolled thawing cycles, surface spoilage can occur before the centre regions have fully thawed.

Conventional thawing and tempering systems supply heat to the surface and then rely on conduction to transfer that heat into the centre of the product. A few, including microwave, use electromagnetic radiation to generate heat within the food. In selecting a thawing or tempering system for industrial use a balance must be struck between thawing time, appearance and bacteriological condition of the product, processing problems such as effluent disposal, and the capital and operating costs of the respective systems. Of these factors, thawing time is the principal criterion that often governs selection of the system. Appearance, bacteriological condition and weight loss are important if the material is to be sold in the thawed condition but are less so if it is for processing.

The main detrimental effect of freezing and thawing meat is the large increase in the amount of proteinaceous fluid (drip) released on final cutting, yet the influence of thawing rate on drip production is not clear. James and James (2002) reported that studies have shown that there was no significant effect of thawing rate on the volume of drip in beef or pork. Several authors concluded that fast thawing rates would produce increased drip, while others showed the opposite. Thawing times from −7 to 0 °C of less than 1 minute or greater than 2000 minutes led to increased drip loss (James *et al.*, 1984). The results are therefore conflicting and provide no useful design data for optimising a thawing system. With fish, fruit and vegetables ice formation during freezing breaks up cell structure and fluids are reduced during thawing.

Fik and Macura (2001) suggested from their results that bread which underwent microwave thawing had generally better quality in comparison with air blast thawing at 50 °C. Riihonen and Linko (1990) studied the effect of thawing conditions on the quality of mechanically deboned beef (MDB) and mechanically deboned pork (MDP). All samples were analysed chemically and microbiologically immediately after thawing. Microwave thawing resulted in a better quality product ($P < 0.05$) than thawing at 4 or 21 °C.

Although there does not appear to be a consensus on the effect of different thawing rates on the quality of the thawed product, it appears that microwave thawing may offer some advantages.

## 10.2 Conventional thawing and tempering systems

The main conduction-based thawing methods rely on air, water or steam condensation under vacuum.

### 10.2.1 Air thawing

Air thawing systems transfer heat to the frozen material by conduction through the static air boundary layer at the product surface; the rate of heat transfer is a function of the difference in temperature between the product and the air and the air velocity. Air systems are very flexible and may be used to thaw any size of product from a whole beef carcass to individual strawberries.

*Still air*

Thin blocks (<10 cm) of meat or fish, or layers of fruit or vegetables, can be thawed overnight at room temperature and, provided the surface of the product does not become too dry, the thawed product can be perfectly acceptable. Air temperatures should not be greater than 15 °C.

For thicker materials still air thawing is not recommended, since thawing times extend to days, rather than hours, and the surface layers may become warm and spoil long before the centre is thawed. Still air thawing is practicable only on a small scale, because considerable space is required, the process is uncontrolled and the time taken is often too long to fit in with processing cycles. The sole advantage is that little or no equipment is required.

*Moving air*

The majority of commercial thawing systems use moving air as the thawing medium. Not only does the increased surface heat transfer ($h$ value) produced by moving air result in faster thawing but it also produces much better control than using still air. Control of relative humidity is important with unwrapped products to reduce surface desiccation and increase the rate of heat transfer to the foodstuff, 85–95% RH being recommended for meat (Bailey *et al.*, 1974).

With 250 g slabs of meat (Zagrodzki *et al.*, 1977) weight loss was a function of temperature, velocity and RH. In all cases, increasing the air temperature or decreasing the air velocity produced a decrease in percentage weight loss at 85–88% RH or an increase in weight gain at 95–98% RH. Changes ranged from a 2.5% weight loss at 5 °C, 5 m s$^{-1}$, 85–88% RH, to a 0.51% weight gain at 25 °C, 1 m s$^{-1}$, 95–98% RH.

*Two-stage air*

Two-stage air thawing has often been proposed as a means of shortening the thawing process. In the first stage a high air temperature is maintained until the surface reaches a predetermined set temperature, thus ensuring a rapid initial input of energy. The air temperature is then reduced rapidly and maintained below 10 °C until the end of the thawing process. Heat flows from the hotter surface regions to the centre of the frozen foodstuff, lowering the surface temperature to that of the ambient air. Since this temperature is below 10 °C, and the overall thawing time is short, total bacteria growth is small. A British patent (1974) has been taken out on a two-stage thawing system using almost saturated air between 35 and 60 °C, followed by air between 5 and 10 °C after the surface temperature of the product has reached 30 to 35 °C. The first stage normally takes 1 to 1.5 hours, the second 15 to 20 hours, and it is claimed that weight loss is low and drip loss minimal.

### 10.2.2 Water thawing

The mechanism of heat transfer in water is similar to that in air, but because the heat transfer coefficients obtained are considerably larger, the thawing times of thinner cuts are effectively reduced. However, there are practical problems that limit the use of water thawing systems; boxed or packaged goods (unless shrink-wrapped or vacuum-packed) must be removed from their containers before they can be water thawed, composite blocks of boned-out pieces or individual fish break up and disperse in the thawing tank, and handling difficulties preclude the use of large cuts such as carcasses.

### 10.2.3 Vacuum-heat thawing (VHT)

A vacuum-heat thawing system operates by transferring the heat of condensing steam under vacuum to the frozen product. Theoretically, a condensing vapour in the presence of a minimum amount of a non-condensable gas can achieve a surface film heat transfer coefficient far higher than that achieved in water thawing. The principle of operation is that when steam is generated under vacuum, the vapour temperature will correspond to its equivalent vapour pressure. For example, if the vapour pressure is maintained at $1106\,\mathrm{N\,m^{-2}}$, steam will be generated at 15 °C. The steam will condense onto any cooler surface such as a frozen product. The benefits of latent heat transfer can be obtained without the problems of cooking which would occur at atmospheric pressure.

With thin materials, thawing cycles are very rapid, enabling high daily throughputs to be achieved. The advantage of a high $h$ value becomes less marked as material thickness increases, and beef quarters or 25 kg meat blocks require thawing times permitting no more than one cycle per day. Under these conditions, the economics of the system and the largest capacity unit available (10–12 tonnes) severely restrict its application.

Vacuum tumble thawing systems, in which the frozen product is continuously tumbled while steam under vacuum condenses on the exposed surfaces of the food, are a recent development. Very fast thawing is claimed to be obtained with small bulk-frozen individual products. However, delicate products such as fish fillets cannot be thawed in such systems.

### 10.2.4 Air tempering

All large-scale industrial tempering is carried out in air. In general, frozen product on pallets is stacked in a temperature-controlled room and left for the time needed for the tempering requirements to be achieved (Table 10.1). In many cases the environment is changed during the process. Tempering times are

**Table 10.1** Tempering configurations, initial and final product and environmental temperatures and tempering times for cartons of frozen meat (approximately 27 kg in weight, 15 cm thick) in industrial systems

| Factory | Configuration | Temperature (ºC) | | | Tempering time (d) |
|---|---|---|---|---|---|
| | | Initial | Final | Ambient | |
| A | Palletised | −14 to −12 | −3 | −8 then −3 to −1 | 5 then 7 |
| | Palletised | −10 | −3 | −8 then −3 to −1 | 1 then 6 |
| | Palletised | −15 | −2.5 | −8 then −3 to −1 | 3.5 then 6 |
| | Palletised | −18 | −3 | −8 then −3 to −1 | 6 then 5 |
| B | Palletised | −18 | −15 to −6 | 0 | 0.9 |
| | Racked | −18 | −4.5 | 14 then 0 | 0.2 then 0.7 |
| C | Palletised | −20 to −18 | −10 to −5 | 0 | 1.0 |
| D | Palletised | −20 | −6 | −5 to −3 | 6 to 7 |
| E | Palletised | −27 to −23 | −8 to −5.5 | −3 to −1 | 0.9 |
| | Racked | −27 to −23 | −5 to −4 | −3 to −1 | 0.9 |
| F | Palletised | −18 | −8 to −3.5 | −4 | 1.0 |
| | On trolleys | −18 | −5 to −3.5 | −4 | 0.8 |

Source: James, 1986.

often very long, up to 12 days. Times of less than one day can only be achieved if the following process can handle product at a much lower temperature.

In a few cases pallets are split up at the start of the process and the frozen material is placed on racks or trolleys. This reduces the path for heat penetration and substantially speeds up the tempering process. However, splitting up pallets requires considerable manpower and substantially increases the space required.

## 10.3 Electrical methods

In all of the methods described above the rate of thawing is a function of the transfer of heat from the thawing medium to the surface of the foodstuff, and the conduction of this heat into the centre of the material. In theory, electrical systems should overcome these problems because heat is generated within the material and the limitations of thermal conductivity are circumvented. In such systems the kinetic energy imparted to molecules by the action of an oscillating electromagnetic field is dissipated by inelastic collisions with surrounding molecules and this energy appears as heat. Thus electromagnetic radiation may be used to heat foodstuffs.

Three regions of the electromagnetic spectrum have been used for such heating: resistive 50 Hz; radio frequency 3 to 300 MHz and microwave 900 to 3000 MHz.

### 10.3.1 Resistive thawing

Placing it between two electrodes and applying a low voltage at normal mains frequency can heat a frozen foodstuff. As the electric current flows through the material, it becomes warm (ohmic heating). Electrical contacts are required and product structure must be uniform and homogeneous, otherwise the current will take the path of least resistance, resulting in uneven temperatures and runaway heating. Frozen food at a low temperature does not readily conduct electricity, but as it becomes warmer, its electrical resistance falls, a larger current can flow and more heat is generated within the product. In practice, the system is only suitable for thin (5 cm) homogeneous blocks such as catering blocks of liver, etc., since current flow is very small through thick blocks and inhomogeneities lead to runaway heating problems.

### 10.3.2 Radio frequency

During radio frequency thawing, heat is produced in the frozen foodstuff because of dielectric losses when a product is subjected to an alternating electric field. In an idealised case of radio frequency heating the foodstuff, consisting of a regular slab of homogeneous material at a uniform temperature, is placed between parallel electrodes and no heat is exchanged with its surroundings. When an alternating electromotive force (emf) is applied through the electrodes the resulting field in the slab is uniform, so the energy and the resultant temperature rise is identical in all parts of the food (Sanders, 1966).

In practice this situation rarely applies. Foodstuffs are not generally in the shape of perfect parallelepipeds; frozen meat, for example, consists of at least two components, i.e. fat and lean. During loading, frozen meats pick up heat from the surroundings, the surface temperature rises and the dielectric system is not presented with the uniform temperature distribution required for even heating.

By using a conveyorised system to keep the product moving past the electrodes and/or surrounding the material by water, commercial systems have been produced for blocks of oily fish and white fish (Jason and Sanders, 1962). Successful thawing of 13 cm thick meat, and 14 cm thick offal, blocks has also been reported (Sanders, 1966) but the temperature range at the end of thawing (44 minutes) was stated to be −2 ° to 19 ºC and −2 ° to 4 ºC respectively, and the product may not have been fully thawed.

To overcome runaway heating with slabs of frozen pork bellies, workers (Satchell and Doty, 1951) have tried coating the electrodes with lard, placing the bellies in oil, water and saline baths and wrapping the meat in cheesecloth soaked in saline solution. Only the last treatment was successful but even that was not deemed practical.

An industrial system was installed to thaw frozen blocks of boned-out poultry in the late 1980s (Anon, 1992). The continuous plant had a throughput of 450 kg per hour with four 12.5 kW generators operating at a frequency of 27.12 MHz providing the heating. It was claimed that the process reduced thawing time from 3 to 4 days to under 2 hours and cut weight loss from 7 to 0.5%.

### 10.3.3 Microwave thawing

Microwave thawing utilises electromagnetic waves directed at the product through waveguides without the use of conductors or electrodes. Whilst the heating of frozen food by microwave energy is potentially a very fast method of thawing, its application is constrained by thermal instability. At its worst, parts of the food may be cooked whilst the rest is substantially frozen. This arises because the absorption by frozen food of electromagnetic radiation in this frequency range increases as the temperature rises, this dependence being especially large at about −5 ºC, increasing as the initial freezing point is approached. If for any reason during irradiation a region of the material is slightly hotter than its surroundings, proportionately more energy will be absorbed within that region and the original difference in enthalpy will be increased. As the enthalpy increases so the absorption increases and the unevenness of heating worsens at an ever-increasing rate. Below the initial freezing point the temperature increase is held in check by thermal inertia, since for a given energy input the temperature rise is inversely proportional to the thermal capacity. If irradiation is continued after the hot spot has reached its initial freezing point, the temperature rises at a catastrophic rate. Lowering the power density to allow thermal conduction to even out the enthalpy distribution through the food can reduce such runaway heating. Orders of magnitude calculations have been made of the times involved for thermal stability and showed that processing times for standard blocks need to be over 8 hours (Jason, 1974; Ohlsson, 1984).

Since the main instability tends to occur at the surface, attempts have been made to cool the surface during thawing using air or liquid nitrogen (Bialod *et al.*, 1978; Les Micro-Ondes Industrielles, undated). Although experimentally successful, the systems were not economically viable.

A hybrid microwave/vacuum thawing system in which boiling of surface water at low temperature was used to cool the surface was developed in the 1980s (James, 1984). The system consisted of a cylindrical vacuum chamber approximately 1 metre in diameter and 1 metre long (Fig. 10.1). The chamber could be evacuated to absolute pressures as low as 10 mbar by a water ring pump in series with a rotary pump. Microwaves at a frequency of 915 MHz were introduced into the chamber via two waveguides positioned near the top at the front and rear of the plant. The microwaves were produced by a 25 kW generator, though power had to be limited to 2.5 kW to avoid arcing problems in the chamber. A large circular twisted disc was rotated within the chamber during thawing to produce a more even microwave field.

In trials chilled meat (85% visual lean) was obtained from a commercial abattoir and made up into either whole blocks with dimensions of 61 × 40 × 15 cm or half blocks 30 × 40 × 15 cm. The blocks were then

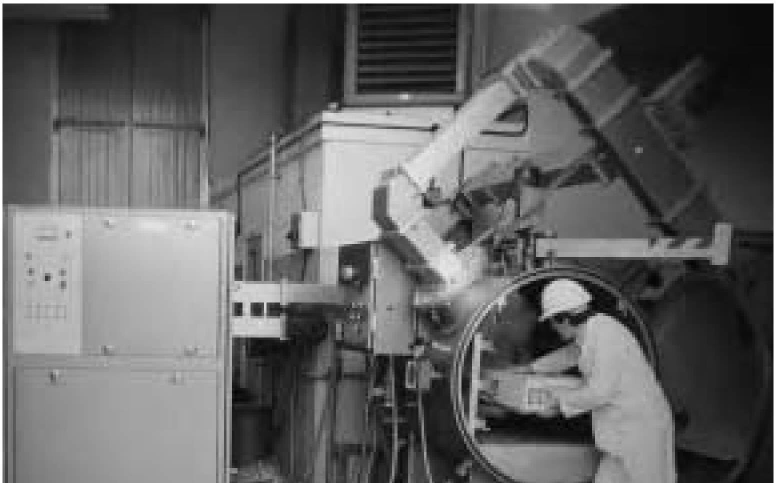

**Fig. 10.1** A hybrid microwave/vacuum thawing system.

wrapped in polyethylene film and placed singly in solid fibreboard cartons before freezing and storage at −20 °C. After thawing, maximum surface temperatures were measured using infrared thermometry. A single-point hypodermic probe was then used to find the minimum temperature within the block. The block was then weighed and placed in an insulated box for 2 hours to determine the average temperature after thawing.

After thawing, the average meat temperature was 9.4 °C (ranging from −1 to 23.3 °C between blocks) and the maximum surface temperature measured on any block was 28.4 °C (Table 10.2). Weight losses averaged 7.6%, which appeared large, but weight loss in commercial systems was stated to range from 2 to 10%. The overall energy efficiency of the plant was 49% with 24% of the energy being absorbed by the structure of the chamber itself.

Virtanen *et al.* (1997) combined microwave energy and cold air with different ambient temperatures to reduce thawing time and avoid runaway heating during microwave-assisted thawing. The microwave power was cycled on and off using two-temperature control schemes to maintain a predetermined temperature gradient based on hot and cold points. Thawing time was reduced by as much as a factor of seven compared to convective thawing at ambient temperature when appropriate conditions were used.

Yagi and Shibata (2002) applied for a patent for a similar process that used microwaves under vacuum to thaw foods. They claim that the rate of sublimation at the surface together with a relatively low microwave power resulted in even product temperatures and low weight losses during the process. The temperatures claimed at the end of thawing processes lasting between 24.5 and 34.25 minutes ranged from −1.1 to −2.0 °C (Table 10.3), are very even and around the final thawing point of the products.

A novel approach was adopted by Fathi *et al.* (2003) for thawing fruit juices or other foods that would flow in the thawed state. Their patent described an apparatus which included a microwave energy source; a microwave applicator which defines a cavity for applying microwave energy from the microwave source to a material to be thawed; and a shielded region which is shielded from the microwave source. The shielded region was in fluid communication with the cavity so that thawed material may flow from the cavity into the shielded region.

Despite a widespread belief to the contrary, microwave-thawing systems have not been commercially successful. However, microwave-tempering systems have found successful niche applications in the meat and dairy industry.

### 10.3.4 Microwave tempering

Despite the widespread industrial use of tempered meat, there is little published process design data for meat tempering operations, with the exception of commercial claims for microwave processing units.

James and Crow (1986) provide some data on the use of microwaves for tempering meat blocks. The batch unit investigated was produced by the Raytheon Company and would accept five meat cartons in a single layer on a

**Table 10.2** Initial weight and percentage weight loss from meat, thawing time, microwave power supplied and maximum, minimum and average temperature after thawing

| Run no. | Weight | | Thawing time | Power | Temperature | | |
|---|---|---|---|---|---|---|---|
| | Initial (kg) | Loss (%) | (h) | (kW) | Minimum (ºC) | Maximum (ºC) | Average (ºC) |
| 1 | 25.6 | 9.0 | 2.0 | 2.5 | 3.0 | 24.3 | 8.0 |
| 2 | 25.5 | 7.9 | 2.0 | 2.5 | 2.6 | 24.0 | 8.1 |
| 3 | 25.6 | 7.3 | 2.0 | 2.5 | −2.0 | 12.7 | 4.0 |
| 4 | 2.5 | 10.3 | 2.0 | 2.5 | 21.2 | 26.7 | 23.3 |
| 5 | 33.2 | 5.9 | 2.0 | 2.5 | −2.0 | 22.0 | 4.8 |
| 6 | 27.9 | 7.1 | 2.0 | 2.5 | −0.2 | 25.0 | 6.2 |
| 7 | 11.9 | 6.5 | 1.0 | 2.5 | 4.6 | 14.9 | 12.2 |
| 8 | 11.9 | 6.2 | 1.0 | 2.5 | 7.0 | 17.5 | 13.0 |
| 9 | 12.3 | 7.0 | 1.0 | 2.5 | −4.2 | 3.2 | −1.0 |
| 10 | 11.5 | 9.4 | 1.0 | 2.5 | 15.5 | 28.4 | 20.5 |
| 11 | 11.9 | 7.5 | 1.0 | 2.5 | −2.4 | 15.2 | 4.3 |

**Table 10.3** Thawing results for claimed process

| Product | Starting temperature (ºC) | Microwave power (kW) | Final temperature (ºC) | | Thawing time (minutes) | Weight loss (%) |
|---|---|---|---|---|---|---|
| | | | Centre | Surface | | |
| 3 × 10 kg blocks pork | −40 | 1.8 | −1.9 | −1.9 | 34.25 | 0.6 |
| 4 × 2 kg blocks tuna | −55 | 0.7 | −1.5 | −1.8 | 27.8 | 0.8 |
| 3 × 2 kg blocks beef | −40 | 0.6 | −2.0 | −1.1 | 24.5 | |

Source: Yagi and Shibata, 2002.

pallet that was pushed over rollers manually into the microwave chamber. Microwave power was provided by a 30 kW magnetron (variable down to 20 kW) operating at 896 MHz, from which the microwaves entered the chamber via waveguides situated at the top and bottom. Rotating metal discs were positioned above and below the product to provide a more uniform microwave field and the loaded pallet was subjected to cyclic lateral movements of 90 mm during irradiation.

It is clear from Table 10.4 that blocks processed directly from frozen storage can be acceptably tempered in a batch microwave unit to a mean temperature of approximately −3 ºC (range −5 to 0 ºC) with no hot spots. Tempering times varied from 3.5 to 5.0 minutes with block types (1) and (2), and at least two combinations of microwave power and processing time produced acceptable results. The frozen cartons of flank that contained a higher percentage of fat caused more runaway heating problems, and low microwave power (20 kW) applied for 6.5 minutes was required to achieve the desired results.

**Table 10.4** Effects of block types, weights of frozen meat and initial meat temperature on final meat temperature and condition of meat blocks tempered in a batch microwave unit

| Block type (weight) | Initial temperature (ºC) | Microwave power (kW) | Process time (min) | Final temperature (ºC) (meat condition) |
|---|---|---|---|---|
| 1<br>25–30 kg | −15 | 28 | 3.5 | −7 to −2 |
| | | | 4.0 | −4 to −2 (soft corners) |
| | | | 4.5 | −4 to −1 (soft surfaces) |
| | | | 4.5 | −3 to −2 (locally +2) |
| | | | 4.75 | −4 to −2 (surfaces +2) |
| | | 25 | 5.0 | −3 to −2 (surfaces 0) |
| | | | 5.0 | −4 to 0 |
| | −8 deep, surface −2 | 30 | 3.0 | −5 to −2 |
| | | 25 | 5.5 | −3 to −2 (corners +3) |
| 2<br>27–37 kg | −15 | 30 | 5.0 | −5 to +2 |
| | | | 4.0 | −5 to −4 (soft spots) |
| | | | 4.5 | −4 to −3 (soft spots) |
| | | 28 | 5.0 | −4 to −2 (surface <2) |
| | −8 deep, surface −1 | 30 | 6.0 | −4 to +27 (v. variable) |
| | | | 6.0 | −6 to +25 (v. variable) |
| | | | 5.0 | −5 to +6 (spot at +54) |
| 3<br>25–27 kg | −15 | 30 | 4.0 | −6 deep, −1 surface |
| | | | 5.0 | −5 deep, 0 surface |
| | | | 6.0 | −5 deep, some cooking |
| | | | 6.0 | −5 deep, some cooking |
| | | 20 | 6.5 | −4 to −2, uniform |
| | −8 deep, surface −1 | 20 | 7.0 | −5 deep, hot spots |
| | | | 5.0 | −5 uniform |
| | | 30 | 5.0 | −5 deep, hot spots |

Source: James and Crow, 1986.

In general, microwave tempering of blocks, which had been allowed to warm up in factory ambient temperatures for 8 h, was unsatisfactory. Surface temperatures, especially at the corners of the meat blocks, rose to unacceptable levels and there was substantial drip loss from thawed surfaces.

These results indicate that it would be difficult if not impossible to produce a uniform power/time combination for all types of 'standard 27 kg blocks'. For optimal tempering, trials have to be carried out to determine the correct power and time setting for each type of block. Blocks sorted into batches of similar type should be processed directly from frozen storage under the predetermined conditions.

Successful tempering can be achieved in minutes using a microwave system, compared with the 1 to 14 days required in industrial air tempering systems. Continuous conveyorised microwave tempering systems using either a single 60 kW magnetron or two 40 kW magnetrons can temper 2 to 2.5 tonnes per hour depending upon fat content.

In large-throughput operations the continuous microwave tempering plant provides considerable flexibility, in that changes in raw material requirements, for the post-tempering processes, can be accommodated in minutes. Using air tempering systems, at least one day and up to eight days are required to accommodate equivalent changes.

Many advertisements for microwave systems claim higher product yield due to reductions in evaporative and drip loss during tempering. Since the majority, if not all, of conventional plants temper material in a wrapped form, evaporative losses are insignificant, while substantial periods at air temperatures above 0 °C would be required before thawing of surface tissues occurred and drip became apparent.

## 10.4 Modelling of microwave thawing

The thawing times of various foods in conventional thawing systems can be predicted using finite difference techniques with good accuracy. Models have been developed and verified for the thawing of meat blocks, beef quarters, pork legs, etc., under a wide range of conditions (James and James, 2002).

However, it is much more difficult to model microwave thawing accurately. Ayappa (1997) in his review of microwave heating stated that early models of microwave heating used Lambert's law to describe the microwave power absorption. In the 1990s models for transport processes were developed with the microwave power derived from Maxwell's equations. The modelling has revealed some interesting effects. When modelling the thawing of 'Tylose' slabs (a meat simulant) Basak and Ayappa (1997) predicted that resonance, during which the microwave power absorption is high, causes a 2 cm thick slab to thaw more quickly than a 1 cm slab. Basak (2003) modelled the thawing of slabs of ice and found that thawing could start at the exposed and unexposed face of a slab when only one face was exposed to microwaves. However, when two faces were exposed thawing could also commence in the centre of the slab.

Taher and Farid (2001) predicted that it is possible to thaw meat under controlled conditions such that its surface temperature never exceeds 10 ºC. They claimed that thawing time would be less than one-fifth of that required in conventional thawing. The results were verified under laboratory conditions by installing a control system that switched off the magnetron when the surface temperature reached 10 ºC. The control cycled the magnetron on and off to maintain the surface temperature at approximately 10 ºC.

Chamchong and Datta (1999) modelled food thawing in a microwave oven. They predicted that power cycling has an almost identical effect as continuous power at the reduced level of the average cycled power. As power level increases, the surface flux increases by the same fraction. At higher power levels, however, the outside thaws relatively faster. A 'shield' develops due to a much reduced microwave penetration depth at the surface. Thus thawing time at higher power levels is reduced considerably. Temperature increases initially are non-uniform since the surface is heated at a faster rate than the interior.

## 10.5 Commercial systems

A wide range of batch and continuous commercial microwave systems for thawing and tempering have been produced since the 1970s. Many of the early systems were sold as thawing plant, i.e. heating frozen food to a temperature where no ice was present in the product. However, most systems could and can only successfully temper the food, and current systems are sold as microwave tempering systems.

In the late 1980s it was believed that approximately 200 industrial microwave tempering systems had been installed (Decareau and Peterson, 1986). Microwave drying and cooking installations numbered 30 and 16 respectively, so tempering was by far the most successful application of microwaves in food processing. The systems were used to temper meat, fish, butter and berries. At that time there were 17 fully operational microwave systems for meat in the UK, 12 of which were small batch units and the remainder continuous tempering tunnels (James, 1986). A number of the batch systems were used either as one stage of a hybrid microwave/conduction system or to augment large conduction systems by fast tempering of small batches of urgently required material.

A list of the companies which have in the past or are currently believed to manufacture commercial microwave tempering systems is given in Table 10.5. Industrial systems can be batch or continuous and range in size from small systems that can process one 25 kg block of food at a time for catering operations, to large continuous tunnels processing up to 8 tonnes per hour.

Typical of a small system is the MIP 4 (Ferrite, Inc., New Hampshire, USA), which has a 0.9 × 1.3 m footprint and is powered by a 40 kW, 915 MHz magnetron. The makers claim that it will temper 680 kg of raw frozen product per hour to a temperature of −2 to −1 ºC. A single 25 kg block of frozen meat can be tempered in 65 s. At the other end of the scale the same company

**Table 10.5** Companies that currently or have in the past produced commercial microwave tempering systems

| Company | Country | Batch (B) or Continuous (C) | Frequency (MHz) | Power (kW) | Contact |
|---|---|---|---|---|---|
| AMT (Advanced Manufacturing Technologies | Australia | C | $915 \pm 10$ | 10 to 75 | davidm@AMTmicrowave.com |
| ANSA Technology | Malaysia | C | | | enquiry@ansatechno.com |
| APV | UK | B, C | 896 | | |
| Hermann Berstorff GmbH | Germany | C | | | |
| Cober Electronics, Inc. | USA | B, C | 915 | 0 to 100 | sales@cober.com |
| Ferrite, Inc. | USA | B, C | 896 or 915 | 0 to 75 | www.ferriteinc.com |
| LMI (Les Micro-Ondes Industrielles) | France | C | 2450 | 30 to 90 | |
| Microdry, Inc. | USA | C | | 0 to 150 | engineering@microdry.com |
| Raytheon | USA | B, C | | | |
| Thermex-Thermatron, Inc. | USA | B, C | 915 | 0 to 200 | sales@thermex-thermatron.com |
| Sairem | France | B, C | 915 | 10 to 60 | commercial@sairem.com |

**Table 10.6** Claimed hourly tempering capacity of MIP 12 for beef at −18 ºC with 100 kW generator to different final temperatures

| Final temperature | 90% lean | 50% lean |
|---|---|---|
| −7 ºC | 6690 kg h$^{-1}$ | 7940 kg h$^{-1}$ |
| −6 ºC | 5670 kg h$^{-1}$ | 7090 kg h$^{-1}$ |
| −4 ºC | 4820 kg h$^{-1}$ | 6180 kg h$^{-1}$ |
| −3 ºC | 3640 kg h$^{-1}$ | 5045 kg h$^{-1}$ |

Source: Ferrite, Inc.

produces the MIP 12 that they claim will temper up to 7700 kg of frozen product per hour. Up to four 75 kW generators can be coupled to each 2.5 m long tunnel. However, the throughput is very dependent on the composition of the product and the final temperature achieved after tempering (Table 10.6).

Typically companies make a number of claims about their systems. For example, Thermex-Thermatron Inc. claim that they can build in a large variety of shapes and sizes according to commercial requirements. Each module can apply up to 75 kW at a frequency of 915 ± 15 MHz to the product being heated, and two or more modules can be installed on the same conveyor. The systems are fabricated out of stainless steel for food applications. They claim that with a uniform load distribution within the oven, a multi-mode cavity applicator develops a uniform heat distribution in the entire oven. The belt material and configuration are selected based on the nature of the product being heated. Each end of the conveyor is provided with a special vestibule to suppress any microwave energy leakage into the environment. To assure uniform heat distribution in a large variety of load configurations, each oven section is provided with a waveguide splitter with dual microwave feed points and mode stirrers.

APV Baker installed probably the largest microwave installation in Europe to temper butter (Anon, 1992). There were three microwave tunnels each equipped with 2 × 60 kW generators operating at 896 MHz and capable of tempering 7 tonnes of butter per hour. Each block can be tempered in 6 minutes so that the average tempering time for a 225 tonne batch has been reduced from 3–4 days to 1 day.

## 10.6 Conclusions and possible future trends

Due to the problems of runaway heating it is not thought that any current commercial microwave systems can produce a controlled industrial thawing process. In such a process the entire product would be above 0 ºC but none above 7 ºC at the end of the process. The product would then be suitable for hand process or sale without any appreciable increase in pathogen levels. If the product were to be heat processed after thawing then these restrictions would not necessarily apply and microwave thawing could be practical.

Microwave tempering systems have been in industrial use since the 1980s. They have many proven advantages over conventional tempering systems, especially in terms of thawing time, space requirements and increased flexibility. However, their penetration has been limited due to their high initial cost and increased manpower and energy requirements.

Developments in modelling and control may lead to more versatile microwave systems that can truly thaw products.

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# 11

# Packaging for microwave foods

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## 11.1 Introduction

Microwave food product development is possibly the most challenging task the food technologist faces. Much of the reason for this surrounds those peculiarities of microwave heating that are so appealing to consumers: the speed of heating and cool oven operation. There are also unusual temperature profiles, in large part due to the dielectric properties of the food, but also influenced by the size and shape of both the food and the container. As a result, the selection of the proper packaging system is more important with microwavable foods than with most other products. It controls how quickly and uniformly a food heats. In some cases, the package may actually contribute to the heating by providing a heated surface for browning and crisping, or a high-heat steam atmosphere for moisture retention and faster heating.

Microwave containers may be broken into two broad categories: passive and active. Passive containers serve to hold the food without contributing any heat to the product, rather like a coffee cup. On the other hand, active containers actually interact with the microwaves to provide a source of heat. A good example is the susceptor trays used for crisping the bottom of microwavable pizza. Therefore, the first thing the product developer must decide is what role the package will have in relation to the heating phenomenon – i.e., will it be passive or active? The passive container would be for general reheating of simple food systems such as vegetables or entrees that do not require additional browning or crisping. The active container affects the heating, perhaps by providing surface heat, or directing the microwave energy to a specific place. Active containers are made of interactive materials such as susceptors for crisping pizza crusts or foil shielding to prevent a food item from becoming too hot, or to direct the microwave energy to specific areas to assist heat distribution. Adopting these two broad definitions, this chapter will examine the technical considerations that should be followed for the selection of the proper package design.

## 11.2 Factors affecting temperature distribution in microwaved foods

Before describing the requirements for various containers, it is important to recognize the factors influencing the distribution of temperature in microwaved foods (Schiffmann and Sacharow, 1992, p. 104). These are:

- Microwave power absorption rate
- The shape of the food, its thickness and density
- The weight of the food
- The thermal properties of the food – specific heat capacity and thermal conductivity
- The dielectric properties of the food
- The starting temperature of the food – refrigerated, room temperature or frozen
- Nature of the food – single or multi-component food
- Covering, stirring, elevation of the product, use of rest periods during or after heating.

Many of these factors are directly related to the container. In those cases in which the heated food is not stirred, the thermal profile is often worse than that encountered when using conventional heating methods. However, the use of a proper container, often employing a cover or lid, can yield comparable results from the microwave oven, except when the food is frozen. In the latter case, the food's temperature distribution will be significantly inferior to that from a conventional oven. This is due to the very large difference in dielectric loss between frozen and non-frozen items, the latter often being several thousand times lossier, i.e. more microwave absorptive, than the former (see Table 11.1).

**Table 18.1** Typical dielectric loss factors and penetration depths for various food materials

| Food | Loss factor | Penetration depth (cm) |
|---|---|---|
| Water (25 ºC) | 12.0 | 1.4 |
| Ice (−12 ºC) | 0.003 | 1160 |
| Beef (cooked, 30 ºC) | 9.6 | 1.1 |
| Ham (precooked, 20 ºC) | 22.8 | 0.6 |
| Mashed potato (30 ºC) | 24.0 | 0.7 |

Another characteristic of microwave heating is that it may produce bizarre thermal profiles in foods. Typical of this is the overheating that may occur in the center of baby food in small jars, while the surface remains much cooler. The cool ambient temperature in the microwave oven may produce other peculiar thermal profiles typified by the low surface temperature of foods that inhibits browning and crisping. The surface is never the hottest place in a microwaved food unless some auxiliary heat form is used, such as hot air or a susceptor.

## 11.3 Passive containers

It was only in the latter half of the 1970s that food containers other than aluminum or glass were used for microwavable foods. Today, plastic and paperboard containers dominate as containers for these products, while there is still some use of glass, but very little for aluminum. The fundamental characteristic of passive containers is that they are made of materials that will not interact with the microwave oven, i.e. will not be heated by the microwaves. Therefore, they are considered to be microwave transparent. Their principal function is to contain the food during storage, distribution and heating. They may also have removable or self-venting covers.

The major considerations when selecting the type of container material are (Schiffmann, 1990):

- Must be microwave compatible – will not heat excessively, or prevent effective microwave heating
- Must be thermally compatible with the food – that is, it should not melt, distort or be otherwise affected by the hot food
- May need to withstand conventional oven temperatures – these are 'dual oven use' containers
- Should provide shelf-life properties commensurate with the food and its use
- Should not ignite, arc or smoke during normal use
- Should not affect the flavor or color of the food
- Should not be discolored by the food
- Should not allow the migration of any materials into the food that might adulterate it
- Should be safe and easy to handle
- Should be grease resistant
- Should provide a moisture and oxygen barrier where required
- Sealability
- Cost.

The product developer must also be concerned with the following issues, described in depth below:

- The maximum temperatures achieved in the food and their effect upon the container

- The general shape and size of the container
- The effects of the mass and distribution of multi-component products
- The materials of construction
- Covering and other handling issues.

### 11.3.1 Temperature

The temperature distribution within microwave-heated foods is primarily controlled by the penetration depth of the microwaves into the food. This is defined by the dielectric loss properties of the food and the wavelength of the microwave energy in a simplified equation as:

$$D_p = \lambda_0 \sqrt{\epsilon'}/2\pi\epsilon''$$

where:

$D_p$ = penetration depth, the depth at which 63% of the energy has been absorbed

$\lambda_0$ = free space wavelength; 12.2 cm at 2.45 GHz

$\epsilon'$ = relative dielectric constant or permittivity

$\epsilon''$ = dielectric loss factor

Microwaves penetrate only short distances into most foods and so heating may be distributed in peculiar ways. Typical penetration depths are shown in Table 11.1. The large discrepancy in penetration depth between water and ice causes unusually large variations in temperature within a frozen microwaved food. This can be improved or lessened by the container, as discussed below.

There are several critical temperature issues that affect the selection of the container:

- The temperature of the food in contact with the container
- The temperature that the container itself reaches
- The effect the temperature of the container has upon the temperature of the food
- The effect of the ambient temperature in a conventional oven.

All four are interrelated in a complex manner.

*Food contact temperature*

Most often, the highest temperature will be found at or near the interface between food and the container, although this may vary considerably and is influenced by the shape and material of the container. If the container is reasonably transparent to microwaves, the container wall temperature will be a result of the food temperature and the cooling influence of the air and the oven floor. Since most microwaved food temperatures are controlled by water, the temperatures at the food/container interface will usually not exceed 100 ºC. However, exceptions do occur. For example, if the food contains large amounts of fat, such as on the surface of soups or in sauces or gravies, or a large amount of sugar as in preserves or syrups, or very high solids, then temperatures may become very high, 150–200 ºC or even higher, sometimes in local areas. For example, the fat on a soup will migrate to the edge of the container, remaining there due to interfacial tension, where it can be heated by the microwaves to localized high temperatures. This can cause the container to melt or scorch.

Another effect sometimes seen is splattering of food onto a container sidewall where it may be dehydrated and carbonize when microwaved, thus reaching temperatures high enough to melt most thermoplastics. Such dehydration may also occur when a partially emptied container is stored for one or more days. This problem can often be prevented by using container-wall draft angles which promote the flow of such splashing back into the food mass. It is important that tests be run to eliminate the problem.

*Microwave heating of the container*

In some cases the container itself may heat and this usually is not desirable. One situation occurs when the dielectric loss of the container material is high enough for microwave energy coupling. Two examples of this are thermoset polyesters in which the fillers may be lossy, or soda-lime glass which is also lossy. The latter should not be used as a microwave container as it will not only heat but is likely to break. Another situation occurs with thermoplastics such as polypropylene. As these materials heat to their heat distortion temperatures or softening points, they suddenly change from being non-lossy (microwave transparent) to highly lossy (microwave absorptive) and may exhibit thermal runaway, heating as fast or faster than the food, as their dielectric loss characteristics increase with temperature. In the example cited above, of the fat in a microwave-heated soup, the polypropylene container at the soup/container interface may reach temperatures above the approximately 115 ºC softening temperature at which the polypropylene absorbs microwave energy; the microwave will heat the container very quickly and nearly uncontrollably, melting a hole in the container. This is a more common occurrence than one might imagine.

Another situation in which the container must have high thermal stability is when it is for dual-use, i.e. microwave and conventional oven heating. The latter may require an oven temperature of 175 ºC or higher, so the container must be able to withstand very high temperatures.

### 11.3.2 Shape and size

The selection of the shape and size of a container, and its material of construction, is the most important decision the developer will make.

*Shape*

Some shapes are more amenable to good microwave performance than others. Some general rules to be followed are:

- Simplicity of design. The shape should be as regular as possible: oval or round, for example. Narrowing or restricting the body of a cylinder can cause the contents to erupt or explode out of it. A ‘lobster-shaped’ container may seem a good way of marketing a microwavable version of this crustacean, but the peculiar shapes, with broad and narrow areas, will cause serious temperature non-uniformity problems.
- Container geometry. The most common non-microwave tray shape is rectangular. However, this is not the best shape for a microwavable tray. The thermal profiles usually found in rectangular trays are that the corners are hottest, the center is coolest, and temperatures near the side walls are slightly less than at the corners. The range of temperature from hottest to coolest is similar to that seen in conventional ovens when the initial food temperature is ambient or refrigerated, i.e. 25 ºC. However, with frozen foods the difference from corners to center may exceed 50 ºC (see Fig. 11.1) (Schiffmann and Sacharow, 1992, p. 106). If corners are unavoidable, they should be rounded as much as possible. Side walls should have generous draft angles commensurate with stacking, but not be so shallow as to allow a thin food profile around the edges that could overheat. A generous bottom radius is also of benefit, i.e. the bottom center should be slightly bowed or raised. This thins the volume above it that is usually the slowest to heat. It also reduces heat loss to the oven floor.

Small cylindrical containers, such as baby food jars, should be avoided since very high internal temperatures may be produced, which can cause injury when consumed or may erupt due to the generation of high internal pressure. Larger cylindrical containers such as glass jars may be acceptable but can be a problem if there is a shoulder in the jar resulting in a neck

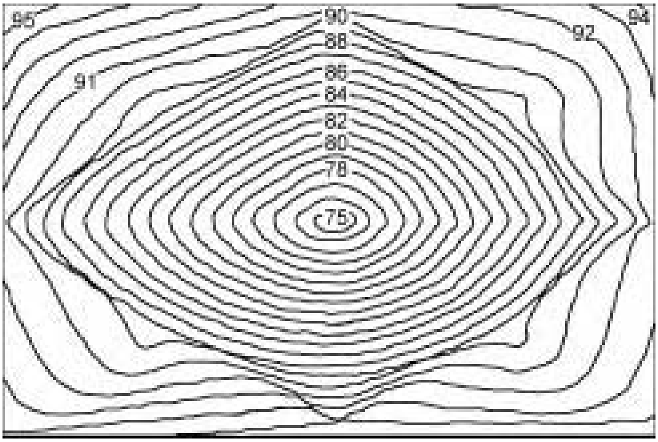

**Fig. 11.1** Temperature distribution in a typical food microwave heated in a rectangular container. Note the highest temperatures are located at the corners and the coolest in the center. (Source: Ministry of Agriculture, Fisheries and Food: UK) (Schiffmann and Sacharow, 1992, p. 106).

**Fig. 11.2** Shelf-stable, single-serve tub product. Note the four vent holes in the lid.

opening significantly narrower than the majority internal diameter since this, too, may lead to excessively high internal pressure and eruption. There may also be a wide variation in internal temperature.

Tub-shaped containers, used for single-serve room temperature products, overcome many of the eruption hazards by using a rounded, sloping wall construction in conjunction with a steam vented cap, as seen in Fig. 11.2. The fairly large internal diameters also reduce intense internal spot heating.

*Size*

The size of containers is controlled by the food product's volume and the need to heat the product thoroughly without overheating any portion. For this reason, the net weight of most microwavable food products is in the range of 250 to 300 g. Although some higher weights are available, as described below, they require other means to improve temperature uniformity. The physical size of the most useful containers is on the order of 15 cm × 20 cm, with depths commonly of 2.5 to 5 cm.

### 11.3.3 Multicomponent containers

Multicomponent meals containing a protein (meat, poultry or fish), starch and vegetable are usually sold as frozen meals in the US, but primarily as refrigerated versions in the UK and continental Europe. The frozen meals are especially challenging due to the sometimes very diverse microwave heating properties of the various components. The formulator must try to balance the mass and dielectric properties of the various components as much as possible, so their final temperatures are similar. The products are usually available in plastic or paperboard containers, often round or oval, although they may also be rectangular. Physically dividing the container into two or three compartments is a good way to keep the components separate during transportation. In that case, the microwave energy sees the separate compartments as separate trays, rather than parts of a single tray. This makes it easier to achieve more uniform heating since the shape, mass, specific heat capacity and dielectric loss of each component may be individually controlled. In cases where the various components are arranged about the circumference of the dish and one meal component, such as ham, heats faster than the others, it is possible to achieve better results by placing the ham in the center of the dish and surrounding it with the other meal components which act as microwave shields. There have also been numerous uses made of foil shielding to achieve similar effects, as will be described below.

### *Covering*

Covering these trays is useful to achieve more uniform heating. Recently, a variety of tray/cover systems have been supplied that contain various self-venting technologies including valves and or other means to release the steam pressure built up during microwaving. The steam itself adds to the uniformity of heating, as well as shortening the heating time and maintaining the moisture level in the food product. Products in these containers may be microwave cooked from raw or processed components.

Three main technologies are used for steam venting (self-venting) packages:

- Valves. These are generally described as 'one-way valves'. These vent the steam through a valve molded into the lid or wrap-film. An example is the 'Wipf' valve made in Switzerland. A one-way valve, it allows the venting of gases evolved during storage as well as steam during cooking. It is claimed by CNF, the group that invented and markets products using this valve under the labels 'Dream Steam' and 'Steamy Wonder', that valves offer an exact method of controlling and releasing the steam pressure, and thereby, controlling cooking better than non-valve procedures (Keller, 1999).
- Non-valve systems
  - Holes. These can be micropores or larger holes or slits, usually covered with a barrier film, adhesive film tape or adhesive label to be removed by the consumer or opened by the internal steam pressure that allows the steam to vent; or the film lid may shrink, thereby exposing the vent hole.
  - Cohesive-seal or seal-break systems. These are various types that use different means to create a steam vent, such as a weak point at a tray/lid seal, or a material or device which is somehow microwave interactive and 'melts' a hole or vent for steam release. Several systems, including Vacsys, are adhesive based. The Vacsys technology is based upon three major elements: special microwave absorptive inks; a gap in lamination adhesive; and slits in sealant film. The ink creates a hermetic seal and helps control venting. The gap allows passage of the steam from inside the

package to come in contact with the special ink. The slit in the film allows the steam to enter between the lamination so it can travel through the adhesive gap until it reaches the special ink for venting (Hagino, 1998).

### 11.3.4 Covers

Covering food during microwaving has been shown by this author and others to improve the cooking performance (Schiffmann and Sacharow, 1992, p. 118). It improves the uniformity of temperature distribution, retains moisture, and shortens cooking time. Recent packaging innovations have included self-venting valves and other structures in or as part of the cover, as was described in detail earlier. These venting systems, in effect, create something similar to a steam pressure cooker within a microwavable container. They are being used extensively in Europe and Japan and are the subject of about 200 patents. The need for venting is necessary where covers are sealed to the container for protection during shipping and storage. If they were not vented in some way, the container cover could burst causing a mess in the oven and even injuring the user. Therefore, users are advised either to slit or, partially or wholly, to remove the cover, prior to microwaving. Self-venting covers add an element of safety by eliminating the need for the consumer's actions, as well as providing product benefits. The materials used for tray covers have been described earlier.

A different cover-vent design is used for the microwavable plastic tub products. These multilayer-barrier cylindrical tub-shaped containers are used for products such as macaroni cheese, lasagna and chili. Because they contain large particulates in viscous sauces or gravies, there is a tendency for them to erupt during microwaving. In order to prevent the contents from erupting out of the container, the flexible polypropylene lid, seen in Fig. 11.2, contains large vent holes and is fitted over the tub, removing a sealed aluminum closure.

## 11.4 Packaging materials

When selecting the proper container material for use with a microwavable food the following guidelines should be followed (Schiffmann and Sacharow, 1992, p. 111):

- Must be microwavable compatible – will not heat excessively, or prevent effective microwave heating
- Must be thermally compatible with the food – that is, it should not melt, distort or be otherwise affected by the hot food
- Should provide shelf-life properties commensurate with the food and its use
- Should not ignite, arc or smoke during normal use
- Should not affect the flavor or color of the food
- Should not be discolored by the food

- Should not allow the migration of any materials into the food which might adulterate it
- Should be safe and easy to handle.

Keeping the earlier guidelines in mind, the following discussion looks at how well these factors are met by the various materials currently on the market.

### 11.4.1 Glass

Soda lime glass should never be used for microwavable products. Borosilicate glass jars are microwave transparent, but should be used sparingly for microwavable foods. However, there are significant drawbacks: the high cost of glass, its breakability, high shipping weight and tendency to become hot due to heat transfer from the contents. As to microwavability, there are additional drawbacks:

- Their usual cylindrical shape causes focused interior heating. In large jars, such as those used for spaghetti sauce, there will be a ring of intense heat near the glass, while the center is significantly cooler. Temperatures near the top will also be high. Small jars, such as those used for baby food, may have intense hidden hot spots in the center, at or near 100 ºC, while the surface of the food and the glass may be only warm, creating a serious hazard (Schiffmann, 1988). For this reason, it is best if small jars of baby food or any other food are not heated in microwave ovens. If they are, the contents must be thoroughly stirred and tested prior to use. Stirring is advised for all foods heated in glass jars, as are very conservative heating instructions.
- Under some conditions, glass jars may break during microwaving. This is especially true if there is a surface flaw that may occur during shipping or handling. If the interior becomes very hot while the outer surface is cool, due to the oven's cool ambient temperature, there can be a large enough difference in thermal expansion to cause the glass to crack.
- The usual cylindrical geometry of glass and the restriction at the neck is likely to cause 'bumping' or eruption of the contents, especially if there are large particulates present.

### 11.4.2 Boil-in-bag and stand-up pouches

These flexible pouches have been used for many years, especially for frozen vegetables and side dishes. Originally heated by immersion in boiling water, they were easily adapted for microwave oven use, but with some problems. Since the melting point of the pouch must be above that of boiling water, they are usually made of co-extrusions or laminations containing layers of medium density polypropylene (MDPE). It is important that these pouches be vented when used in the microwave oven or they will burst. Also, handling of the hot pouch can be difficult. The consumer can simply cut or pierce the pouch but the contents may spill out, so they should be placed on a microwavable plate.

Today, many self-venting pouches are available and in use, especially in Europe and Japan, using some of the same technology described above.

*Stand-up pouches*

While boil-in-bag pouches are usually placed horizontally inside the microwave oven, stand-up pouches are heated vertically. They also have all their graphics on the pouch, whereas a boil-in-bag pouch is usually enclosed in an overwrap carton that contains the graphics and heating directions. Stand-up pouches are constructed of multiple layers of thermoplastics and other materials to provide structural support and barrier properties. Since aluminum cannot be used as a barrier in a microwavable pouch, other barriers must be used. A unique pouch construction employing a silicon oxide barrier is used for a wild rice product by Fall River Mills in California (Lingle, 2003). The structure is 48-ga PET/48-ga PET copolymer with a silicon oxide coating/60-ga biaxially oriented nylon/2.4-mil cast polypropylene. The outer PET is reverse gravure printed in eight colors. It may be retorted.

An often unsuspected problem may arise when microwaving a high fat content food such as a soup or a meat-in-sauce. If the fat separates and floats to the food's surface it will attach to the pouch's interior wall by interfacial tension. When microwaved, this interfacial fat can become exceptionally hot and melt through the pouch. It is, therefore, essential that the product formulation prevent fat separation in these products. It is also important that the stand-up pouch be properly vented to prevent excess pressure build-up and eruption. Several self-vented pouches are available commercially.

### 11.4.3 Paper and paperboard

A large number of different paperboard containers, folded or press-molded, dominate the container market for microwavable foods in the United States. They are coated with various polymers for different food applications, the paperboard providing structural rigidity, while the coating provides chemical resistance and sealability. The choice of coating, and hence the choice of container, largely hinges on the maximum temperature likely to be reached by the food during microwaving. Other considerations are grease resistance, extent of oxygen and moisture barrier, sealability, dual-ovenability and price.

There are three different paperboard tray types based upon their polymer coating. These coatings on the paperboard result from either extrusion coating of a molten polymer resin, adhesive or extrusion lamination of a previously fabricated polymer film, or roll coating of a polymer solution.

- Low-density polyethylene (LDPE) coated paperboard: since the polymer has a low melting point, this is only for the lightest microwave use, such as microwaving frozen vegetables. Food temperature should not exceed that of boiling water. LDPE also has poor grease resistance and is not suitable for conventional oven use, i.e., it is not dual-ovenable.

- High-density polyethylene (HDPE): has better temperature and grease resistance, but its higher cost and difficult sealability have blocked its adoption for food packaging.
- Polypropylene (PP): has a higher melting point and better grease resistance than polyethylene. However, it is still not suitable for dial-ovenable use.
- Polyester (PET): has a use temperature of up to 205 ºC, so these trays are ideal when dual-ovenability is required. Such high temperatures may also occur during microwaving, especially at the surface interface between the food and the tray. They are also grease resistant and have modest gas barrier characteristics. PET coated trays, pressed and folded, have become the package of choice for many microwavable food products in the United States.
- Covers: either polymer coated paperboard or polymer films may be heat sealed to the trays. Commonly, both heat-sealable oriented PP and PET films are employed and their characteristics are shown in Table 11.2 (Bohrer and Brown, 2001, p. 402). These covers may also be steam-vented in the manner described above.

### 11.4.4 Polymer trays

The use of polymer trays was first encountered in the early 1980s when thermoset polyester trays were used for various frozen meals. Many consumers saved these trays for reuse and soon found themselves with more trays than they needed and stopped buying the products. High tray cost also led to their disuse. Replacing them are trays made from two of the three polymers noted above: polypropylene (PP) and polyester (PET). Since there is no paperboard to offer structural rigidity, low-density polyethylene (LDPE) is not useful for microwavable trays since it begins to distort at about 75 ºC.

### 11.4.5 Polypropylene (PP)

These trays are useful only for high-water containing products where temperatures are unlikely to go above 100 ºC. This means that they are not suitable for use with such high-fat products as soups, sauces or gravies, or high-sugar products such as syrups and glazes. However, the cost of these trays is low and they are optically clear, so they are used for many microwavable products.

### 11.4.6 Polystyrene (PS)

Foamed PS is popular for its thermal insulating properties and is used for take-out coffee cups and food trays. However, its thermal stability (softens or melts at <100 ºC) is too low for it to be usable as a tray material for microwavable processed foods.

### 11.4.7 Crystallized polyester (CPET)

Whereas amorphous PET begins to soften at temperatures over 63 ºC, trays made from CPET are stable up to 230 ºC, and thus are dual-ovenable

**Table 11.2** Properties of microwavable paperboard trays

| Package type | Materials | Maximum service temperature | Oxygen barrier | Moisture barrier | Grease resistance | Sealability | Dual ovenable? | Comments |
|---|---|---|---|---|---|---|---|---|
| **TRAY** | | | | | | | | |
| Tray | PET coated paperboard | 205 | Poor | Fair | Good | Fair | Yes | Pressed or folded trays |
| Tray | PP coated paperboard | 125–135 | Poor | Fair | Good | Good | No | Pressed or folded trays |
| Tray, sleeve, support, overwrap | LDPE coated paper or paperboard | 95 | Poor | Fair | Good | Fair | Yes | Light duty reheating |
| **OVERWRAP** | | | | | | | | |
| Overwrap | Heat sealable oriented PET film | 220 | Poor | Good | Good | Good | No | Needs venting during reheat, barrier improved by coatings |
| Overwrap | Heat sealable oriented PP film | 110 | Fair | Fair | Good | Good | No | Needs venting during reheat, barrier improved by coatings |

Source: Bohrer and Brown (2001), p. 402.

(Robertson, 1993). They are manufactured by thermoforming an extruded PET sheet containing an added nucleating agent. Thermoforming is done in a hot mold where the tray is held long enough for the crystalline structure to develop. It is then transferred to a second mold for cooling (Proffit, 1991). Since they are not optically clear, these trays are usually pigmented, black being the color of choice for most products. These characteristics are summarized in Table 11.3 (Bohrer and Brown, 2001, p. 402).

### 11.4.8 Multilayer PP and PET

Containers made from these materials may have three or more layers to provide rigidity, moisture and oxygen barriers, and come in a variety of shapes and sizes. They may be hot-filled or retorted at 70 ° to 120 °C and have room temperature shelf-lives on the order of 24 months. The favored barrier options are EVOH or Nylon. Graphics are supplied using adhesive labels, shrink sleeves, silk screen printing or more. In some cases a foam-structured sleeve is used to provide some heat insulation, as on the tub-shaped products described earlier.

### 11.4.9 Aluminum

This material has always been controversial for microwave oven use. However, it has several distinct advantages which, over the years, led many packaging and food processors to consider its use for microwavable foods. On the plus side is aluminum's cost, versatility in molding different shapes and sizes, excellent heat transfer characteristics when freezing, shelf-life properties and recyclability. However, it has an image among consumers and most food processors that it is not suitable for microwave oven use. There are two major concerns – potential for damage to the magnetron and arcing. Numerous tests by this author and others have shown these concerns to be largely unjustified. Coated aluminum trays were marketed for microwave use for a period, the coating disguising the aluminum and forming a partial electromagnetic barrier to control arcing. However, this failed to overcome both consumer misperceptions and the real problems when use of foil packaging. Since foil is reflective, microwaves can only enter through the open top, causing heating profiles that are very different from those in transparent trays. Since heating though the sides and top are not possible, foil trays must be rather shallow, more in line with the penetration depth of the food therein, and probably should not exceed 2.5 cm deep. Two other phenomena are encountered with foil trays:

- Unusual thermal profiles, especially with rectangular shapes. These often have more exaggerated hot or cold spots than are seen with transparent trays. This results from the foil tray as a resonant structure and the creation of a standing wave pattern within the tray. Changing to oval or round containers can alleviate, but not eliminate, this problem.

**Table 11.3** Properties of microwavable polymer trays

| Package style | Materials | Maximum service temperature | Oxygen barrier | Moisture barrier | Grease resistance | Sealability | Dual ovenable? | Comments |
|---|---|---|---|---|---|---|---|---|
| **TRAYS** | | | | | | | | |
| Thermoformed tray | CPET | 220 | Good | Fair | Good | Fair | Yes | Generally pigmented white or black |
| Thermoformed tray | PP | 110 | Poor | Good | Good | Good | No | Brittleness an issue at freezer temperatures |
| Thermoformed trays, clamshells | PS and foamed | 80 | Good | Fair | Good | Poor | No | Light duty reheating only |
| Thermoformed tray | LDPE | 75 | Poor | Good | Fair | Good | No | Light duty reheating only |

Source: Bohrer and Brown (2001), p. 402.

- The lack of heating close to the foil/food interface. The foil suppresses the electric field close to its surface so there is little heating except by conductive heat transfer from the food zones beyond this. This can be particularly problematical with frozen foods.

## 11.5 Active containers

Unless auxiliary heating means is provided within a microwave oven, it is not possible to crisp or brown foods unless special packaging techniques are employed. While combination ('combi') ovens are popular in Europe, where the mains voltage is of the order of 240 volts, they represent less than 5% of annual sales in the United States where the ordinary household supply is only 120 volts and 15 amperes in the kitchen, making it nearly impossible to operate the magnetron plus an auxiliary heater simultaneously. Microwave-only oven cavities have ambient temperatures at or only slightly above room temperature, which is unsatisfactory to achieve the high temperatures required for browning and crisping, whose requirements are described below. To meet these needs, various active packaging technologies have been successfully developed.

### 11.5.1 Browning and crisping

Both are high-temperature phenomena but they differ in very specific ways.

*Browning*

This is a surface color change caused by the complex organic Maillard reaction, and is associated with such things as the browned crust on bread and pastry. The Maillard reaction depends upon four things:

- The presence of the Maillard reactants: an amino acid such as glycine and a reducing sugar such as fructose.
- A surface temperature of 100 °C or more. Below this temperature the reaction proceeds very slowly, if at all.
- A water activity of approximately 0.8: above this, the reactants are too dilute; below it they are too concentrated. The reaction requires water to proceed.
- A neutral or slightly alkaline pH, approximately 7 and above.

Since the air in the microwave oven is cold, it is difficult to achieve the high surface temperature required. The cold temperature also causes surface condensation of water being pumped out of the food. This, combined with the increasingly high humidity in the oven during its operation, raises the water activity close to 1.0. So, at least two of the elements for Maillard browning are difficult to achieve by ordinary means. While browning coatings, both liquid and powders, have been used to create a pseudo-browning effect, microwave susceptors are used in many products.

*Crisping*

Crisping requires still higher temperatures, 190 ºC and above, in order to dehydrate the surface and achieve the required water activity of approximately 0.1. Since microwaves heat the interior of the food, thereby raising the internal vapor pressure, a phenomenon called water-pumping occurs which actively forces water to the surface where it condenses, saturating it and making crisping impossible without additional means.

### 11.5.2 Characteristics of active containers

Active containers are defined as packages containing elements that interact with the microwave field to create conditions other than simply holding or containing the food while it is being microwaved. There are three basic classes of active container:

- Shields: these prevent the microwaves from reaching all or part of the food.
- Susceptors: these become hot and transfer heat to the surface of the food being microwaved.
- Field modifiers and patterned susceptors: these improve or focus the microwave energy distribution.

Steam-venting containers, as described above, may also be considered to be active containers since the contained steam pressure positively affects the cooking performance.

*Shields*

Shielding is achieved by incorporating aluminum foil as part of the container. For example, for a frozen meal in a multi-compartment tray, it is possible to place ice cream in a totally shielded compartment of the tray – surrounded with aluminum foil – and keep it frozen while the rest of the frozen meal is heated by microwaves. It is also possible to place aluminum foil around portions of the tray to prevent overheating of the corners, sides or edges of the food.

*Susceptors*

The purpose of susceptors in various tray types is to provide the high temperature surfaces required for browning and crisping. Susceptors have been in commercial use since 1975 and, except for microwave popcorn bags, are used to achieve the localized effects of browning and crisping. Three classes of susceptor have been developed: pigment/binder coatings, chemical susceptors, and metalized conductive coatings. Only the latter are in extensive use for microwavable packaging. Vacuum-deposited aluminum is the most common metalized susceptor material in general use, although sputter-coated stainless steel has seen some commercial applications. The four basic layers consist of the following (see Fig. 11.3):

1. A polymer film heating surface (often 0.012 mm of heat-set, biaxially orientated PET) onto which is deposited:

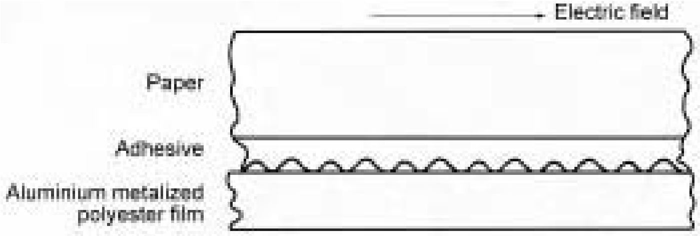

**Fig. 11.3** Construction of a typical microwave susceptor (Schiffmann and Sacharow, 1992, p. 123).

2. a thin metal layer (usually vacuum deposited aluminum at 50–250 ohms per square).
3. An adhesive to bond the film to:
4. a substrate (usually paper or paperboard) that provides structural stability.

Vacuum metalization creates microscopically tiny islands of aluminum separated by microscopically tiny distances. As the microwave field oscillates, a current flows across these aluminum islands with the gaps providing a resistance to the flow, thereby causing resistive ($I^2R$) heating of the susceptor film. In order to be effective the metal thickness must be of the order of 30–60 angstroms, with a surface resistivity of approximately 0.01 mhos. Figure 11.4 shows the absorption of microwave power as a function of surface resistivity (Andreasen, 1986). A comprehensive theoretical discussion of these structures was published in *Microwave World* (Habeger, 1997).

The food is usually in direct contact with the heating surface which may have a release coating. The metalized side of the susceptor is separated from the food surface by the PET film, which also protects the metal from chemical or physical damage. While the mass of the thin conductive coating in a susceptor is

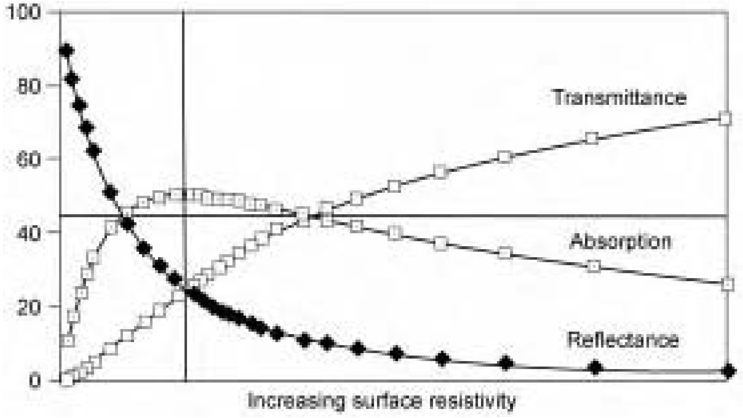

**Fig. 11.4** Percent microwave power absorption, reflection and transmittance as a function of surface resistivity (Andreasen, 1986).

extremely small by comparison to that of the food, its lossiness is much greater than that of any food. Consequently it absorbs microwaves well despite being in intimate contact with the food, thereby providing high surface temperature. However, when the film temperature reaches approximately 190 ºC the oriented PET film cracks or crazes and becomes discontinuous, and there is a sharp, irreversible drop in lossiness and the susceptor's temperature falls. This mechanism provides a temperature safety limit. This is especially important for areas in which there is no food contact to act as a heat sink, otherwise the susceptor could cause the paper to burn. Such films can be used only once.

For effective use the susceptor must be in intimate contact with the surface of the food, otherwise there is a dramatic fall-off of temperature between the susceptor and the food surface. Most susceptors are designed to provide such contact and may even be folded to provide good contact for such products as egg rolls. A unique susceptor sleeve is provided for the Hot Pockets® brand of stuffed sandwiches (Chef America®). The sleeve also has two large vent holes that allow water vapor to escape which would otherwise prevent effective surface heating of the pastry shell (Pawlowski and Brown, 1988) (see Fig. 11.5).

Another problem encountered with susceptors is uniformity of heating. Since these products are usually of large surface area, they exhibit hot and cold spots partially due to the oven's properties and also because of unevenness of deposition of the aluminum film. This is one reason it is best not to make the susceptor dimensions too large – a diameter of 20 cm is a useful limit.

**Fig. 11.5** The unique susceptor sleeve used with the Hot Pockets® filled pastry. Note the large moisture-release vent hole that enhances the crisping efficiency.

Susceptors can also be quite sensitive to location in the vertical plane. Raising them from the floor of the oven can improve susceptor performance simply by reducing heat loss to the floor. However, once raised, small changes in height can have major effect upon efficiency of energy deposition in the susceptor.

One method for preventing overheating of the susceptor in areas at which it is not in good contact with the food is to use a patterned or fused susceptor as described in a US patent (Walters *et al.*, 1996). Here, a regular pattern of X's that do not have heating capability will generate current concentrating paths when imposed on a susceptor film. The pattern forces a concentration of currents between the aligned points of the X's and generates a series of sites at which the breakdown occurs if heat transfer is poor (Bohrer and Brown, 2001, p. 416) A grid pattern of lines of active microwave heating function serves a similar role, and both are in commercial use.

Matching the active heating area to the shape of the product and varying the heating rate applied to different areas of the product may provide better browning and crisping performance than a single overall susceptor design. Patterned susceptors are useful for achieving different heating distributions.

Another problem of susceptors is their low thermal mass. If a large amount of water vapor is produced from the food it will inhibit the heating and effective use of the susceptor. For this reason, paperboard-backed susceptors often have superior browning and crisping performance.

### *Popcorn bags*

The largest volume of metalized susceptors used in the United States is for the production of approximately one billion popcorn bags annually. This has nothing to do with browning or crisping. In this application, the susceptor film is bonded directly to the middle third of the interior of the down-side of the bag. The susceptor's function is to melt rapidly the hydrogenated soy bean oil (which otherwise couples microwave energy poorly) in which the popcorn kernels are mixed. Once melted, the microwave coupling to the oil is improved and this enhances the popping performance as measured by the volume of popped kernels and the number of non-popped kernels remaining following popping. The use of susceptor lined popcorn bags has become standard for this industry. There have been a few successful non-popcorn applications of susceptor bags. In the USA this includes the heating and puffing of pork rinds, resulting in very large volume expansion and creating a crunchy edible foam-like structure, often spice-coated.

### *Other susceptor designs*

Susceptors have been bonded to either face of corrugated paperboard. When applied to the fluted side of the corrugate, the food contacts only the tips of the susceptor but the channels between them provide a convenient means for the escape of water vapor. When the susceptor is applied to the flat side, the food, such as pizza, is placed thereupon, while the fluted non-susceptor side provides insulation to prevent heat loss to the floor of the oven. See Fig. 11.6.

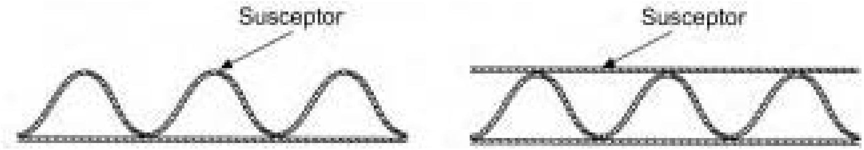

**Fig. 11.6** Two types of fluted or corrugated susceptor. On the left, the fluted surface is coated with the metalized susceptor and provides channels for evolved moisture to escape. On the right, the metalized susceptor is on the flat top surface – the fluted corrugations insulate the susceptor from the floor.

### *Field modification*

Field modification packages for microwavable foods redirect the energy of the microwave field in a predictable fashion to optimize the microwave heating performance of foods, overcoming two major drawbacks of microwave cooking with respect to heating rates. The first is the tendency for overdone edges and underdone centers of food items. The second is providing different heating rates to different components of multicomponent meals.

The pioneering work in this area was done by The Aluminum Company of Canada and resulted in patented technology and a line of trays and lids named Microwave Match$^{TM}$ (Keefer, 1987, 1989). The lids were designed to affect the distribution of microwave energy in the container so as to cause more uniform heating. Some browning of the top surface was also demonstrated. The lid structure was not in contact with the surface but remote from it and contained a multitude of pieces of foil bonded to the lid. The pieces of foil took various geometric shapes such as a group of squares with rounded corners, or of arcs of different length, and so on. Both the shape of the foil and spacing were critical and selected for specific food items. The plastic dome lid was mated to an aluminum tray, in the original designs, or plastic or paperboard thereafter. This concept had limited success and is no longer in use. Since then, a great deal of research and development has been done by others, leading to a large number of patents and some commercial success.

There are three main uses of field modifiers: shields (described earlier), field distribution and field intensification. These may be used singly or in combination to achieve the desired results. They have also been combined with susceptors, where the former redirects the microwave energy to these heating elements.

### *Theoretical basis for field modification*

Electrical conductors, such as aluminum, of sufficient thickness prevent the transmission of microwave energy, thereby acting as reflective shields. However, when properly designed in strips and geometric patterns, the aluminum conductor can act as a *field intensifier* where it locally intensifies the microwave energy; or as a *field distributor* by transmitting the microwave energy to areas in the food that would otherwise not receive enough microwave energy. The value of such containers is shown in the following examples:

- Foods of large dimension: conventional pizzas can be quite large, 12 inches (30 cm) or more in diameter. However, microwave pizza is likely to be only 8 inches (20 cm) or less, even on a susceptor tray. The reason is that the pizza is 'self-shadowing'. That is, it prevents the microwave energy from reaching the center of the crust. In a microwave oven, the energy approaches the food load from all sides. However, the energy distribution is not equal. Edges and corners are heated from the side, top and bottom, but the center of a dimensionally large food such as pizza is microwave heated from only the top. While energy may be reflected from the floor, the outer portions of the pizza absorb microwave energy and effectively block it from reaching the bottom center of the pie. The situation is even worse in foods of considerable depth, as shown in Fig. 11.7. It is possible to improve this condition by raising the pizza, or other large food item, an inch or more from the floor or turntable. But another solution is to use a field modifier placed under the pizza that causes more microwave energy to reach the bottom center. An example of such a field distributor is shown in Fig. 11.8. This is the MicroRite® combined field distributor and susceptor tray manufactured by Graphic Packaging International, Inc. In this case it is combined with the microwave susceptor that provides the actual heat needed to crisp the crust.
- Another problem arises when the food load is very large, for example, a 1 kilo (2.2 lb) lasagna. If heated in a passive container the temperature distribution is very non-uniform. The large mass requires an especially long time to heat thoroughly, particularly if the lasagna is frozen. Edges and corners not only will overheat but may char and dry out while the center remains relatively cold. By shielding the outer walls, energy deposition and, therefore, temperature rise are significantly reduced in those zones. The addition of a

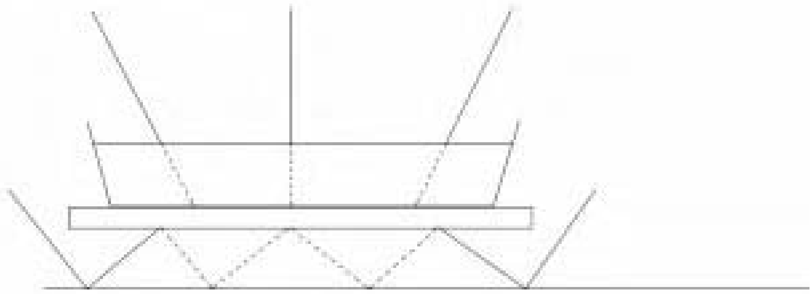

**Fig. 11.7** Self-shadowing reduces or prevents microwave energy reaching the bottom center of large food items. The energy is absorbed and attenuated as it passes through the food, thereby reducing or eliminating the energy that can be reflected from the oven floor.

**Fig. 11.8** The MicroRite® field distributor and susceptor tray for microwave pizza (courtesy of Graphic Packaging International).

resonant loops structure to the bottom of the tray increases energy coupling (*field intensification*) and energy transfer from the tray bottom, thereby reducing the overall cooking time. Figure 11.9 shows the energy distribution in lasagna cooked with and without using this technology, the graphs being provided by Graphic Packaging International, which manufactures these containers.

- A third problem addressed by these field-modifying structures is improving the heating of multicomponent meals. As noted above, each meal component may have significantly different dielectric properties, as well as different specific heat capacities, masses and shapes. So, temperature uniformity is difficult to achieve. A typical example is shown in Fig. 11.10 showing

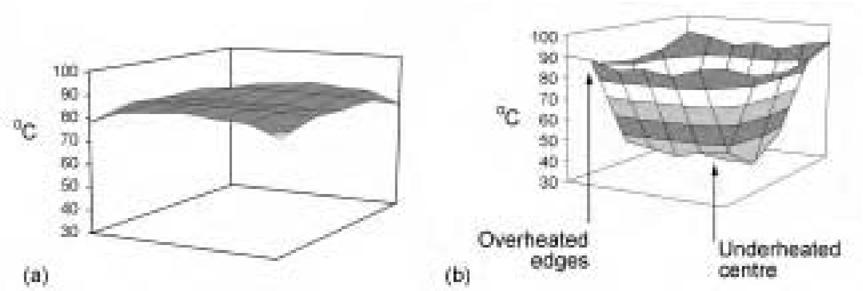

**Fig. 11.9** Temperature distributions in microwaved lasagna (a) with (a) and (b) without field modification (courtesy of Graphic Packaging International).

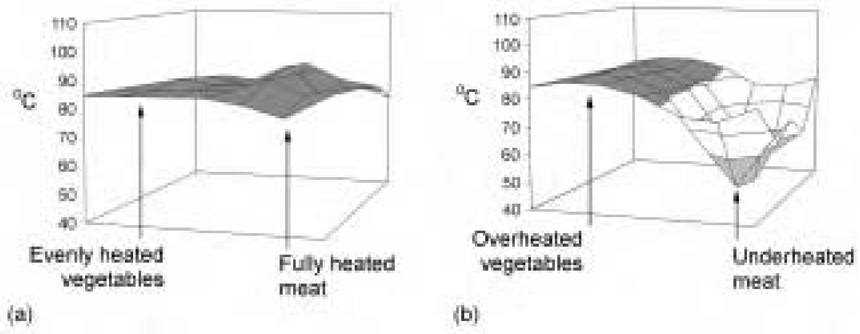

**Fig. 11.10** Temperature distributions in a multicomponent meal (a) with and (b) without field modification (courtesy of Graphic Packaging International).

overheated vegetables and underheated meat. By combining shielding on the sides of the tray and resonant loops under the meat, it is possible to improve this situation dramatically.

The design and placement of all field modifiers must be tailored to specific food combinations, shapes, sizes and temperature storage conditions. They are usually made by demetalization techniques employing chemical etching. However, simple designs can be produced by adhesive bonding of the aluminum strips onto the fiber substrate. A third manufacturing option is rotary die-cutting. In all these cases, the conductive metal is aluminum, usually at the thickness of common foil, 6–7 $\mu$m, at which it is both dimensionally and electrically stable.

Field modifiers may also be combined with metalized susceptors, enhancing the heating of the latter in shadowed areas in products such as fruit pies and pot pies.

## 11.6 Future trends

*Passive containers*

The area of greatest current interest is self-venting containers. Manufacturers claim significant product advantages with these containers, especially in improving texture and eating quality. Numerous examples are found throughout Europe and Japan. For example:

- UK: all large supermarket chains have their own store brands of 'microwave-steamables'. All are refrigerated ready-meals.
- Mainland Europe: many products in Belgium, France, Germany and the Netherlands, both frozen and refrigerated and including main meal entrees and side dishes.
- Japan: a large number of products of all types. The big-name processors are Nestlé Japan, Ajinomoto, Nicherei, Kagome, and Otsuka Foods.

The situation in the United States is complicated by the additional costs involved in applying any of the technologies. US manufacture is very price driven and that inhibits the adoption of technologies that may add $0.10 or more to the retail price of each package. However, many processors are looking at how it can be adapted to their own products without adding significantly to the cost.

*Active containers*

There is likely to be further work employing patterned susceptors and field modifiers to improve product performance. But, again, the additional cost of goods may limit its adoption in the United States except for higher priced entrees. An interesting new development is seen in a new container that uses a patterned susceptor inside a folded paperboard carton for the microwave cooking of fresh meat, poultry and fish, along with some vegetables, and is available in the United States from Caraustar (Rittman, Ohio). However, its relatively high cost may inhibit its adoption.

Whatever container the product developer settles upon, it cannot replace good food technology and formulation. One should never start by first picking the container and then trying to develop the product to match the container. Nor should one fully develop a product and then search for the proper container. The best and most successful technique is to bring packaging technology into the product's development early, once the basic form and characteristics of the product have been settled upon. Then the right container can be matched to optimize the product to achieve the greatest consumer satisfaction.

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# Part III

# Measurement and process control

# 12

# Measuring the heating performance of microwave ovens

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## 12.1 Introduction

Since the 1980s the market for chilled and frozen food has grown rapidly. This is especially true for convenience products that are reheated rather than fully cooked in the home or at a catering establishment. The majority of these products are designed for rapid reheating in a domestic or commercial microwave oven as well as in conventional ovens. During processing the manufacturers of these products aim to cook the products to a temperature that would ensure the reduction of pathogenic bacteria to a safe level. However, it is possible that the required reduction has not been achieved during processing or the product can become contaminated during distribution or in the home. In particular, there has been concern over the growth of *L. monocytogenes* at the storage temperatures commonly encountered in retail and domestic storage of chilled foods (James and Evans, 1989). Walker *et al.* (1991) showed that *L. monocytogenes* could survive after microwave heating. It is therefore recommended that when a food is reheated in a microwave oven it reaches a minimum temperature of 70 ºC for at least 2 minutes or an equivalent temperature/time condition, e.g. 75 ºC for 30 seconds, 65 ºC for 10 minutes, etc. (European Chilled Food Federation, 1996). Interestingly, studies on the microwave cooking of raw chickens (Farber *et al.*, 1998) showed that *Listeria* spp. survived after microwave cooking even though the temperatures measured were above 87 ºC.

A small change in heating time in a microwave oven has a large effect on the survival of *Salmonella* spp. Levre and Valentini (1998) found that in inoculated meat loaves *Salmonella* survived after 3.5 minutes heating followed by a 2-minute holding time but was not found when the heating time was increased to 4 minutes, while Tassinari and Landgraf (1997) found that *Salmonella typhimurium* survived in baby food, mashed potato and stroganoff after microwave heating.

There are at least three recorded occurrences of food poisoning associated with microwave heating. In one case (Gessner and Beller, 1994) it was related to microwave reheating of cooked pork slices. In the second (Evans *et al.*, 1995) five individuals had food poisoning after consuming microwave-heated cooked rice that contained *Salmonella enteritidis* phage type 4 (PT4), while in the third (Bates and Spencer, 1995) *Salmonella* in microwave-poached eggs was believed to be the source.

At the same time as ensuring microbial safety it is important that the food is not overheated so that the eating quality is unacceptable. This second criterion is far more difficult to define and is a function of time, temperature and the food being heated. Some obvious limits can be set. If parts of the food rise to 100 ºC or above for any length of time the food will dry out and ultimately burn. With some foods the eating quality will be unacceptable long before this can occur. If the time/temperature treatment is too mild then the food may appear undercooked.

Investigations carried out since the late 1980s have revealed considerable variability in the ability of different models and types of domestic microwave oven to reheat chilled convenience meals. They have also revealed a large degree of non-repeatability during heating. Some of the reasons for the variability and non-repeatability have been identified whilst others are less defined. The development of a protocol to produce microwave reheating instructions for ready meals needs to take into account all the factors that are currently undefined as well as those that can be quantified.

## 12.2 Factors affecting food heating: power output

The rate of temperature rise at a point in a food depends on the power (rate of energy input) at that point and the thermal properties of the food at that point. A microwave oven differs from a conventional oven because the presence or absence of a food and its dielectric properties change the amount of microwave power delivered.

Since September 1990, most microwave oven manufacturers have adopted a single standard for measuring the power output for microwave ovens. The current standard (IEC, 1999) uses a 1 kg water load and the test is carried out using a cold oven in defined ambient conditions. A standard borosilicate glass dish is filled with 1 kg of water at 10 ºC, the dish placed at the centre of the base of the oven and the time required to heat the water to 20 ºC determined. Since the amount of heat required to heat water by 10 ºC is known, the average power (W) delivered by the oven to the load can be calculated.

James *et al.* (1994) used five ovens with different characteristics (Table 12.1) to look at the effect of size of load, repeated use and mains voltage supply on power output.

**Table 12.1** Characteristics of ovens used

| Oven code | Cavity size cu.ft ($m^3$) | Type of turntable | Recommended food position | Combination |
|---|---|---|---|---|
| A | 1.3 (0.037) | Metal | Metal rack | Yes |
| B | 1.0 (0.028) | Glass | Centre | No |
| C | 1.45 (0.041) | Glass | Plate off-centre | No |
| D | 0.6 (0.017) | Glass | Plastic rack | No |
| E | 1.15 (0.033) | None | Offset | No |

### 12.2.1 Size of load in oven

Since convenience meals commonly range in weight from 0.2 to 0.4 kg, the amount of power delivered to 0.42 and 0.25 kg water loads was measured and compared to the standard 1 kg load.

The power output into the different-sized water loads is shown in Fig. 12.1 together with the standard deviation of five replicated tests. In all ovens there was a reduction in power output as the size of the water load was reduced. In three of the five ovens reducing the load from 1.0 to 0.42 kg produced a small, <20 W, change in power output. In the other two the reduction was far higher. The power loss when the load was reduced from 1.0 to 0.25 kg was substantial, ranging from 64 to 263 W. In percentage terms the reduction in power output when the load size was reduced from 1.0 to 0.42 kg ranged from 0.1 to 9.7%, and when the load was reduced from 1.0 to 0.25 kg it ranged from 11.1 to 30.8%.

Experimental work reported by Persch and Schubert (1995) on two different microwave ovens identified a similar trend in the reduction of power output as the volume of water load was reduced. Small amounts of microwave energy were absorbed by the small loads, increasing to a maximum for volumes greater than 1 litre.

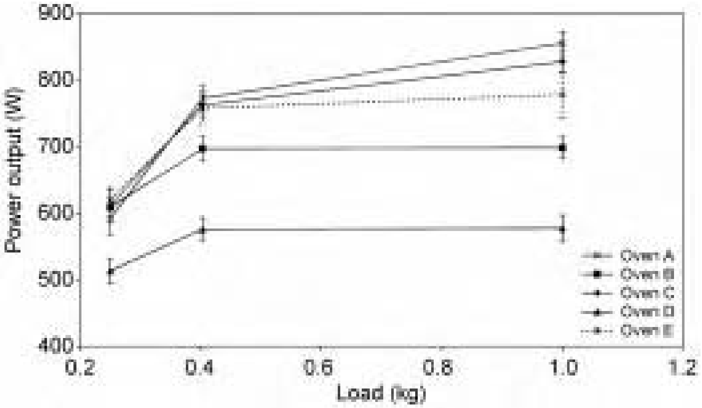


**Fig. 12.1** Power output into different sized water loads. Error bars ±1 standard deviation.

### 12.2.2 Repeated use of oven

IEC power determinations are carried out in cold ovens, i.e. ovens that have not been used for at least 6 hours. In domestic situations many occasions occur where an oven may be used sequentially and the oven and its components will heat up. To measure the effect of warming up on the power delivered into water loads, ovens were operated from cold and subjected to repeated water load power determinations over a period of 0.5 to 1.5 hours. Tests were carried out using 1.0, 0.42 and 0.25 kg loads and each complete trial was replicated five times.

In the five ovens the power delivered to a water load decreased as the oven became warm. The magnitude of the reduction over 0.5 hours ranged from 35 to 167 W and in percentage terms from 6 to 20% (Fig. 12.2(a)). However, the measurements underestimated the reduction in microwave power because a proportion of the heat gained by the food was by conventional heat transfer. Heat was transferred to the water by conduction and radiation from the warm walls and convection from the warm air. Separate experiments carried out without the microwave source being switched on showed that conventional heat input accounted for between 67 and 118 W of the warm power. The true reduction in microwave power output due to oven warming was between 20 and 35% of the cold power (Fig. 12.2(b)).

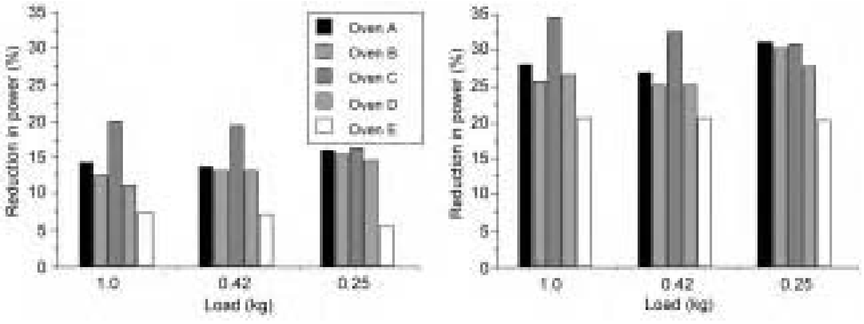


**Fig. 12.2** Percentage (a) apparent and (b) real reduction in power output after 0.5 h use.

### 12.2.3 Variation in mains supply voltage

Microwave ovens are designed to operate at a specified supply voltage. In the United Kingdom in the 1980s the electricity supply industry was contracted to provide its consumers with an electricity supply of 240 V, which could deviate by not more than ±6% of this value.

There was a substantial reduction in power delivered to a 1.0 kg water load as the voltage input to the oven was reduced through the permitted range (Fig. 12.3). The magnitude of the change varied considerably between ovens. In four of the five ovens the change was less than ±8% of the output at 240 V. In the fifth oven the total change over the ±6% voltage range was almost 36%.

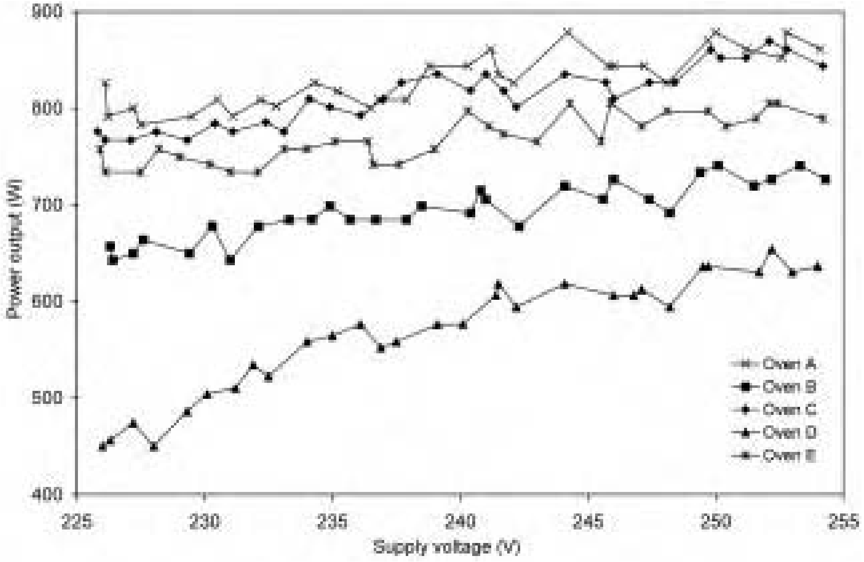


**Fig. 12.3** Power delivered into a 1 kg water load at different mains supply voltages.

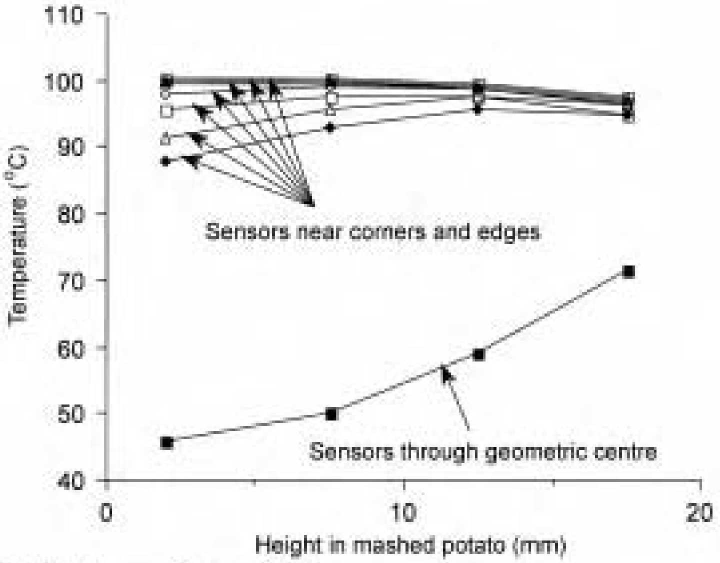
## 12.3 Factors affecting food heating: reheating performance

Studies were carried out by Burfoot *et al.* (1990) using 102 individual ovens from 70 different models to look at variability between and within models and the effect of oven features on reheating performance, while studies by Swain *et al.* (1994, 1995) looked at the effect of initial product temperature, continuous use of the oven and variability in commercial meals on reheating.

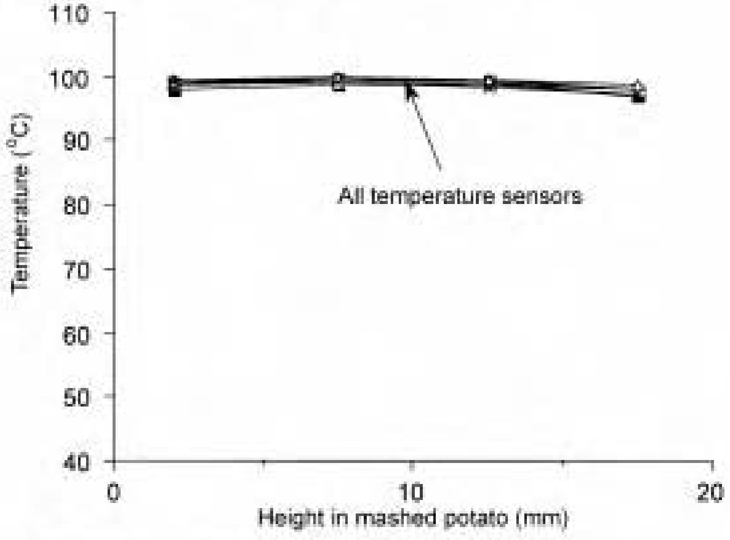
In the Burfoot studies a standard tray of mashed potato was placed at the geometric centre of the turntable, or floor of the oven where no turntable was present. Each oven was operated at its power setting closest to 650 W and the time of heating was determined such that the product of the stated power rating and the heating time equalled 240 kWs (kilowatt seconds).

After heating, the tray was placed into a polystyrene mould and a 'temperature hedgehog' inserted into the potato. The 'hedgehog' consisted of nine probes made from 2 mm diameter wooden rods with four thin wire (0.076 mm diameter) chromel–alumel thermocouples located along each rod. The temperatures in the mashed potato were monitored at 4-second intervals for 2 minutes after the probes were placed in the potato. Data on the highest temperature achieved at each location were analysed.

The mean temperature of the mashed potato, calculated from measurements made at 36 positions replicated five times, ranged from 92.8 to 98.9 ºC. Thirty-two of the 36 positions were close to the periphery of the pack and these means provided a very biased average temperature of the potato. The maximum temperature of the 180 measured, in the mashed potato, in any of the ovens was always within ±1.1 ºC of 100 ºC which indicates that localised boiling occurred in all the ovens. Minimum temperature of the 180 measured, in the mashed potato, in any of the ovens ranged from 44.4 to 95.6 ºC.



(a) High degree of non-uniformity



(b) Very uniform temperature distribution

**Fig. 12.4** Temperature at different heights in mashed potato after heating in ovens that produced (a) a high or (b) a low degree of non-uniformity of temperature distribution.

### 12.3.1 Uniformity of reheating

There are considerable differences in the uniformity of reheating in different microwave ovens. Figures 12.4(a) and (b) show examples of temperatures measured at each position on sensors within mashed potato in ovens that showed the lowest and highest degree of non-uniformity of heating. In a small number of ovens the lowest temperature was not located on the sensor that passed through the geometric centre of the potato.

The difference between the highest and lowest temperatures measured in each oven, which is the strictest test of non-uniformity, ranged from approximately 5 to 57 °C (Fig. 12.5). Temperature differences of <10 °C were measured in 39 of the ovens, <20 °C in 49 and <30 °C in 67 ovens from the 102 tested. The respective figures for numbers of models were 22, 30 and 43 of the 70 tested. However, because the highest temperature was always 100 ± 1.1 °C, the minimum temperature achieved is a good measure of non-uniformity. The mean of the lowest temperatures measured in the five trials with each oven is used in the following comparisons.

### 12.3.2 Repeatability within ovens

Tests using mashed potato were repeated five times with each oven. The standard deviation on the mean of the five lowest temperatures achieved with each oven varied from 0.6 °C to 8.0 °C. Reheating in 63 of the 102 ovens was very repeatable with standard deviations of approximately 2 °C or less. Nine ovens produced standard deviations greater than 4 °C, and in four of these, standard deviations were greater than 6 °C. Respective figures for models were 44 $\leq$ 2 °C, five > 4 °C and one model of the 70 had a standard deviation over 6 °C.

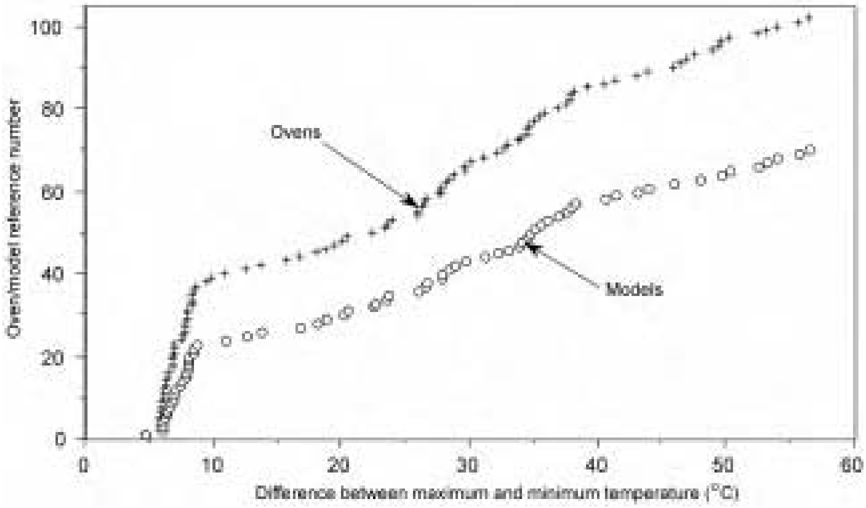


**Fig. 12.5** Maximum difference between measured temperatures in microwave ovens.

Forty of the 41 ovens that achieved a lowest temperature of ≥90 ºC also produced standard deviations of <2 ºC. Standard deviations at high temperatures are lower because water in the mashed potato boils at approximately 100 ºC, producing a natural limit to the temperature that can be achieved during the heating process. There was no other apparent relationship between the variability in lowest temperatures and the magnitude of the temperature.

### 12.3.3 Repeatability within replicate models

The differences between the mean of the lowest temperatures of five replicate ovens of each of four models that achieved temperatures >90 ºC (models A to D in Fig. 12.6) were less than 2 ºC and there were no significant differences between the replicates within a model type. In the other four models, higher differences (4 to 8 ºC) were measured between mean lowest temperatures from ovens of the same model. However, because the variations in reheating performance of these ovens were greater, only the highest and lowest means from models E, F and G were statistically different. The maximum temperature difference in the means (8 ºC) represents a variation of approximately 10% in temperature rise.

### 12.3.4 Oven features

There was no statistically significant relationship between the maximum stated power or the power used in the tests of the microwave ovens and the lowest

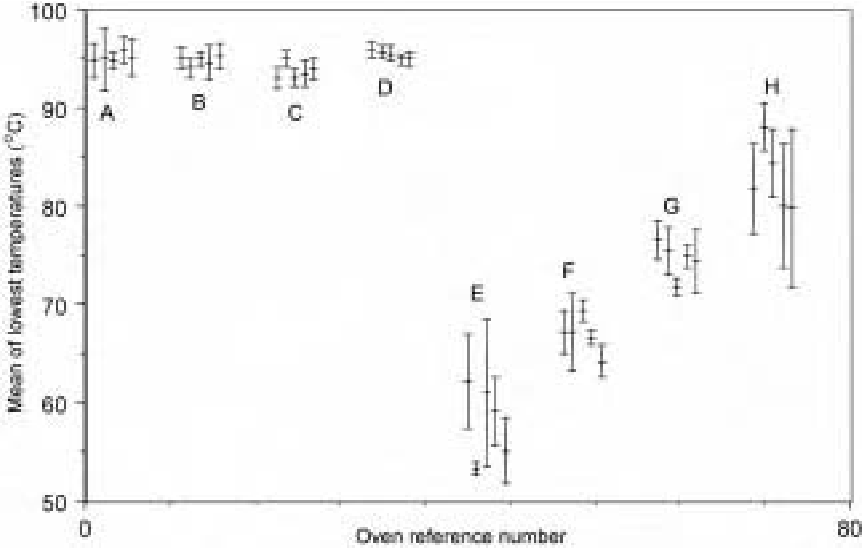


Fig. 12.6 Mean of lowest temperatures in replicated models.

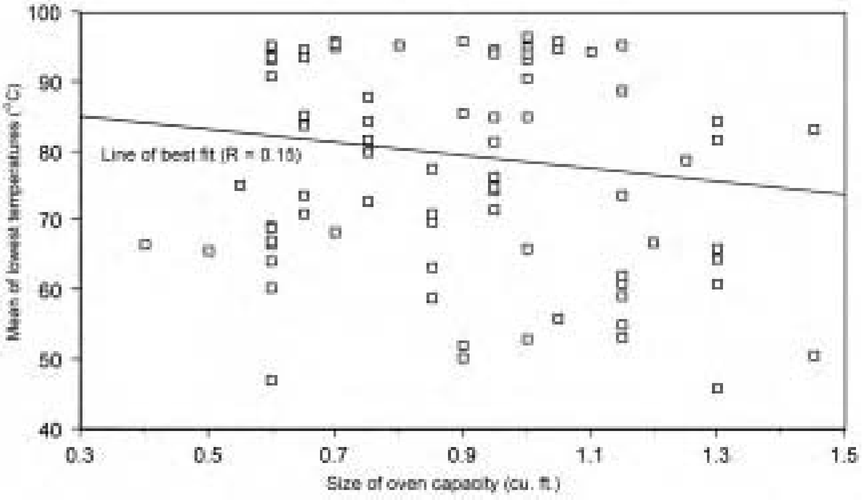


**Fig. 12.7** Mean of the lowest temperature measured in ovens of different cavity size.

temperature. Cavity size had little effect on the lowest temperature (Fig. 12.7) with both very high (>90 °C) and low (<60 °C) temperatures being found at all cavity sizes from 0.6 to 1.2 cu.ft (0.017 to 0.034 $m^3$). Too few ovens with sizes outside this range were present to see if there was any trend in large or small cavities. There was no significant linear relationship between the mean of the lowest temperature and the oven power to cavity size ratio (Fig. 12.7) as the degree of fit ($R = 0.15$) was exceptionally poor. A range of mean lowest temperatures from <50 to >95 °C were measured in ovens with and without grill elements. The sample size was too small to see if there was any significant effect of the presence or absence of a grill element or of its type of construction. However, these data show that it is possible to produce minimum temperatures above 90 °C in a microwave oven with a grill.

No oven with a metal turntable achieved a mean lowest temperature above 80 °C, and two of the ovens without turntables achieved temperatures above 80 °C (Fig. 12.8). Fifty-four of the 77 ovens with non-metallic turntables achieved mean lowest temperatures above 80 °C, and 42 of these achieved temperatures above 90 °C. Temperatures below 50 °C were measured in two ovens, one with a non-metallic and the other with a metallic turntable.

### 12.3.5 Initial product temperature

To determine the effect of initial temperature, Swain *et al.* (1995) measured temperatures in trays of mashed potato after heating from −20, −5, 5 and 20 °C. Reheating times used, with each oven/food temperature combination, were calculated from energy/mass data obtained from a summary of information printed on commercially available ready prepared meals. Energy/mass (heating

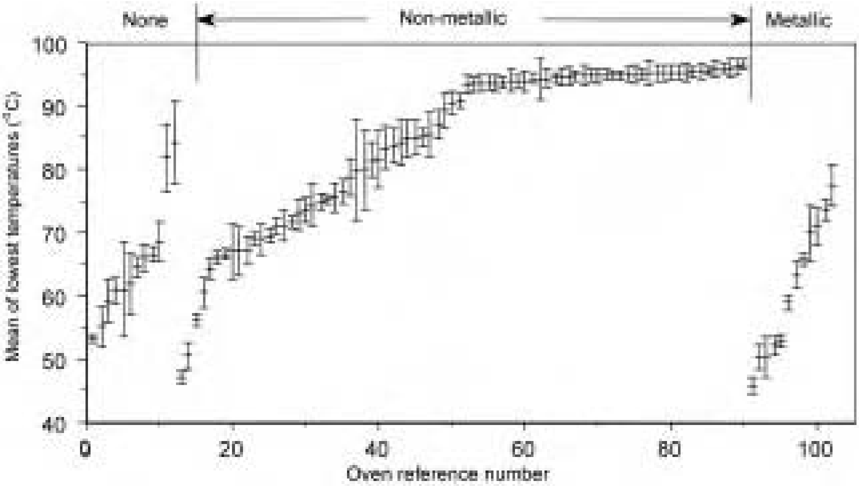


**Fig. 12.8** Mean of lowest temperature measured in ovens with different turntables. Error bars ±1 standard deviation.

time × power/mass) values of 958, 918, 571 and 515 kJ kg$^{-1}$ were used when heating from −20, −5, 5 and 20 °C, respectively.

The lowest temperatures measured in the potato after heating increased with the initial temperature of the potato (Table 12.2). As the lowest temperature in the potato increased, the temperature uniformity tended to improve. Only one oven produced a mean lowest temperature below 70 °C and that only occurred after heating from −20 °C.

Ovens which heated the frozen potato to above 90 °C also performed well when heating the chilled potato. The smaller lower-powered ovens performed better than other models when heating from frozen temperatures, which suggests that the use of low operating powers may be beneficial when reheating foods from frozen.

**Table 12.2** Mean and standard deviation of lowest temperature measured after heating from different initial temperatures

| Oven code | Lowest temperatures achieved after heating from initial temperatures of | | | |
|---|---|---|---|---|
| | −20 °C | −5 °C | 5 °C | 20 °C |
| 1 | 61.0 (6.6) | 73.2 (11.3) | 84.8 (2.6) | 90.9 (2.6) |
| 2 | 93.1 (2.3) | 90.8 (3.4) | 93.6 (1.0) | 94.2 (2.1) |
| 3 | 93.0 (1.3) | 91.4 (1.6) | 93.3 (1.0) | 94.8 (1.3) |
| 4 | 75.3 (1.7) | 81.5 (12.9) | 84.4 (4.4) | 89.3 (5.2) |
| 5 | 72.9 (8.4) | 80.8 (4.1) | 87.2 (3.0) | 89.9 (4.2) |
| Overall mean | 79.1 | 83.5 | 88.7 | 91.8 |

### 12.3.6 Repeated use of oven

Since the output power of domestic microwave ovens was known to fall with continuous use, Swain *et al.* (1995) investigated whether such a fall in power would affect the temperatures achieved in foods during reheating.

A polyethylene terephthalate (PET) tray containing mashed potato (0.42 kg) was heated in an oven operating at the setting closest to 650 W for a time sufficient to provide an apparent energy input of 240 kJ. Immediately after heating, a further tray of potato was heated and the process continued for 1.5 hours. The lowest temperature achieved in each tray of potato was measured after the tray was removed from an oven.

Two ovens, consistently over the 1.5 hour period, produced mean lowest temperatures in the potato which exceeded 90 ºC and no significant fall in temperature with time. The mean lowest temperatures achieved in the potato in the other ovens fell from approximately 81 to between 71 and 76 ºC during prolonged use.

### 12.3.7 Variability in foods

Swain *et al.* (1994) investigated the variability of reheating chilled ready meals using a regime that minimised the other factors known to influence reproducibility of power output or temperature distribution in domestic microwave ovens. Forty-four packs of each of lasagne, chicken with pineapple and cashews (chicken meal), and vegetable rogan josh (vegetable meal), bought from a local supermarket, and 44 packs of prepared mashed potato (mash) were stored for 22 to 30 hours in a chillroom at 5 ± 1 ºC. A microwave oven was then preheated by using it to heat 1.5 kg of water for 30 minutes and each of the meals heated for a set time. When the meal was removed from the oven a pre-warmed temperature 'hedgehog' with 20 temperature sensors was inserted into the meal and the temperatures logged for 20 seconds. The whole procedure was repeated in three different microwave ovens.

The lowest mean standard deviations (20 temperature positions) were found in the mashed potato. They ranged from 2.9 to 3.9 (Table 12.3) and were a factor of between 1.3 and 2.1 lower than those found in the meals. Based on the average standard deviation, no particular ready meal stood out as being any less or more reproducible than any other. Similar factors, 1.3 to 2.0 fold differences, were found in the mean range data (Table 12.3). There was no clear indication in these data of any consistent difference between the ovens.

In two of the ovens (Y and Z) the minimum temperature in the mashed potato packs after heating was always found in the same position. However, in the third oven (oven X) the minimum temperature was found in eight different thermocouple positions measured by the 'hedgehog'. The minimum temperature position was most variable in the chicken ready meal, ranging from eight different positions in oven Z to 14 in oven X. In the vegetable meal the minimum temperature position was equally variable (seven positions) in all three ovens. The lasagne minimum temperature positions ranged from four (oven Y) which

**Table 12.3** Mean standard deviation (mean SD) and mean range (ºC) at the 20 thermocouple positions

| Oven code | | Chicken | Lasagne | Vegetable | Mashed potato |
|---|---|---|---|---|---|
| X | Mean SD | 5.3 | 5.2 | 6.1 | 3.9 |
| | Mean range | 22.7 | 22.7 | 26.6 | 17.8 |
| Y | Mean SD | 6.1 | 5.0 | 6.2 | 2.9 |
| | Mean range | 24.4 | 22.1 | 26.5 | 13.2 |
| Z | Mean SD | 6.6 | 6.0 | 6.2 | 3.6 |
| | Mean range | 26.2 | 26.0 | 25.9 | 16.0 |

was the least variable of all the meals (excluding mashed potato) to eight different positions (oven Z) which was as variable as the chicken meal in the same oven.

Data from the position that had the lowest temperature on average over the 44 replicates are shown in Table 12.4. At these positions the standard deviations in the mashed potato ranged from 2.7 to 5.0 and were a factor of between 1.1 to 2.5 lower than those found in the meals. At the lowest temperature position no ready meal was consistently more repeatable than any other in all ovens. In oven X the lowest temperature position was towards the base of the centre probe in the three ready meals but towards the base of the probe to the right of centre in the mashed potato. In all four cases in oven Z the lowest temperature position was towards the base of the centre probe. In all four cases in oven Y the lowest temperature position was towards the base of the probe furthest away from the centre of the oven on the right.

The 44 replicated temperatures at each lowest average temperature position for all oven/food combinations were allocated to 5 ºC temperature bands to produce the percentage temperature distributions shown in Figs 12.9, 12.10 and

**Table 12.4** Mean, standard deviation (SD) and range (ºC) at the thermocouple position which has the lowest mean temperature (44 replicates)

| Oven code | | Chicken | Lasagne | Vegetable | Mashed potato |
|---|---|---|---|---|---|
| X | Mean | 78.7 | 71.9 | 68.4 | 69.5 |
| | Position | 2 | 2 | 2 | 10 |
| | SD | 8.4 | 5.7 | 7.2 | 5.0 |
| | Range | 31.0 | 23.3 | 31.0 | 25.3 |
| Y | Mean | 69.8 | 72.5 | 60.9 | 63.1 |
| | Position | 9 | 10 | 10 | 9 |
| | SD | 5.3 | 6.8 | 5.9 | 2.7 |
| | Range | 23.7 | 36.3 | 25.7 | 12.9 |
| Z | Mean | 70.4 | 74.6 | 70.0 | 64.1 |
| | Position | 1 | 2 | 2 | 1 |
| | SD | 7.1 | 4.9 | 6.4 | 3.1 |
| | Range | 28.1 | 26.6 | 26.0 | 14.0 |

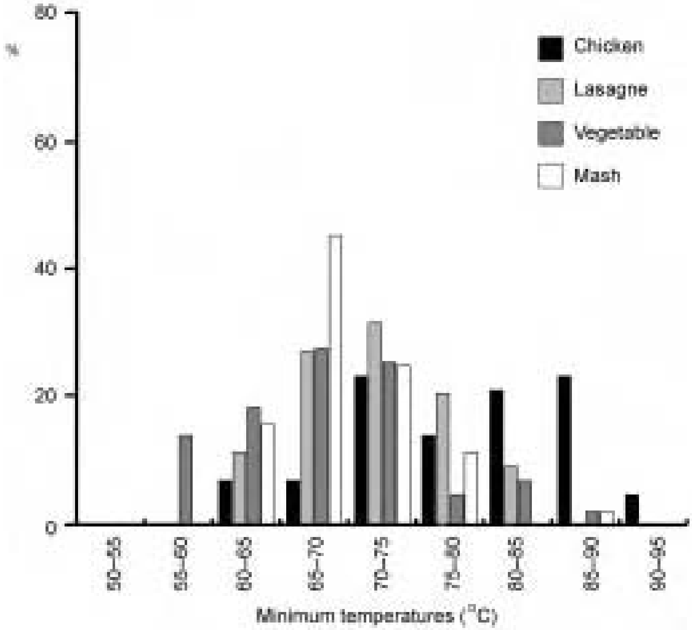


**Fig. 12.9** Distribution of replicated temperatures at mean lowest temperature position (44 replicates) after reheating of three meals and mashed potato in microwave oven X.

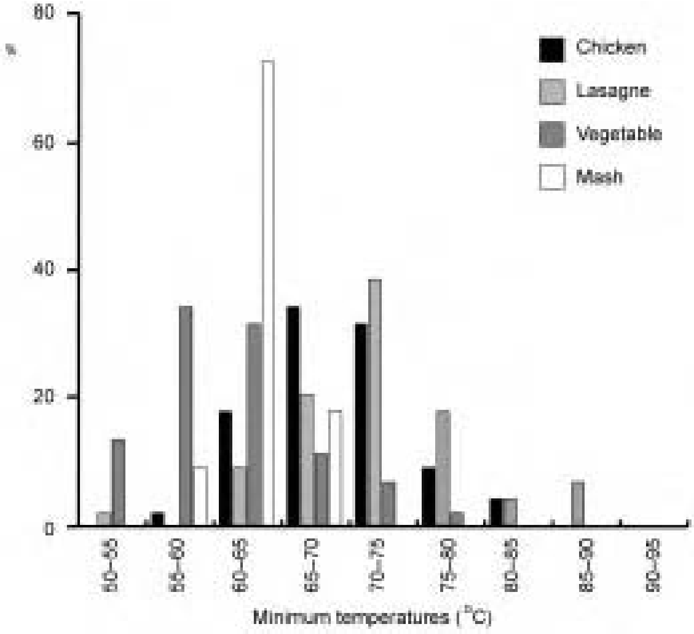


**Fig. 12.10** Distribution of replicated temperatures at mean lowest temperature position (44 replicates) after reheating of three meals and mashed potato in microwave oven Y.

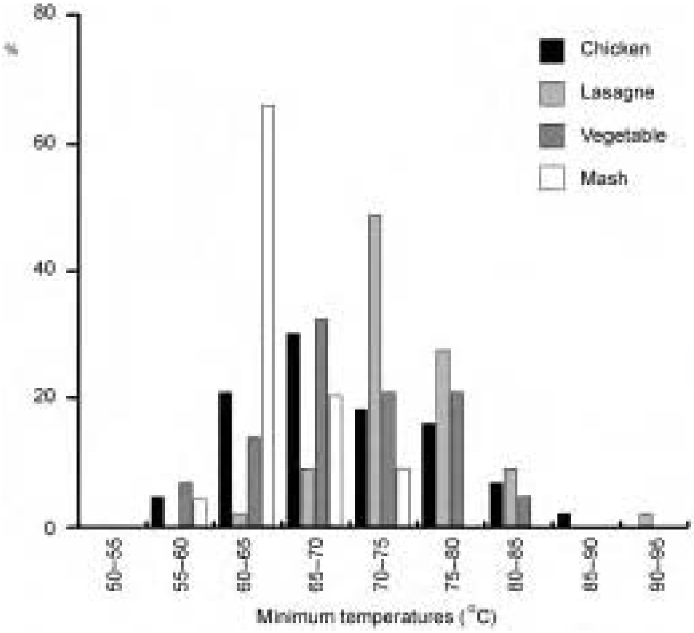


**Fig. 12.11** Distribution of replicated temperatures at mean lowest temperature position (44 replicates) after reheating of three meals and mashed potato in microwave oven Z.

12.11. In all the mashed potato cases the temperature distributions tended to follow a bell-shaped normal distribution and were more compact than those for the ready meals. The chicken and vegetable based meals tended to have an uneven distribution, indicating less repeatability than lasagne at the lowest average temperature position.

## 12.4 Methodology for identifying cooking/reheating procedure

Developing microwave reheating instructions for a food product is not a trivial task. The food manufacturer or testing laboratory will only have a limited time, access to only a small range of ovens and a limited space on the packaging for the instructions. Until the mid-1990s the only information on an oven would be the power delivered into a 1 kg water load. Investigations carried out by George *et al.* (1992) led to an alternative categorisation in the UK which labelled ovens from A to E in five steps based on the power delivered to a 0.35 kg water load (O'Leary, 1993).

When George *et al.* (1995) investigated the results of following manufacturers' heating instructions on chilled and frozen packs of lasagne, they reported that 'the reheating instructions given on the food package failed to deliver a thermal process equivalent to 70 °C for a period of two minutes.' Microwave reheating instructions based on the 0.35 kg power test were developed. These used longer reheating times, rest periods, a 90 ° turn and retention of the film lid (pierced). The reheating instructions had six stages:

1. Leave film lid on, pierce with fork.
2. Heat on full power for half the reheating time stated.
3. Leave product to stand for 2 minutes.
4. Rotate product 90 °.
5. Heat on full power for remainder of reheating time.
6. Leave product to stand for 2 minutes.

Reheating times ranged from 6.25 to 12.75 minutes depending on the product and the oven used, resulting in total heating times from 10.25 to 16.75 minutes for an individual meal.

James (1993) suggested a 14-point plan that, if used to develop reheating guidelines for a convenience meal, would take into account most of the available technology and knowledge:

1. Select a robust (power output little influenced by voltage, load, etc.) oven.
2. Carry out standard 1 kg water load power output test (5 replicates).
3. Carry out 0.35 kg water load power output test with a cold oven (5 replicates).
4. Carry out 0.35 kg water load power output test with a hot oven (5 replicates).
5. Locate hot and cold spots using IEC standard carrageenan-based gel of same weight and in same package as product in hot controlled oven (5 replicates).
6. Obtain reheating curves using fibre optic probes in cold spots [minimum 3] and hot spots [minimum 2] in hot controlled/product oven (10 replicates).
7. Analyse time–temperature curves.
8. Plot distribution of hottest and coldest values at 0.5-minute intervals.
9. Decide on optimum time or decide unsuitable for microwave reheating or repeat 6 to obtain more data and add standing time/stirring, etc.
10. Heat for optimum time, check temperature distribution (using a temperature hedgehog) and quality (10 replicates).
11. Select nine different models of oven with same 0.35 kg output power rating and range of characteristics.
12. Carry out cold and hot 0.35 kg power determinations (5 replicates).
13. Heat for optimum time in each oven and check temperature distribution with hedgehog (10 replicates).
14. Modify optimum time if required.

He suggested that many of the points identified in the protocol would have already been covered during the development of the product being tested. In these cases the whole process could be condensed and carried out in a few days.

In an attempt to help ensure the highest standards of safety and quality for microwave reheated products, the UK Microwave Working Group (made up of representatives from oven and food manufacturers, the UK Ministry of Agriculture, Fisheries and Food, retailers, consultants, academics, trade, research, consumer and standards organisations) developed guidelines (Richardson and Gordon, 1997) for food manufacturers and retailers that set out procedures necessary for the development and verification of reheating instructions for foods intended for use in microwave ovens. The guide also provides advice on the equipment and environment for controlled testing, power output measurement, the UK labelling scheme for ovens and foods, the symbols for use on microwave ovens and food packs, and references to the relevant European standards. It also includes guidance on the assessment of the impact of consumer abuse of the developed instructions in terms of product safety and quality. The verification section of the guidelines is in three stages:

Stage 1 – New product development, which includes establishing the suitability of the product for microwaving.
Stage 2 – Controlled testing, using production samples heated in a minimum of four different microwave ovens ranging in power output. Temperatures are measured in a minimum of six positions after heating, and the maximum and minimum temperatures are recorded. Appearance, taste (if safe minimum temperature has been attained) and texture assessments should be made. Pass/fail criteria are applied, including achieving a minimum process of 70 °C for 2 minutes or equivalent and being of acceptable sensory quality in each oven used. Failure requires modification of the instruction and re-testing.
Stage 3 – Optional abuse testing, to evaluate all factors that may influence the performance of the product when reheated by the consumer. These include the influence of warm ovens, storage temperature, mains supply voltage, overweight product, meal component layout/ratio, failure to follow instructions accurately, and variability in oven timers.

## 12.5 Determining the heating performance characteristics of microwave ovens

At the time of writing, the only performance-related information provided to the consumer purchasing a microwave oven is the power output measured using a standard 1 kg water load, which provides little information about how well the oven actually heats such a food product as a chilled convenience meal. In the UK, a categorisation letter (A to E) corresponding to the power output into a 0.35 kg water load is also stated. This goes some way towards informing the consumer how much power is available to heat a smaller food load, but does not give any indication about how well that power is distributed within the food. For example, two ovens having an identical power output may heat the same type of food load very differently; one may be prone to produce unacceptable ‘cold spots’ whereas the other may achieve a more satisfactory uniform temperature distribution.

Swain *et al.* (1998) proposed a test procedure to determine specifically the heating performance of domestic microwave ovens when heating chilled convenience meals. The procedure uses standard test loads that simulate the heating and weight loss characteristics of chilled convenience food. It aimed to be reproducible, relate to consumer use, ensure that the test load attained specified minimum temperatures for food safety, provide a measure of consumer acceptability, and be equally applicable to all types of domestic microwave oven. In order to carry out tests that met all the stated requirements, it was necessary to replace foods having inherent biological variability with a heating test load that had reproducible behaviour. Swain *et al.* (2004) carried out an extensive literature search to identify potential food simulant materials that could be used to mimic heating responses of chilled foods heated in microwave fields (Table 12.5). Each prospective food simulant material was initially assessed against a set of criteria that included ease of manufacture, stability and formability. More recently a model food was developed specifically for microwave vacuum drying by Knoerzer *et al.* (2004) which was composed of water, fructose, NaCl, $CuSO_4$, cellulose, agar-agar and starch.

Tests on a range of chilled convenience meals available in the UK, using continuous fibre-optic temperature measurement during heating, indicated that

**Table 12.5** Some of the materials proposed for simulants

| Material name | Use |
|---|---|
| Bentonite (bentonite + glycerin) | Thermal sterilisation in cans |
| EWSG/Gellan gum | Muscle phantom |
| EPG (ethylene glycol + polyethylene powder) | Fat phatom |
| Gelatine | Gelling agent |
| Sodium alginate | Gelling agent |
| Hydrophilic organic polymer (TX151) | Muscle phantom |
| Laponite | Synthetic clay |
| Carbopol | Ohmic heating test liquid |
| SIK gel (carrageenan, sugar, glycerol) | Food simulant |
| SIK liquid (sugar, glycerol) | Liquid food simulant |
| IEC batter (wheat flour, eggs, sugar) | Test batter |
| Bacto agar | Gelling agent |
| Polyvinyl alcohol + sodium borate solution | Crosslinked gel |
| Gellan gum | Gelling agent |
| Whey protein | Gelling agent |
| Starch solutions (soup analogues) | Soup simulant |
| Biogel (methylmethacrylate *n*-vinyl-2-pyrolidone) | Hydrophilic food simulant |
| Plasticine | Modelling material |
| PVA + Dimethylsulphoxide | Gel |
| Tylose (hydroxyethylmethylcellulose) | Meat thermal simulant |
| Carboxymethylcellulose | Cellulose gum |
| Glycol + cellulose | Cellulose based material |
| Glucomannan | Gelling agent (foam) |
| Mashed potato | Fast food test simulant |
| Polyacrylamide + polyacrylic acid | Hydrogel |

the meals could be separated into two broad categories according to heating times, i.e. 'slow' and 'fast' response. Food simulants were developed to represent the two food categories. A good match between food simulant and meal was achieved for the main indicators, i.e. temperatures at central and intermediate locations and weight loss. A close match (a difference of 2% between food simulant and meal) was achieved for the centre location, which is important, as this is often the coolest area in the meal after heating in domestic microwave ovens.

A food simulant made from TX151 (Oil Center Research International, Lafayette, Louisiana, USA), a hydrophilic polymer, in a TX151 : NaCl:$H_2O$ ratio of 22.2 : 0.7 : 77.1 by weight was the best match to a 'slow' heating chilled convenience meal like lasagne. A simulant made up using Carbopol (BF Goodrich Performance Materials, Cleveland, Ohio, USA), a cross-linked polyacrylic acid copolymer, in a Carbopol : polyethylene:$H_2O$ ratio of 10 : 10 : 80 by weight was the best match to a 'fast' heating chilled food like rice. The manufacture of the simulants only required the use of standard test kitchen equipment (e.g. standard liquidiser, bowl mixer, refrigerator). Both food simulants have the advantage that their heating characteristics can be modified by changing these ratios to match other food products.

The simulants were placed into three different types of microwaveable food trays (rectangular, two compartment and four compartment) to provide three alternative simulant/packaging combinations to represent the range available. The most commonly available meal was represented by the rectangular crystalline polyethylene terephthalate (CPET) tray (external dimensions 156 × 111 × 35 mm) containing 0.35 kg of the TX151 based 'slow' heating food simulant.

Figure 12.12 shows a flowchart that outlines the sequence of events required to carry out the test procedure. The temperature distribution after heating from 5 °C to a defined minimum temperature (72 °C) was measured in the food simulant using a specially designed multipoint thermocouple 'hedgehog' probe consisting of 39 fine hypodermic stainless steel sheathed type 'T' thermocouples. The sensors were arranged in a matrix of four discrete layers, with the spacing set to best determine the areas of likely 'hot' and 'cold' spots, provide an indication of the degree of edge overheating and the evenness of energy distribution. The probes were secured to a flat rigid plate which was able to slide up and down on vertical rods. To measure temperatures post heating, the test load was placed horizontally in a locating fixture, and the horizontal plate with the probes attached (protruding vertically downwards) was quickly and accurately lowered into the food simulant.

The weight of the food simulant was recorded before and after heating and used as an indicator of product deterioration. The greater the weight lost after heating to a minimum temperature of 72 °C, the greater the likelihood of irreversible degradation. A relatively small weight loss (<5%) would indicate that the consumer would be unlikely to notice any quality degradation. With product weight loss above approximately 15% the consumer would notice excessive shrinkage, with edges of the product dried out and in extreme cases

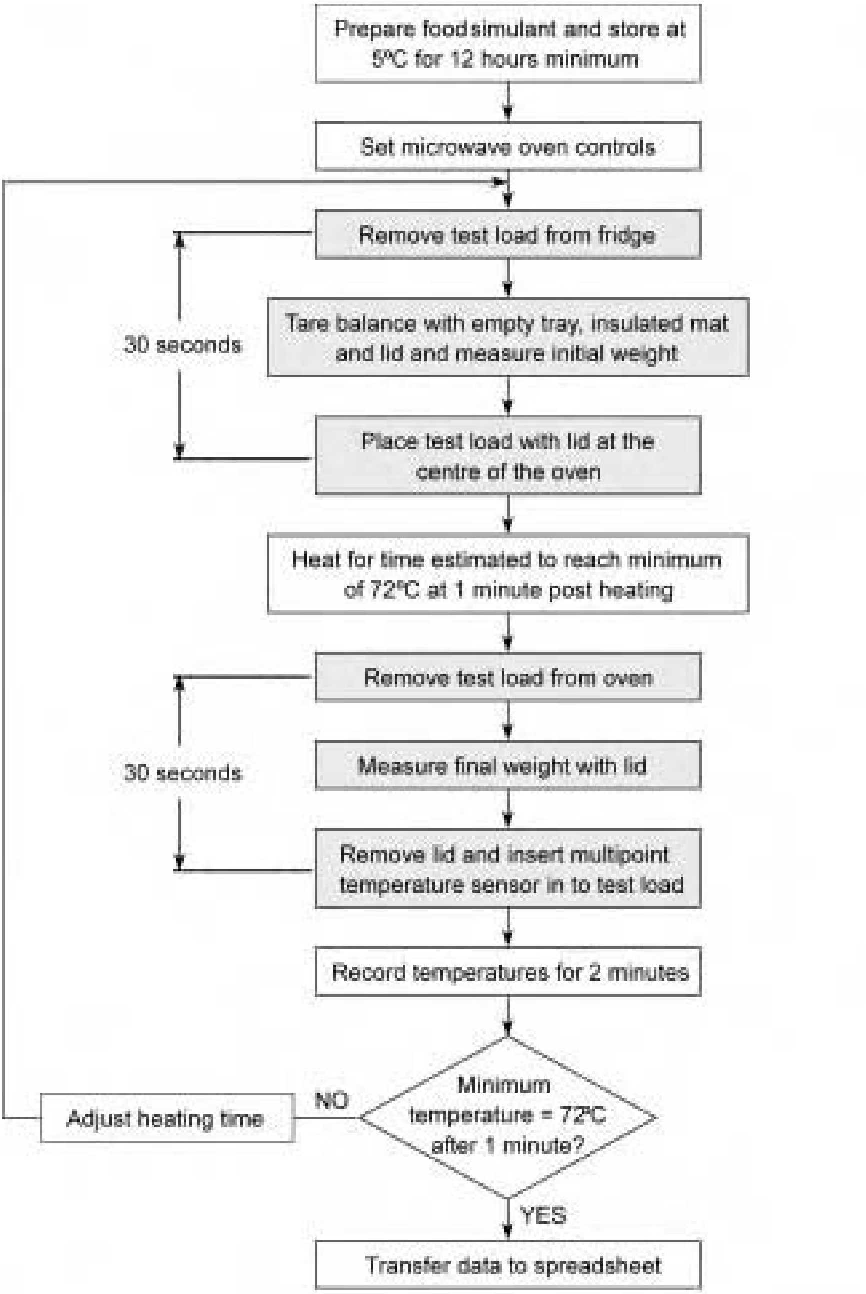


**Fig. 12.12** Flowchart of the sequence of events required to carry out the test procedure to determine the heating performance of microwave ovens.

evidence of burning or charing. The TX151 based simulant mimicked these quality deterioration effects.

The simulant load temperatures at 60 and 120 seconds post heating, weight loss, heating time and power output data were entered onto a spreadsheet template which automatically analysed the data. The tester could choose to view the detailed analysis, which evaluated such characteristics as evenness of heating; top to bottom, side to side and front to back heating balance; edge overheating; and average rate of heating or a simplified analysis based on a scoring system of oven performance. A '3-D' plot representing the temperature distribution within the food simulant load after heating was also automatically produced. This test has subsequently been adopted for comparative consumer testing of domestic microwave ovens.

James *et al.* (2002) stated that 'many of the tests currently used to assess the reheating of a foodstuff in microwave ovens are either subjective, or use commercially produced chilled meals.' Previous studies have clearly shown that there is considerable variability between individual packs of the same commercial product. Consequently when using commercial packs there is a considerable degree of uncertainty whether differences in performance between ovens are true differences, not artefacts caused by pack to pack variability. Additionally, it is difficult to compare current tests with those carried out in previous years due to changes in commercial production and in some cases the unavailability of some of the meals previously used.

The authors developed a simple procedure for comparing the three most important reheating characteristics of a domestic microwave oven – its 'true' power, temperature variability and repeatability. The 'true' power being absorbed by the food governs the reheating time. The temperature variations within the food after reheating control the safety and quality of the food. An oven's repeatability shows its ability to produce the same performance on subsequent occasions and hence reliably produce an identical product.

The procedure required two simply prepared test materials made up from readily available chemically consistent raw materials. Samples were prepared using a simple protocol in the type of packs commonly used for commercial ready meals. The only addition was an easily manufactured PTFE frame, which divided the pack into 12 compartments. Three identical tests, one with the liquid test material, the second with the solid and the third with a combination, were required to perform the whole procedure. It was recommended that each be replicated a minimum of five times. One additional stage was carried out with the liquid test material.

The data produced in each replicated test was reduced to three numbers that were measures of the true power, variability and repeatability of the oven. Further simple analysis, which weighted the relative importance of each factor to the consumer, produced a single value for the oven's relative reheating performance. Any simple spreadsheet program could reduce the 195 individual pieces of temperature data gathered in the total procedure to a measure of oven performance.

## 12.6 Conclusions and future trends

It is clear that many factors relating to the design and operation of a microwave oven and the product being heated affect the temperatures reached in the product, their uniformity and their repeatability. Current standard methods of assessing microwave power provide limited information for the food manufacturers developing heating instructions for chilled and frozen foods.

Although reproducible methods in addition to the standard methods of testing the performance of domestic microwave ovens have been developed for specific products (e.g. chilled convenience meals) their uptake has been mostly limited to consumer test and academic research laboratories. Further methods of testing need to be developed (and greater use made of them) to provide reliable data to assess both the oven itself and the suitability of foods for safe heating.

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# 13

# Measuring temperature distributions during microwave processing

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## 13.1 Introduction

Microwave ovens are commonplace in households and are established there as devices of everyday use. Unfortunately in industry the distribution of microwave processes is still sparsely spread. Reasons for this fact are for example the conservatism of the food industry (Decareau, 1985), the lack of simulating microwave processes and the relatively low research budgets.

In many food manufacturing processes, microwave heating has been proposed as an alternative to traditional heating methods for several decades. Examples are (re)heating, baking, (pre)cooking, tempering of frozen food, blanching, pasteurization, sterilization and dehydration. For a complete survey see Decareau (1985), Metaxas and Meredith (1983), Metaxas (1996), Roussy and Pearce (1995), Buffler (1993), various authors (1986) and other chapters of this book. Although their objectives differ, the aims are established in similar means: an increase of temperature.

Where the process has a preservation function, as in drying (Chapter 8), pasteurization and sterilization, it is very important to reach a minimum time–temperature treatment or a minimum water content and thus a minimum water activity for assurance of microbial safety. In other processes temperatures have to remain below certain values for achieving a desired product quality (Chapters 5 and 10) with maximum preservation of colour, flavour, etc.

In traditional heating and drying methods heat transfer is mostly limited by heat conduction and so it is usually simple to identify locations of slowest heating or drying. This fact could lead to overheating near surface regions and thus microwave heating, as a volumetric heating method, is proposed to improve product quality. Unfortunately, there are a number of well-known microwave specific factors that cause a non-uniform heating pattern, e.g. focusing effects, corner and edge heating, inhomogeneous electromagnetic field, and especially the shape and composition of the heated material (see Chapter 15). As a consequence heating patterns can differ significantly from one product to another and thus in industrial microwave processes the quality and safety of the products are compromised (Mudgett, 1986). It is largely for this reason that microwave processes have not been widely adopted in the food industry. So for optimizing microwave processes and controlling already applied ones it is indispensable to know the three-dimensional temperature distributions of the heated products.

## 13.2 Methods of measuring temperature distributions

Up to now there have been several methods of determining temperature distributions, such as thermocouples, fibre optic thermometers, the use of model substances, infrared (IR) thermography, liquid crystal foils, thermo paper, microwave radiometry and the use of magnetic resonance imaging (MRI). Unfortunately many of these methods have great disadvantages:

### 13.2.1 Thermocouples

Without enormous efforts normal thermocouples cannot be used in microwave devices, since the intense electromagnetic fields which cause heating also disturb the operation of these conventional temperature probes. Furthermore, these probes contain metallic wires and cause unacceptable disturbance of the fields, leading to overheating and possible arcing and destruction of the device, as well as damage to the product. Moreover the method is invasive and only a poor spatial resolution is achievable.

### 13.2.2 Fibre optic probes

While the use of fibre optic sensors avoids the problem of a strong interaction with the electromagnetic field, the spatial resolution attainable is often not sufficient. Furthermore, fibre optic thermometers are rather delicate and expensive in comparison to conventional thermocouples and must be placed in contact with the product to be measured.

### 13.2.3 Model substances

A different approach to determine temperature distributions in microwave devices is the use of model substances that change their properties (e.g. colour, pH value, structure, etc.) after reaching a certain temperature. One published method uses the colour change of the model substance (Risman *et al.*, 1993); another uses a coagulation effect of contained proteins (Wilhelm and Satterlee, 1971). Care has to be taken to match the other important physical properties of the model (e.g. dielectric and thermal properties) to the real product.

### 13.2.4 Infrared thermography

Infrared thermography provides very good local resolutions and is established for measuring surface temperatures. Even online the infrared sensors provide a reasonably accurate readout of the surface temperature of an object that is in the sensor's field of view. However, in common with conventional contact probes, infrared sensors are metallic and cannot be placed inside the electromagnetic fields of a microwave heating assembly. Furthermore, most measurements have to be done through a shield window because the sensitive electronics inside the infrared sensors require extensive electromagnetic shielding to allow accurate measurements in the presence of electromagnetic (EM) fields. Thus, the efficiency and accuracy of the temperature measurement, which in any case represents only the surface temperature of one part of the heated product, are reduced.

### 13.2.5 Microwave radiometry

The principle and thus the assets of microwave radiometry are similar to those of infrared thermography (Stephan, 2004), except that the thermal energy detected and used as basis for temperature estimation is in the microwave frequency range rather than the infrared region. As the penetration depth of radiation in the microwave frequency range is much higher than in the IR frequency range, internal temperatures not too far away from the surface can also be observed. But again, especially in volumetric heating methods like microwave heating, the measuring of surface or near-surface temperatures is not sufficient. For information about the whole internal temperature distributions the product has to be destroyed.

### 13.2.6 Liquid crystal foils and thermo paper

Liquid crystal foils and thermo paper are also established methods for measuring temperature distributions (Grünewald and Rudolf, 1981; Feher, 1997). But both methods also provide only surface temperature mapping. Furthermore the use of thermo paper only conveys information about the temperature being above or below a certain threshold.

### 13.2.7 Magnetic resonance imaging (MRI)

By using magnetic resonance imaging as a tool for temperature measurement, almost all the above-mentioned problems can be avoided (Nott *et al.*, 2000;

Knoerzer *et al.*, 2004a). MRI allows a non-invasive three-dimensional measurement of temperature distributions even inline, meaning that the probe does not have to be in contact with the product, the product does not have to be destroyed for information about internal temperature measurements, every wet product can be observed during or after microwave heating, good spatial resolutions can be achieved, and not only surface temperatures but also inner temperature distributions can be measured. The large drawback of this technique is that the costs for an MRI tomograph exceed the costs for all devices mentioned above by orders of magnitude.

## 13.3 Physical principles of different temperature mapping methods

### 13.3.1 Thermocouples

Thermocouples are fabricated from two electrical conductors made of two different metal alloys. The conductors are typically built into a cable having a heat-resistant sheath, often with an integral shield conductor. At one end of the cable, the two conductors are electrically shorted together. This end of the thermocouple – the hot junction – is thermally attached to the object to be measured. The other end – the cold junction, sometimes called the reference junction – is connected to a measurement system. The objective, of course, is to determine the temperature near the hot junction. It should be noted that the 'hot' junction, which is somewhat of a misnomer, may in fact be at a temperature lower than that of the reference junction if low temperatures are being measured.

Thermocouples generate an open-circuit voltage, called the Seebeck effect or Seebeck voltage, discovered in 1821 (Seebeck, 1823), that is proportional to the temperature difference between the hot and reference junctions:

$$\Delta V = S(T_{\text{hot}} - T_{\text{ref}}) \qquad [13.1]$$

where:

$\Delta V$ = change in voltage
$S$ = Seebeck coefficient (dependent on the thermocouple's metal composition)
$T_{\text{hot}}$ = temperature at hot junction (K)
$T_{\text{ref}}$ = temperature at cold/reference junction (K)

Since thermocouple voltage is a function of the temperature difference between junctions, it is necessary to know both voltage and reference junction temperature in order to determine the temperature at the hot junction. Consequently, a thermocouple measurement system must either measure the reference junction temperature or control it to maintain it at a fixed, known temperature. Figure 13.1 shows the sketch of a thermocouple junction formed by joining two metallic alloys, A and B. Figure 13.2 shows standard commercial thermocouples.

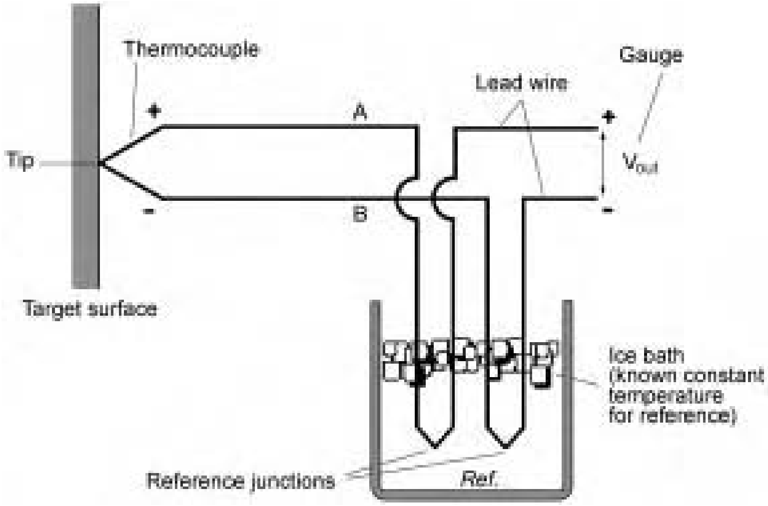

**Fig. 13.1** Sketch of thermocouple junction (efunda, 2004).

**Fig. 13.2** Standard industrial commercial thermocouples (Globalspec, 2004).

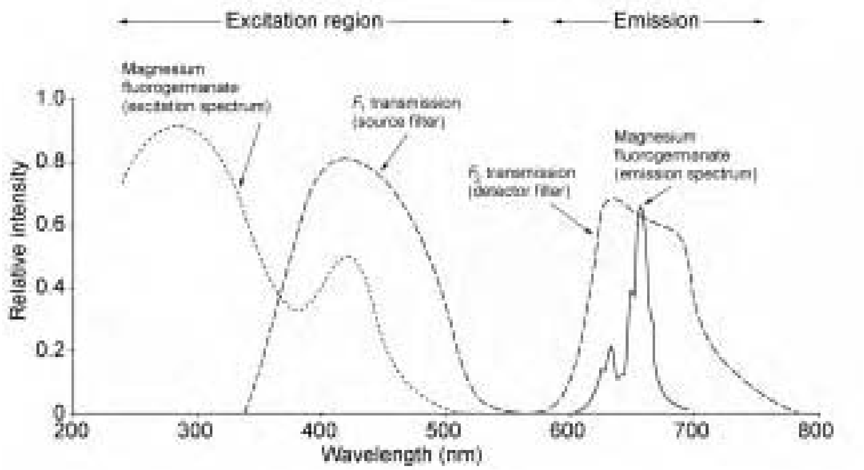

**Fig. 13.3** Room temperature spectrum of magnesium fluorogermanate. Dashed lines showing passbands of source and detector filters (Luxtron, 1992).

### 13.3.2 Fibre optic probes

The basis of the fibre optic thermometry used in general is the temperature dependent photoluminescence of optical excited phosphors. The key element of fibre optic probes is the sensor consisting, for example, of a small amount of manganese-activated magnesium fluorogermanate mounted at the tip of the optical fibre working in a temperature range from −200 °C up to +450 °C. When the sensor material is excited with blue-violet light, the phosphor exhibits a deep

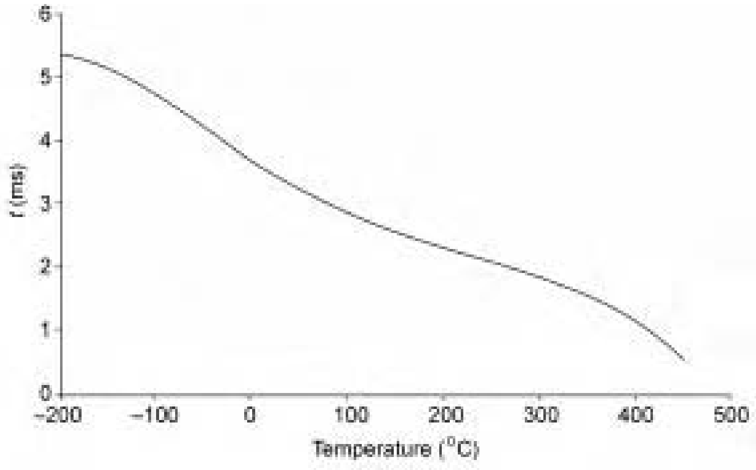

**Fig. 13.4** Fluorescent decay time of the magnesium fluorogermanate phosphor as a function of temperature (Luxtron, 1992).

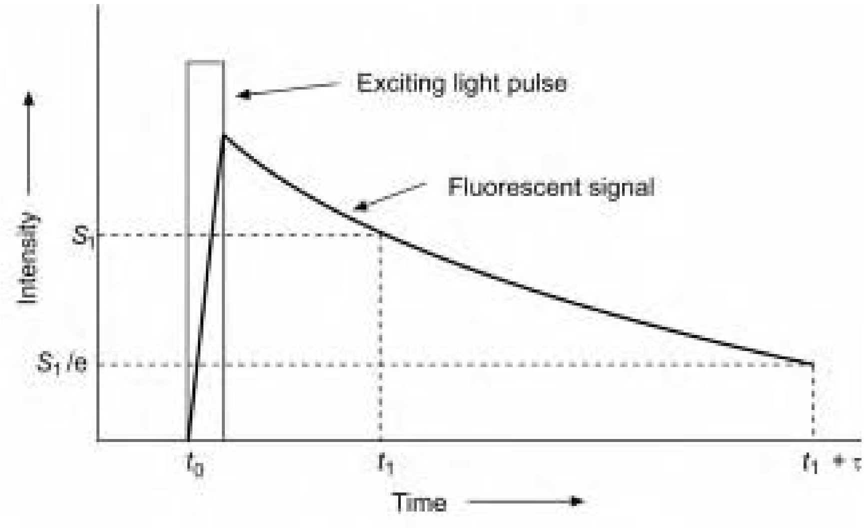

**Fig. 13.5** A schematic representation of the method used to extract the fluorescent decay time of the phosphor sensor (Luxtron, 1992).

red fluorescence. Figure 13.3 shows the spectrum of this material. A pulse of blue-violet light to excite the phosphor to fluorescence is provided by a filtered xenon flashlamp.

After the activation pulse is over, the intensity of fluorescent radiation decays exponentially. After a certain time $t_1$ the signal $S_1$ is measured and the time $t_1 + \tau$ is determined where the signal decayed to $S_1$/e. The actual phosphor temperature can be correlated with a digital look-up table (see Fig. 13.4). The method for measurement of the decay time is shown schematically in Fig. 13.5. A sketch of a fibre optic device is shown in Fig. 13.6.

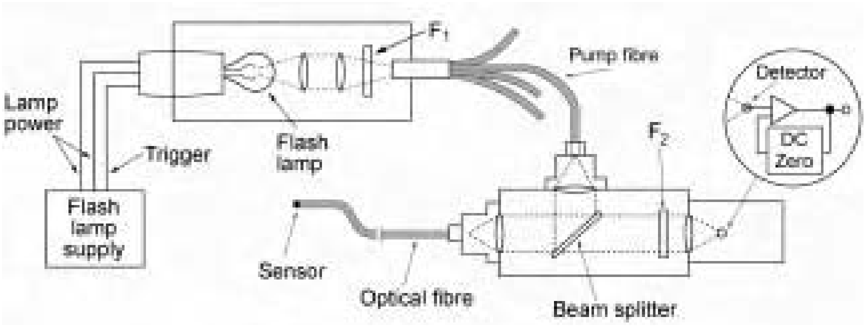

**Fig. 13.6** Cross-sectional view of Luxtron's model 755 (Luxtron, 1992).

### 13.3.3 Model substances

Model substances must represent foods, but only with regard to certain properties. For microwave heating scenarios it is sometimes sufficient that only the dielectric properties (permittivity $\epsilon'$ and loss factor $\epsilon''$) are representative for those of the food, in a certain temperature interval and at a frequency of 2.45 GHz (Risman *et al.*, 1993). But often (especially at lower microwave powers or longer heating times) it is also indispensable that the thermal conductivity and the heat capacity of the model food also fit the values of real foodstuff.

The following factors can be temperature dependent and have been used for temperature mapping (Risman *et al.*, 1993):

- texture (or viscosity)
- optical transparency
- melting temperature
- coagulation or solidification
- colour change (e.g. by changing the pH value with added indicator).

Often gels are used, because they are easy to cut and mould to an exact shape. Colour change over small temperature intervals of optically transparent gel helps to determine hot or cold spot areas. Also melting or coagulation of model foods can indicate temperature changes (Risman *et al.*, 1993).

### 13.3.4 Infrared (IR) thermography

All objects (especially hot ones) emit thermal radiation that is in the visible and even the ultraviolet portion of the EM spectrum as well as the infrared, e.g. an incandescent light bulb or the sun. Furthermore, every object at temperatures above absolute zero (0 K or −273.15 °C) emits electromagnetic radiation, the so-called thermal radiation, for ambient temperatures much in the infrared portion of the EM spectrum. The reasons for this radiation are vibrating atoms and molecules behaving like Hertz dipoles emitting electromagnetic waves. The frequency of the corpuscle vibration and thus the intensity of the EM radiation increase with increasing temperature. Planck's radiation law (eqns 13.2a and 13.2b) describes the radiation intensity at one discrete frequency:

$$I(\nu)\mathrm{d}\nu\mathrm{d}\Omega = \frac{2h\nu^3}{c^2}\cdot\frac{1}{\mathrm{e}^{h\nu/kT}-1}\mathrm{d}\nu\mathrm{d}\Omega \tag{13.2a}$$

$$I(\lambda)\mathrm{d}\lambda\mathrm{d}\Omega = \frac{2hc^2}{\lambda^2}\cdot\frac{1}{\mathrm{e}^{hc/\lambda kT}-1}\mathrm{d}\lambda\mathrm{d}\Omega \tag{13.2b}$$

where:

$k$ = Boltzmann constant
$T$ = absolute temperature (K)
$h$ = Planck's constant
$c$ = speed of light (m/s)

$\lambda$ = wavelength (m)
$\nu$ = frequency (Hz)
$\Omega$ = solid angle element

Stefan-Boltzmann's law (eqn 13.3) describes the total energy emitted by a black body integrated over all wavelengths. It is directly proportional to $T$ to the power of 4:

$$I = \frac{2k^4T^4}{h^3c^2} \cdot \int_0^\infty \frac{x^3}{(e^x - 1)} dx = \frac{2k^4\pi^4}{15h^3c^2} T^4 = \sigma T^4 \quad \text{with} \quad x = \frac{hc}{k\lambda T} \qquad [13.3]$$

where:
$I$ = intensity of radiation (W/m$^{2)}$
$\sigma$ = Stefan–Boltzmann constant

For real foods, Stefan–Boltzmann's law has to be extended with an efficiency factor $\epsilon$ (eqn 13.4):

$$I = \epsilon\sigma T^4 \qquad [13.4]$$

where $\epsilon$ is the emission coefficient, which has to be known for the studied material, but is close to 1 for many food substances.

What is invisible to humans, particularly when only thermal infrared is present, can be 'seen' by a thermal imager (see Fig. 13.7), or more precisely, a thermal imaging camera. A thermographic recording camera can be constructed in two different ways:

- First-generation IR systems from the mid 1960s up to the early 1990s included a lens and moving mirrors or prisms that scan the image, focusing the heat rays on *one* infrared sensor. The scan moves over the subject area in a television-like pattern. These mechanical scanning devices increased the size of the system as well as their weight and power consumption. Also, because of this mechanical scanning system the thermal sensitivity is compromised.
- From the beginning of the 1990s the thermographic systems evolved and matured and a new detector technology, the so-called focal plane array

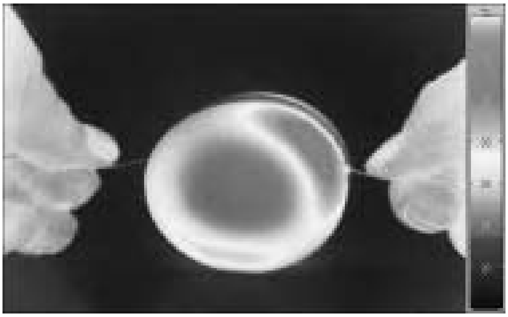

**Fig. 13.7** IR image of slicing of a heated model food cylinder.

(FPA), was introduced. This FPA is an IR detector that incorporates rows and columns of individual sensors, eliminating the requirement for scanning systems. An FPA system usually utilizes a 256 × 256 (even up to 720 × 480) infrared detector with more than 65 000 infrared sensors. This was a great improvement on the scanning systems with only one IR sensor. Furthermore, the new system allows camera size to be significantly reduced.

The basis of both systems is the same: from the measured radiation pattern the actual temperatures can be calculated.

In general, commercial infrared cameras integrally detect a certain bandwidth of the radiation emitted by the observed object (approximately $1\,\mu\text{m} < \lambda \leq 6\,\mu\text{m}$) according to Planck's radiation law (see eqn 13.2), and the temperature is calculated from the calibration curve of the camera manufacturer.

### 13.3.5 Microwave radiometry (MWR)

Microwave radiometry allows one to measure the power in the microwave region of the thermal radiation of heated food. In analogy to IR thermography, it is possible to observe brightness temperatures of the sample. The brightness temperature is:

$$T_{B,i} = \frac{P_i}{k \cdot Df_i} = (1 - R_i)\frac{P_{\text{sample}}}{k \cdot Df_i} = (1 - R_i)T_{B,\text{sample}} \qquad [13.5]$$

where:

$P_{\text{sample}}$ = thermal radiation power emitted by the sample (W)
$P_i$ = power received by the antenna in a bandwidth $Df_i$ around a centre frequency $f_i$ (W)
$R_i$ = power reflection coefficient at the skin–antenna interface at $f_i$
$k$ = Boltzmann constant

According to the Rayleigh–Jeans law (an approximation of Planck's law (eqns 13.2) for large frequencies), at microwave frequencies the thermal radiation intensity is proportional to the absolute temperature and thus

$$T_{B,i} = \int_{\text{afv}} W_i(r) \cdot T(r) \cdot \mathrm{d}\nu \qquad [13.6]$$

where:

$T(r)$ = absolute temperature in an incremental sample of volume $\mathrm{d}\nu$ located at $r$ (K)
$W_i(r)$ = radiometric weighting function
afv = antenna's field of view

Thus the measured brightness temperature $T_{B,\text{meas},i} = T_{B,\text{sample},i} = (\int_{\text{afv}} W_i(r) \cdot T(r) \cdot d\nu)/(1 - R_i)$ and, in general, is dependent upon:

- The actual temperature distribution throughout the samples viewed.
- The receiving antenna's weighting function, which in turn depends upon its

operating frequency, dimensions, the permittivity of the material with which it is filled and the microwave attenuating properties of the samples.

- Microwave reflections occurring at interfaces between different sample regions and between these regions and the measuring equipment.

Since the attenuation of microwaves in samples and the antenna characteristics are frequency dependent, the temperature–depth profile within the sample beneath the antenna can be found using a multifrequency radiometer, and a stable solution to the inverse problem of retrieving the temperature–depth dependence from a set of $T_{B,\mathrm{meas},i}$. Internal temperature at depths of up to 4 cm or more in samples may be obtained using multi-frequency MWR (Hand *et al.*, 2000).

### 13.3.6 Liquid crystal foils

Liquid crystal is a unique substance, which exists between the solid and the isotropic–liquid phase of some organic compounds. It scatters incident light very selectively. The theory behind its optical characteristics involves the behaviour of the molecular structure. Each liquid crystal compound possesses a helical structure with a characteristic pitch length. The helix pitch lengths are in the range of the wavelength of visible light. The pitch length can be altered by changing the external stimulus, typically temperature or shear stress. Since the fundamental chemical structure is unaffected by the external stimulus, a liquid crystal coating can respond repeatedly to the same physical changes. There are two families of liquid crystal materials, which have the helical structure. These are chiral-nematic and cholesteric.

The event temperature and clearing point temperature are used to describe the properties of liquid crystals. The lowest temperature at which liquid crystals scatter visible light is called the event temperature. At a temperature below the liquid crystal's event temperature, the liquid crystal will be in the solid state and will appear transparent. At a temperature above the clearing point temperature, it will enter the pure liquid state and will revert back to being transparent. At the clearing point temperature, the helical pitch of the liquid crystal exceeds the wavelengths of visible light. The reflected colour spectrum of liquid crystals varies continuously from the longer wavelengths (i.e., red) corresponding to event temperature to shorter wavelengths (i.e., blue) corresponding to clearing point temperature (see Fig. 13.8). Liquid crystals transmit a significant amount of the incident light with virtually no modification.

Therefore they are viewed against a non-reflecting, i.e. black, background. This prevents the transmitted light from getting reflected without adversely affecting the interpretation of selectively scattered light from the liquid crystals. (Liquid crystals show a similar response when subjected to an external shear stress.)

A colour/temperature designator describes the response of a typical liquid crystal chemical make-up. This helps in selecting the liquid crystal composition

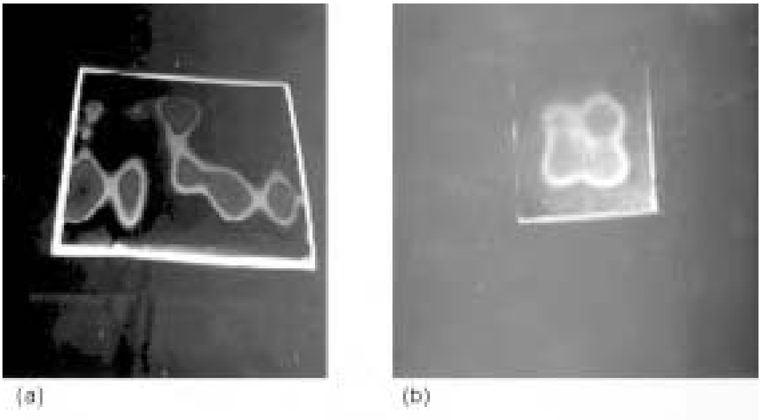

**Fig. 13.8** (a) Temperature distribution at the bottom of an empty microwave oven after introducing power; (b) surface temperature distribution of a microwave heated cube. Both determined by liquid crystal foils.

(called the formulation) for a particular application. For example, 'R35C5W' designates a formulation which signifies that the red start or event temperature of the liquid crystal is 35 ºC and the blue start temperature is 5 ºC above the red start temperature. This provides a crude estimate of the bandwidth of liquid crystals. The liquid crystals can be either narrowband or wideband formulations. The narrowband formulations have bandwidths below 1 or 2 ºC while wideband formulations have bandwidths between 5 ºC and 30 ºC (Panigrahi, 2000).

### 13.3.7 Thermo paper

The basis of using thermo paper as a temperature indicator is its special coating. The active slice of the thermo paper contains temperature sensitive chemicals, the so-called colour developer, that starts to melt after reaching a certain temperature and change their appearance from transparent to black (see Fig. 13.9).

Generally, the thermo paper consists of three different slices (see Fig. 13.10):

- The relatively thin basis paper, with a specific weight of 41.5 $g/m^2$ (compared with the specific weight of normal paper of 80 $g/m^2$; the Z-slice and thermo active slice together have a specific weight of 11.5 $g/m^2$).
- The thermo active slice, with a thickness of approximately 5 $\mu$m, containing thermosensitive chemicals and additional ingredients, e.g. against static electrical charge, durability, UV-resistance, etc.
- The Z-slice as an isolating slice between the basis paper and the thermo active slice, containing isolating pigments and/or polymers.

Commercial thermolabels are formulated to react within a few seconds when the rated temperature is reached. Various single and multi-temperature labels have ratings falling within an overall temperature range from 32 ºC to 260 ºC. As each

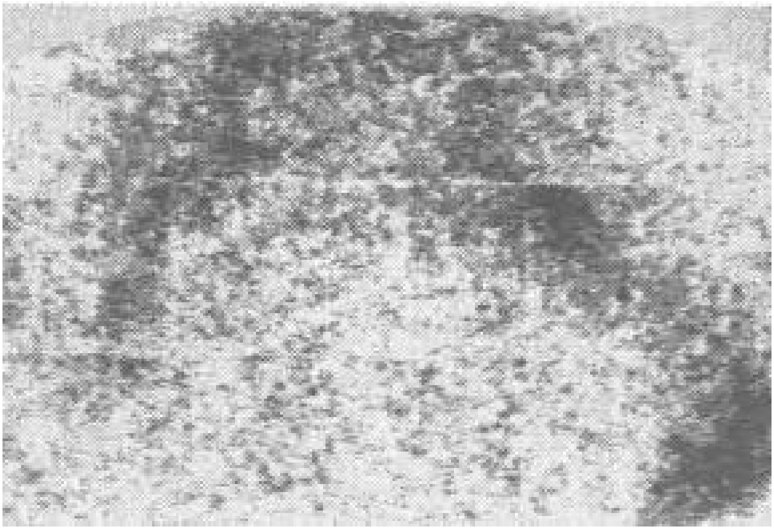

**Fig. 13.9** Typical appearance of a heated thermo paper (black regions are above a certain temperature, white regions below) (Feher, 1997).

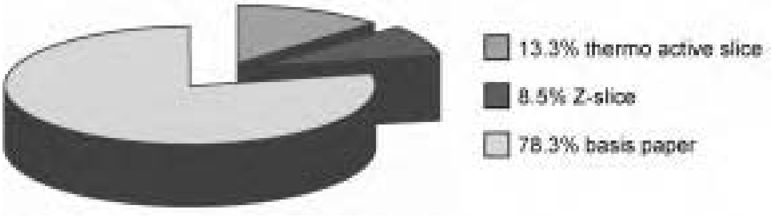

**Fig. 13.10** Composition of thermo paper (percentage referred to the thickness of the thermo paper) (Umweltberatung Bayern, 1997).

section of a label reaches its rated temperature, that section responds with a sharply defined colour change from white to black.

### 13.3.8 Magnetic resonance imaging (MRI)

Many protons (like $^1$H, the hydrogen proton) have a nucleus spin and thus a magnetic moment $\mu$ (see Fig. 13.11). Bringing the non-arranged magnetic moments (see Fig. 13.12(a)) in a magnetic field $B_0$ (see Fig. 13.12(b)) causes an alignment in parallel or antiparallel orientation according to the external magnetic field, and as a result causes the magnetization $M$ (see Fig. 13.12(c)).

$$\vec{\mu} = \gamma \cdot \vec{I} \qquad [13.7]$$

$$\vec{M} = \sum \vec{\mu} \qquad [13.8]$$

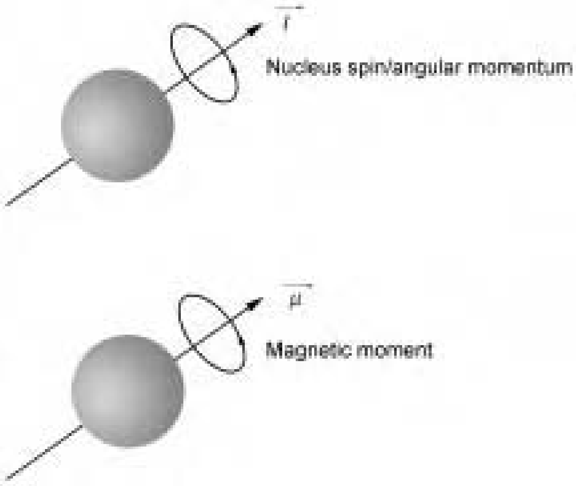

**Fig. 13.11** Nucleus spin and magnetic moment of the hydrogen proton.

where:

$\mu$ = magnetic moment
$\gamma$ = gyromagnetic relation (constant for $^1$H)
$I$ = angular momentum
$M$ = magnetization

If a radio frequency (RF) pulse is applied by a surrounding radio frequency coil, the alignment of the magnetization $M$ can be inverted in the $XY$ plane and thereby brought into phase (see Fig. 13.13).

After switching in the $XY$ plane the external magnetic field causes a precession of the magnetization $M$ with the so-called Larmor frequency:

$$\omega_L = \gamma \cdot B_0 \qquad [13.9]$$

where:

$\omega_L$ = Larmor frequency in $s^{-1}$
$B_0$ = external magnetic field in $T$

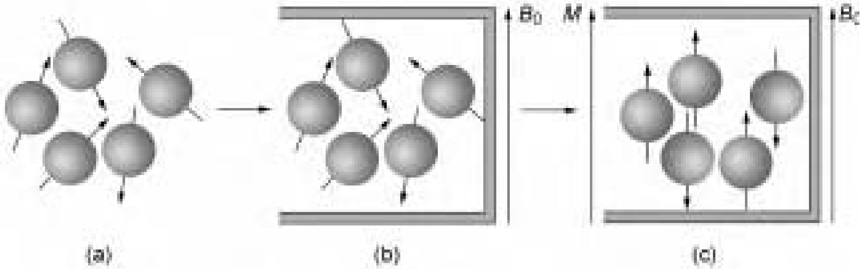

**Fig. 13.12** (a) Non-arranged magnetic moments; (b) brought into an external magnetic field $B_0$; (c) alignment of magnetic moments.

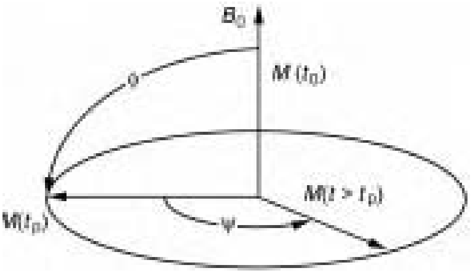

**Fig. 13.13** Sketch of inverting the magnetization *M* in the *XY* plane and bringing into phase.

This precession causes an AC voltage in the RF coil, the measurable MR-signal which is directly proportional to the spin density, thus the H-density and thus the water content.

When the RF pulse is switched off, the phase relationship will decay with a characteristic time constant (referred to as $T_2$) and their orientational alignment will relax with a different time constant $T_1$; both those parameters are temperature dependent. A further parameter measurable by MRI and temperature dependent is the self-diffusion coefficient, but as well as the time constants this parameter also shows a strong dependence on the composition (and thus the viscosity) of the solution in the food.

Another parameter almost independent of the composition of the solution in the food and measurable by MRI is referred to as the chemical shift. The method of temperature mapping using this parameter is based on the temperature dependence of the water proton chemical shift: increasing temperature leads to breaking of hydrogen bonds and thus to a stronger shielding of the hydrogen proton due to a reduced hydrogen–oxygen distance by oxygen-located electron clouds. As a result the precession frequency decreases and thus the phase (spin angle) of the processed signal, $\Delta f/\Delta T = 0.01$ ppm/°C (Hindman, 1966). From

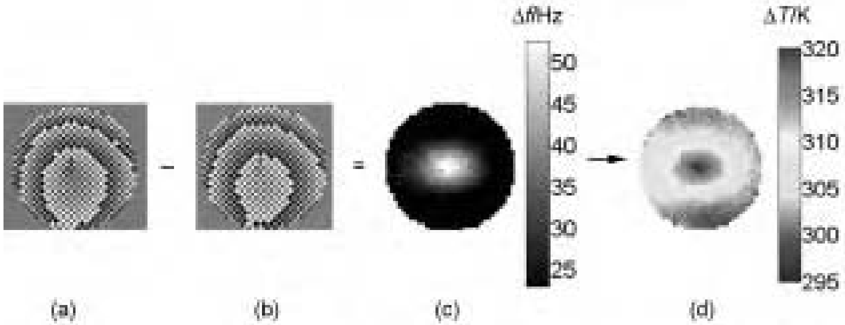

**Fig. 13.14** (a) MRI phase image of a model food at known initial temperature ($T_1$ = const); (b) phase image of heated sample; (c) phase difference distribution ($c = a - b$); (d) temperature distribution (calculated from phase difference with knowledge of a chemical shift of $\Delta f/\Delta T = 0.01$ ppm/°C).

a measured phase difference between the sample with known initial temperature and the heated sample, the actual temperature distribution can be calculated (see Fig. 13.14).

Because of the universality and great advantages of temperature mapping using magnetic resonance imaging (already mentioned in Section 13.2), experiments and results of MRI studies are presented in detail here.

## 13.4 Measurement in practice: MRI analysis of microwave-induced heating patterns

The experiments were done in a Bruker Biospin/Oxford Instruments Super-Wide-Bore cryomagnet with a maximum sample diameter of 64 mm and a magnetic flux of 4.7 T (see Fig. 13.15). For measuring temperature, respectively

**Fig. 13.15** Tomograph used for temperature mapping experiments.

phase distribution a gradient echo pulse sequence (Kimmich, 1997) was used. We measured a variable number of slices (from 10 up to 50 slices) perpendicular to the *z*-axis with a thickness of 1 mm, a two-dimensional resolution of 64 × 64 pixels and thus a three-dimensional resolution of 1 $\mathrm{mm}^3$. The overall measuring time was below 13 s with an accuracy of approximately ±2 K. The obtained MRI data (binary 3D matrices) was exported and analysed with self-developed scripts in Matlab $6.5^{\mathrm{TM}}$.

### 13.4.1 External microwave heating

Model food samples with a height of 30 mm and a diameter of 54 mm (see Fig. 13.16, (Knoerzer *et al.*, 2004b)) were heated in a microwave oven (Panasonic Pro II NE 2740; continuous power supply) with varying heating time and microwave power. Before and after microwave heating the samples were brought into the tomograph for measuring phase distributions. In order to verify the temperature distribution measured by MRI, three single slices were compared qualitatively and quantitatively with two-dimensional temperature distributions measured using infrared thermography (Mitsubishi IR-M700).

### 13.4.2 Internal microwave heating

To avoid temperature equalization between heating and measuring temperature distribution in the tomograph, a microwave device was developed jointly with Gigatherm AG (Hermann, 2004) which allowed us to introduce microwave power directly into the magnet (see Fig. 13.17). With this device it was possible to measure three-dimensional temperature distributions simultaneously with

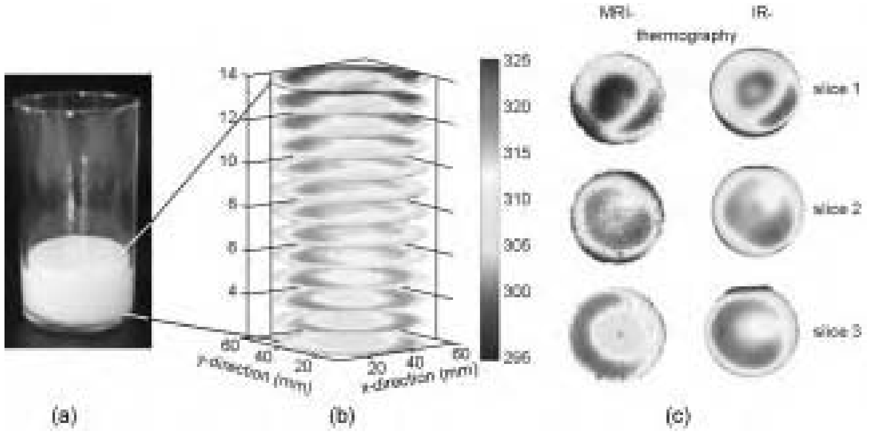

**Fig. 13.16** (a) Heated model food cylinder (qualitative) comparison in (c); (b) MRI determined temperature distribution of heated model food (15 slices, slice thickness 1 mm, slice distance 1 mm); (c) comparison of MRI and IR thermography of three selected slices.

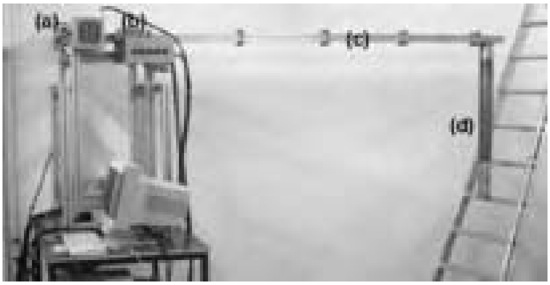

**Fig. 13.17** (a) Absorbing units; (b) microwave generator; (c) rectangular waveguide; (d) circular waveguide (for introducing microwaves in tomograph).

microwave heating. Heating experiments with different shapes of the model food and different real foods were carried out and temperature changes at discrete points measured by MRI were validated using fibre optic thermography.

### 13.4.3 Results and discussion

*External microwave heating*

As explained above, heating experiments were performed externally in a microwave oven with continuous power supply. Figure 13.16 shows a qualitative comparison of temperature distributions measured by MRI and infrared thermography. Obviously the MRI data qualitatively agree well with the data obtained from infrared thermography. However, a quantitative comparison showed a strong deviation of temperatures measured by these methods (see Fig.

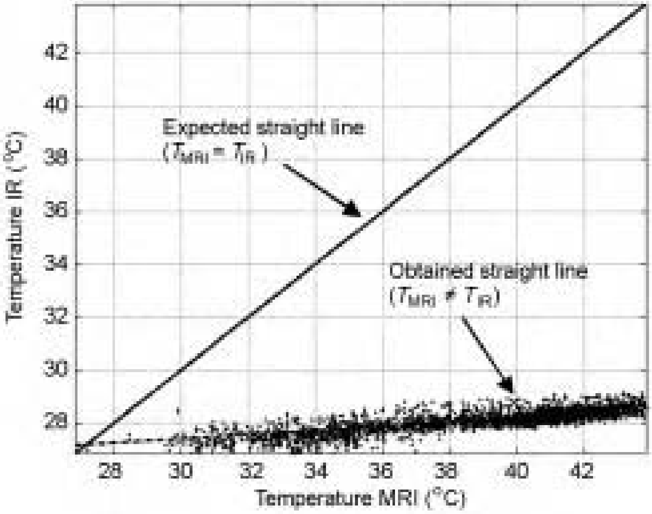

**Fig. 13.18** Quantitative comparison of temperature distributions measured by MRI and IR thermography.

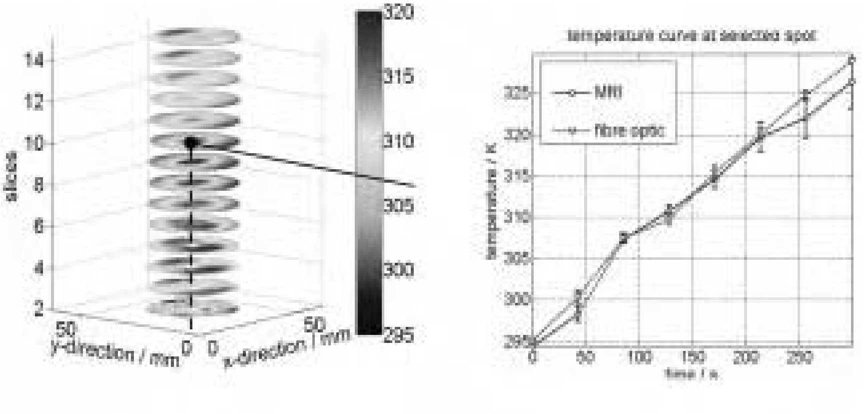

**Fig. 13.19** (a) Heated model food sphere with marked point for comparison with fibre optic sensor; (b) comparison of temperature curves measured by MRI and fibre optic thermography.

13.18). This strong deviation of the expected agreement ($T_{\mathrm{MRI}} = T_{\mathrm{IR}}$) can be explained by temperature equalization and surface cooling after slicing of the model food for IR measurements.

*Internal microwave heating*

Measuring inline microwave heating makes the observation of temperature changes at discrete spots of the heated food possible. Figure 13.19(a) shows the three-dimensional temperature distribution of a heated model food cylinder at a certain time ($d_{\mathrm{modelfood}} = 32\,\mathrm{mm}$, $h_{\mathrm{modelfood}} = 30\,\mathrm{mm}$, $P_{\mathrm{microwave}} = 20\,\mathrm{W}$). Figure 13.19(b) shows the temperature curve at the marked point (Fig. 13.19(a)) measured by MRI (solid line) and fibre optic thermography (dotted line). Good agreement between the two methods was observed.

## 13.5 Conclusions

In this chapter, different methods for measuring temperatures during and after microwave processing, their assets and drawbacks and their basic physical principles have been presented and discussed. It has been shown that thermocouples, probably the cheapest method for temperature mapping, are not suitable in a microwave field because of their metal components; furthermore, the achievable local resolution is not sufficient. While the first drawback of thermocouples can be overcome by using fibre optic probes, this does not solve the problem of insufficient spatial resolution. Besides, fibre optic probes are rather delicate and expensive in comparison to conventional thermocouples.

A different approach is the use of model substances that change their properties after reaching a certain temperature. Care has to be taken to match the important physical properties of the model to the real food.

For determining surface temperatures three methods have been presented: infrared thermography, liquid crystal foils and thermo paper. However, even though these methods are established for surface temperature mapping, especially in microwave processing as a volumetric heating method, they are limited to measuring only surface temperatures.

For measuring internal temperatures non-invasively, two methods have been presented. Microwave radiometry gives information about temperatures not too far below the surface. However, in microwave heating this is often not sufficient, and a better method of temperature mapping uses magnetic resonance imaging. It has been shown that this technique avoids almost all the problems of the other methods. Using MRI it is possible, even inline during heating (Knoerzer *et al.*, 2004a), to measure three-dimensional temperature distributions non-invasively.

All these methods can give useful hints on temperature distribution, but only the sophisticated method of nuclear magnetic resonance imaging can measure temperature distributions within the product. The disadvantage of MRI is that it is a very complex and expensive technique, which makes it currently only suitable for research, but not yet for industrial-scale processes with very high throughputs.

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# 14

# Improving microwave process control

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## 14.1 Introduction

Heating and drying have become important in almost all areas of industrial processing. Apart from the popular conventional procedures based on conduction, convection and infrared radiation, heating and heat-drying utilising microwave energy is an attractive solution to many problems arose in process technology.

In microwave heating and drying, heat is generated by directly transforming the electromagnetic energy into kinetic molecular energy, thus heat is generated deep within the material to be heated and dried. The fast heat transfer has to be controlled so that a stable and reproducible process is guaranteed. Therefore process control in combination with good microwave design is the key point in successful microwave applications. The basic and simple requirement of the process is for work to run independently without user interference.

The bottom line is that people are not interested in microwave technology as such, but in the functional results and benefits obtained from the technology. As more complexity is involved in controlling microwaves, the design and control system have a much higher impact compared to conventional heating systems.

## 14.2 General design issues for industrial microwave plants

### 14.2.1 Microwave system

Figure 14.1 shows a basic industrial design of a microwave system. The magnetron is installed on a waveguide launcher where microwave energy is generated. The generated electromagnetic energy is then guided within the

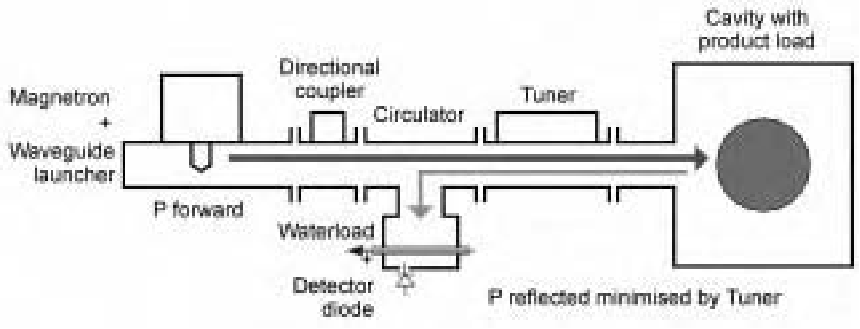


**Fig. 14.1** Schematic design of an industrial microwave plant according to GMP microwave.

waveguide structure and coupled into the cavity where the product is placed.

Reflected electromagnetic energy is detected within the structure. The amount of reflected energy varies according to the dielectric properties of the product and the dimensions of the cavity. In order to achieve the best possible efficiency, the amount of reflected energy must be minimised using a tuner.

The installed circulator works as a load protector for the magnetron. Depending on the quality of the used circulator, the reflected energy is absorbed by the water load.

The directional coupler measures the forward or incident microwave power. Its position for installation within the waveguide system may vary. The accurate measurement of the reflected power in the water load of the circulator is usually sufficient in most applications.

### *Magnetron*

A magnetron is an oscillator tube that converts dc energy with small current at high voltage supplied to the magnetron anode into microwave energy. The efficiency is around 70–90%. Magnetrons are classified into pulsed and continuous-wave (cw) magnetrons. The pulsed magnetron is mainly used for radar application, and the cw magnetron for microwave ovens and industrial heating applications.

The mechanical structure of the internal resonant cavities determines the operating frequency. Because there is a filament emitting electrons in an enclosure that is under vacuum, magnetron tubes have a limited lifetime and require periodic replacement. Figure 14.2 shows a cross-section along the axis of a magnetron as well as the footprint across the resonator cavities.

To gain a rough idea of how a magnetron generates microwaves, one can resort to a simple acoustic analogy. If air is blown across the mouth of a bottle, a tone or oscillation will be generated which has a wavelength proportional to the size of the bottle. If you fill the bottle partially with water, the frequency of the acoustic tone generated increases. In the case of a magnetron tube, the electron cloud generated by the cathode is the ‘air’ and the resonant cavities of the anode

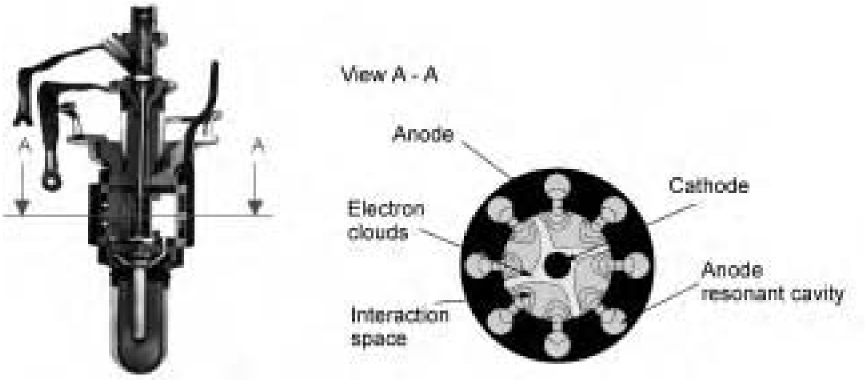


**Fig. 14.2** 25 kW/915 MHz magnetron BM-25L from EEV/Marconi (left) and principal footprint of the resonator structure.

surrounding the cathode are the 'bottles'. As electrons leave the central anode they are induced into circular rotation by a magnetic field, passing many resonator 'bottles' before finally being captured by the anode. The result is microwave energy generated within a very narrow frequency bandwidth.

The range of power levels of industrial magnetrons varies from 100 W to 30 kW for 2450 MHz and from 5 to 100 kW using 915 MHz. Water-cooling is required above 3 kW. For industrial applications it is recommended to use water-cooling also for smaller magnetrons, as shown in Fig. 14.3.

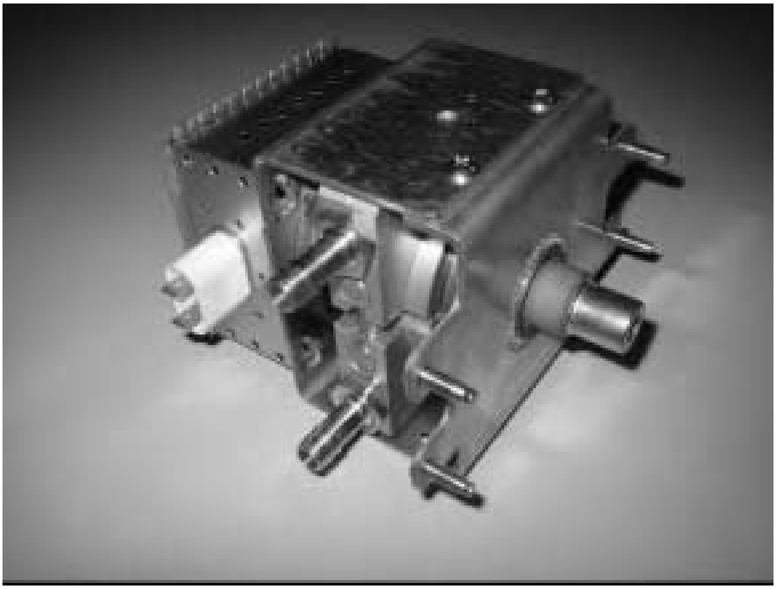


**Fig. 14.3** 1.2 kW/2450 MHz magnetron 2M137 type with a water-cooling jacket.[1]

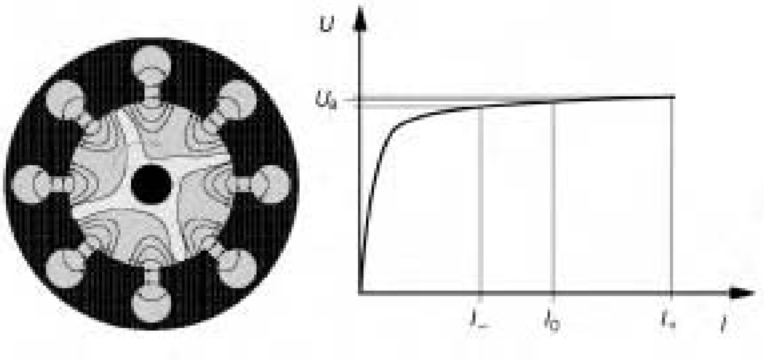


**Fig. 14.4** *U/I* chart of a magnetron; a flat characteristics requires stabilised power supplies.

*Power supply*

After the tube starts oscillating, the anode current *I* varies with small changes of the anode voltage – as shown in Fig. 14.4. Therefore, to ensure stable performance against variation in line voltage, it is necessary to stabilise the anode current. There are two methods for stabilisation of the anode current for power control:

- By magnetic field
- By power supply circuit.

An example of a simple LC stabilised half wave power supply used in commercial household microwaves is shown in Fig. 14.5. LC stabilised half wave power supplies cause high ripple for the connected magnetron. Beside the LC stabilised half wave systems, also full wave rectified power systems are available.

An example of an industrial power supply based on a 6-diode rectifier unit is shown in Fig. 14.6. High voltage and anode current ripple are in the range of

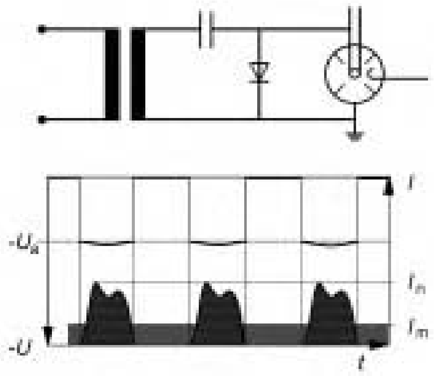


**Fig. 14.5** Simple high ripple LC power supply.

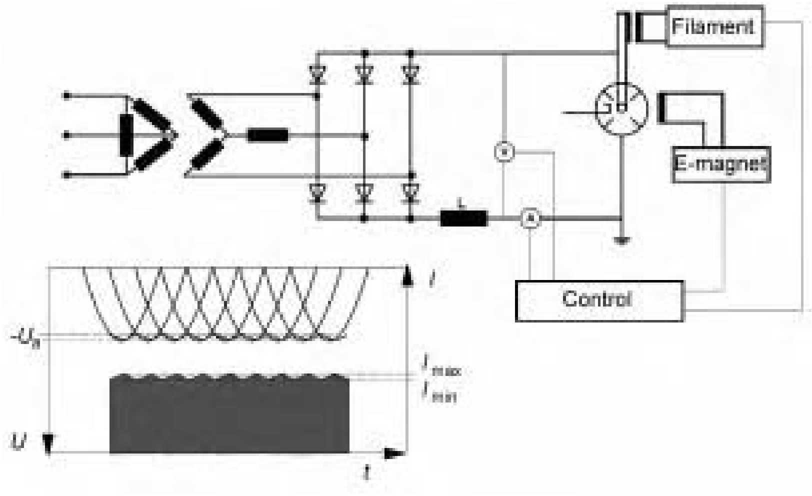


**Fig. 14.6** Magnetic field controlled power supply using a 6-diode rectifier unit.

**Table 14.1** Microwave power supply technologies for different applications and future trends[1]

| Type | Features | Applications | Trend |
|---|---|---|---|
| LC half wave | Low cost<br>Few components<br>Up to 1500 W | Heating slow process<br>Heating multi chamber<br>Plasma | Low cost SMPS |
| LC full wave | Up to 3000 W | Heating slow process<br>Heating multi chamber<br>Plasma | Low cost SMPS |
| Thyristor | Continuous power control<br>50/60 Hz | Heating fast processes<br>Plasma | Will be replaced by SMPS |
| SMPS–HR | Light weight | Multimode<br>Heating<br>Plasma | Decreasing prices |
| SMPS–SR | Light weight<br>Low storage energy | Vacuum drying<br>Ceramics | Decreasing prices |
| E-magnet | Low cost<br>High MTBF | Heating<br>Vacuum<br>Plasma | Continue |
| Linear-regulated | Low ripple | Monomode | Continue |
| Pulse-power | Fast rise time<br>Low ripple | Pulse-plasma | Niche product |

**Table 14.2** Microwave power supply technologies depending on power levels, efficiency, ripple, etc.[1]

| Type | Power (W) | Efficiency (typically) | Ripple (peak to peak at full power) | Regulation | Pulsing/ repeition up to | Band width (MHz) |
|---|---|---|---|---|---|---|
| LC half wave | <1500 | >95% | high, 50 Hz | on/off | 10 Hz | 40–80 |
| LC full wave | >1500 | >95% | high, 100 Hz | on/off | 10 Hz | 20–40 |
| Thyristor | 150–3000 | >95% | high, 100 Hz | 0–100% | 10 Hz | 15–30 |
| SMPS-HR | 150–3000 | ~90% | high, 100 Hz + 50 kHz | 0–100% | 1 kHz | 40–80 |
| SMPS–SR | <100 k | 90% | 10% | 10–100% | 300 Hz | 8–15 |
| E-magnet | <100 k | >96% | 5% | 10–100% | 5 Hz | 4–10 |
| Linear-regulated | 300–3000 | <85% | 1% | 10–100% | 50 kHz | 4 |
| Pulse-power | 3 k–50 k | <85% | <1% | 10–500% | 50 kHz | 2 |

±5% peak to peak. The microwave power can be continuously driven from 10 to 100%.

Other power supply technologies are:

- Thyristor controlled power supplies
- Switch mode power supplies (SMPS)
- Linear regulated low ripple with <1% peak to peak.

Table 14.1 gives an overview and shows future trends. In general, switch mode systems will replace the LC and thyristor technology in the near future. Table 14.2 gives an overview of some technical specifications.

*Isolator*

Ferrite circulators are widely used as isolators to protect high power microwave tubes, such as klystrons and magnetrons, from damaging reflections. With a suitable high power load at Port 3, a three-port junction circulator functions as a low loss isolator. It effectively decouples the tube from particle accelerator cavities and microwave heating applicators, by diverting undesired reverse power into the load as shown in Figure 14.7.[2]

*Tuner*

Tuners are used to minimise microwave reflections within the microwave system. The microwave cavity with the product load has to be matched to the microwave source. For this task tuners are used. The most common 3-stub tuner is shown in Fig. 14.8.

### 14.2.2 Cavity designs

The microwave energy, having been generated by a magnetron, either directly or by means of intermediate waveguides, is transmitted into the heat chamber. The

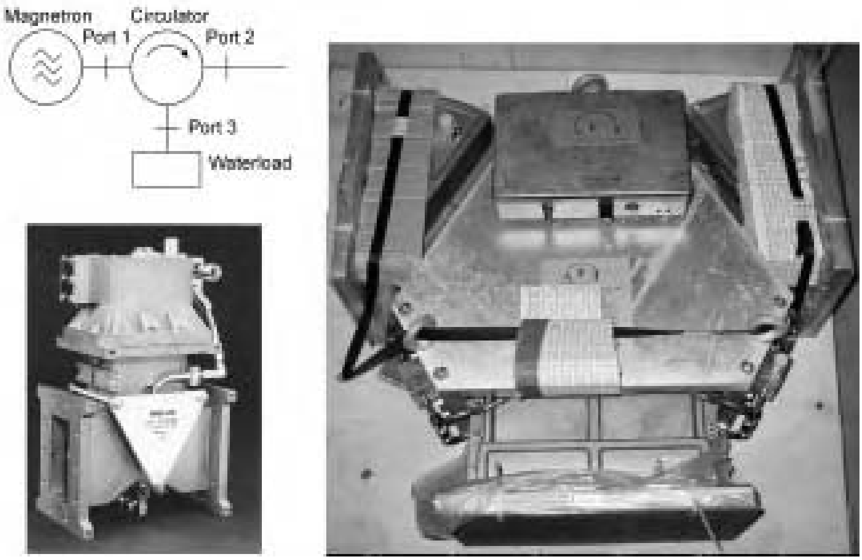


**Fig. 14.7** Port numbers of a circulator (left top), a 6.5 kW/2450 MHz circulator from Philips (bottom left) and a 75 kW/915 MHz circulator from AFT (right).[2]

heat chamber is called the cavity, where the material to be processed is kept, as shown in Fig. 14.9. For more uniform heating, a rotating disc and/or a mode stirrer in the form of a metallic turning structure are often incorporated into the chamber design. The cavity design falls into two main categories:

- Multimode cavities
- Monomode cavities.

*Multimode cavities*
A widely used microwave applicator, as used in domestic household microwave ovens, is the multimode applicator. In principle the applicator is a metal

**Fig. 14.8** Three-stub tuner.

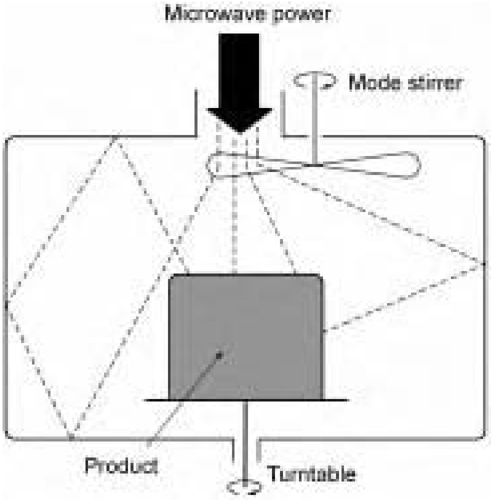


**Fig. 14.9** Schematic representation of a microwave heat chamber with microwave launcher from top.

chamber whose dimensions are much longer than the wavelength of the frequency, which is coupled into the cavity. Using a mode stirrer and/or a rotating disc as well as the conveyor belt can equalise the field distribution. Figure 14.10 shows a batch-type multimode cavity as well as a multimode cavity with an installed conveyor belt system.

*Monomode cavities*

Electromagnetic waves are known to propagate in ground waveguides with a single mode field distribution. Figure 14.11 shows the field distribution of a rectangular ground mode (TE10) in the cross-section of a waveguide. These waveguides can also be used as applicators. The main benefit is where field

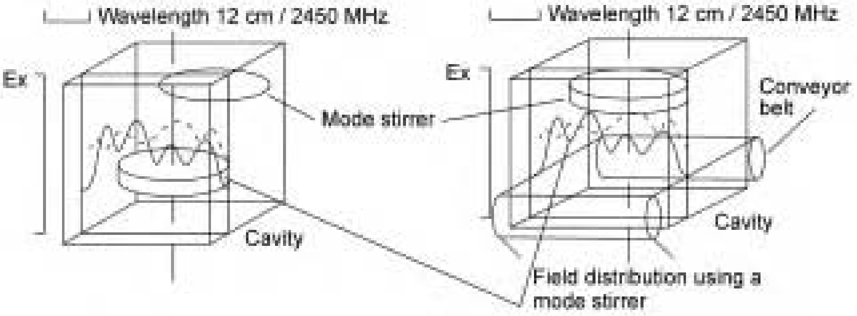


**Fig. 14.10** Batch multimode cavity (left) and cavity with conveyor belt (right).

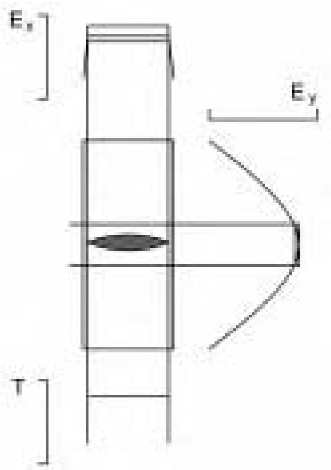


**Fig. 14.11** Cross-section of a TE10n monomode cavity with a conveyor belt in the middle.

distribution in the cross-section is defined. The inner section in Fig. 14.11 shows the use of a conveyor belt system for feeding product through the system. The disadvantage of the monomode system is that it is fixed by the ground dimensions of the waveguide, and the small waveguide dimensions limit its use for big-volume products.

### 14.2.3 Microwave good manufacturing practice (GMP)

In order to guarantee a stable and reproducible process, the design of the microwave system has to ensure constant process results. Therefore a well-designed system as shown in Fig. 14.1 and high-quality microwave components for installation are important in meeting these requirements. In cases where a circulator is not used, the reflected energy is thus hitting the magnetron and results in a shortened lifetime of the magnetron. The phenomenon also reduces the forward or incident power generated by the magnetron, causing the amount of power needed for the process to be unstable. Thus, the process is irreproducible.

More background on why a magnetron deserves the protection of a circulator is shown in Fig. 14.12. The generator diagram of a 1.2 kW/2450 MHz magnetron is shown in the left chart. The centre of the circle indicates the condition without reflections, $r = 0\%$, which is guaranteed when using circulator protection with the magnetron. The outer circle represents the condition with 100% reflection, meaning that all incident power by the magnetron is returned as reflected power. The simplified Smith chart (right) shows the operating condition under different reflection conditions. It consists of lines of resistance and reactance plotted in a polar form.

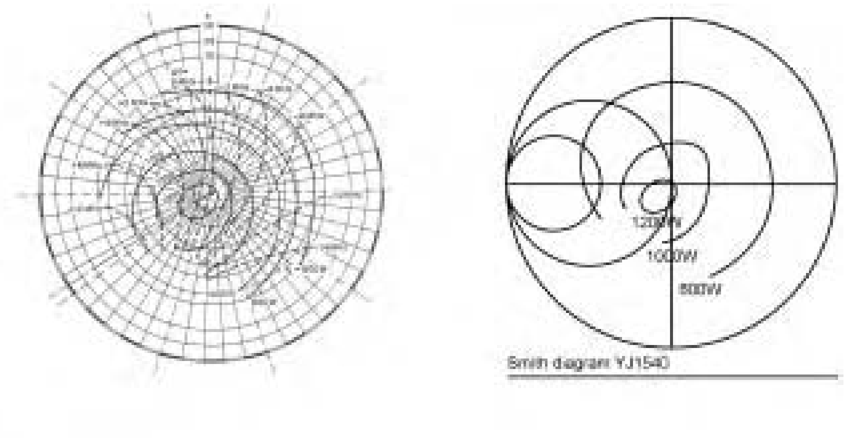


**Fig. 14.12** Generator chart (Rieke) for an industrial 1.2 kW/2450 MHz magnetron.

In view of such a background, it is necessary to protect magnetrons using high-end circulators. High-end circulators have an isolation of more than 20 dB (typically 21–26 dB). The advantages of a GMP microwave system are:

- The magnetron will last for its specified lifetime.
- The incident or forward power of the magnetron for the system is constant (the magnetron is operated within its specifications).
- Using a directional coupler or a detector diode, the reflected microwave power can be measured. With the measured incident power of the magnetron, a calibrated microwave system is able to calculate the absorbed power by the product:

  $P_{\text{ab}} = P_{\text{inc}} - P_{\text{refl}}$

- The efficiency of the microwave system can be optimised using a tuner.

The maximum specified microwave power of an industrial microwave plant has to be measured and labelled according to the international standard IEC60307. The standard ensures that different manufacturers are using the same power requirements so that a buyer can compare different systems offered on the market.

### *Disadvantages of multi-magnetron systems without protection*

In order to understand the disadvantages of systems using multiple single magnetrons without protection and tuning, Figure 14.13 demonstrates the point using a multimode cavity with four magnetrons coupling directly into the cavity. As a three-dimensional mode distribution is travelling within the multimode cavity (the distribution depends on the load condition of the cavity), the E field distribution in Fig. 14.13 is shown in the cross-section plane of the four magnetrons.

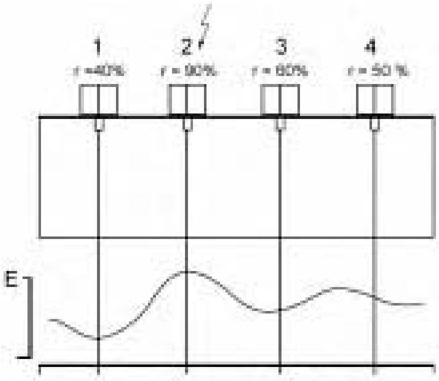


**Fig. 14.13** Design of microwave system without protection and tuning of four magnetrons in a multimode cavity.

Due to the value of the standing wave ratio of the E field at the magnetron antenna location, the magnetron faces different load conditions which result in different reflections. In the example of Fig. 14.13 magnetron 2 is stressed by high-reflected energy levels. As a result, the magnetron incident power is reduced and its lifetime is shortened. Therefore the power actually for the process is determined by undefined changes, which finally result in an irreproducible process.

During operation of the magnetrons in Fig. 14.13, a condition like moding may occur. The magnetrons consume higher anode currents, which cannot be maintained by the power supplies. This may cause damage to both the magnetrons and the power supplies, especially when cheap LC power supplies are used.

### 14.2.4 Field distribution and the process

To achieve an even temperature distribution, multimode cavities for heating applications with high requirements have to be carefully designed. Poorly designed cavities will cause hot spots, which means parts of the product are overheated. Because dielectric losses depend on temperature, these hot spots can result in a thermal runaway. This means that the high temperature causes higher dielectric losses and therefore the amount of energy absorbed by the hot spot increases.

Today's simulation computer programs allow designing the cavity in a way that the ground E-field distribution created by different modes within the cavity can be optimised by varying the cavity ground dimensions as well as the locations of the coupling systems. An example of a modelling result is given in Fig. 14.14 based on the computer program Concerto performed at the Institute ITACA in Valencia.[3] An IR array camera image from FLIR shown in Fig. 14.15 confirms the trial result later.

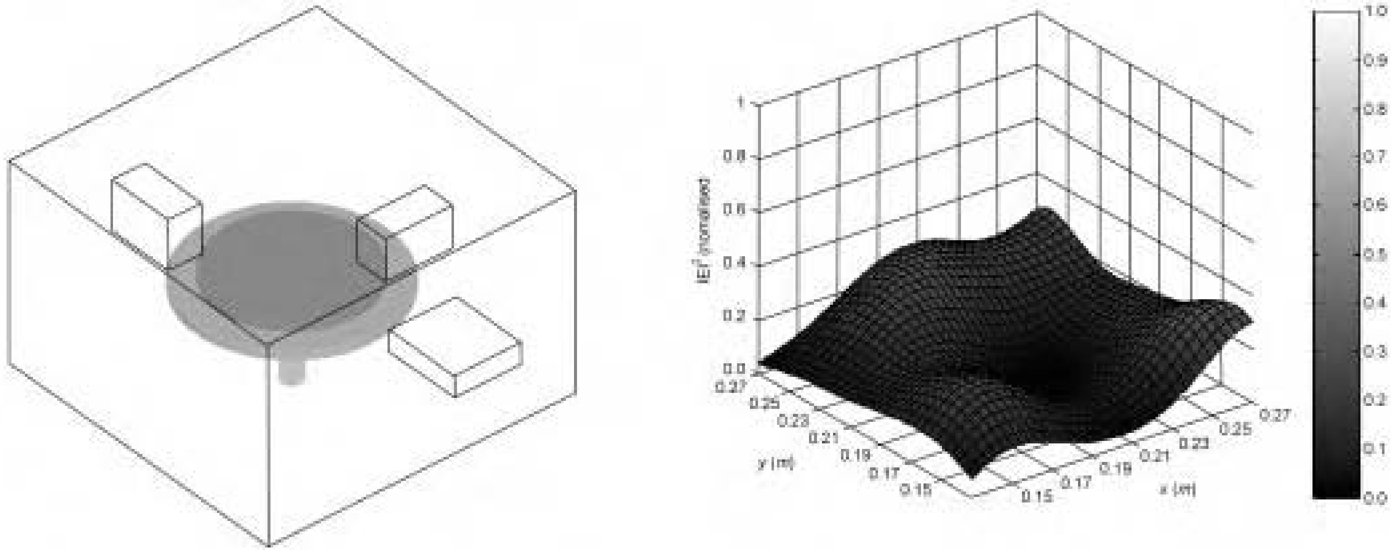


**Fig. 14.14** Electric field distribution as the loaded material location SIC d140 × 5 mm load (right) and after optimised feeds positioning of a 400 mm$^3$ cavity (left).

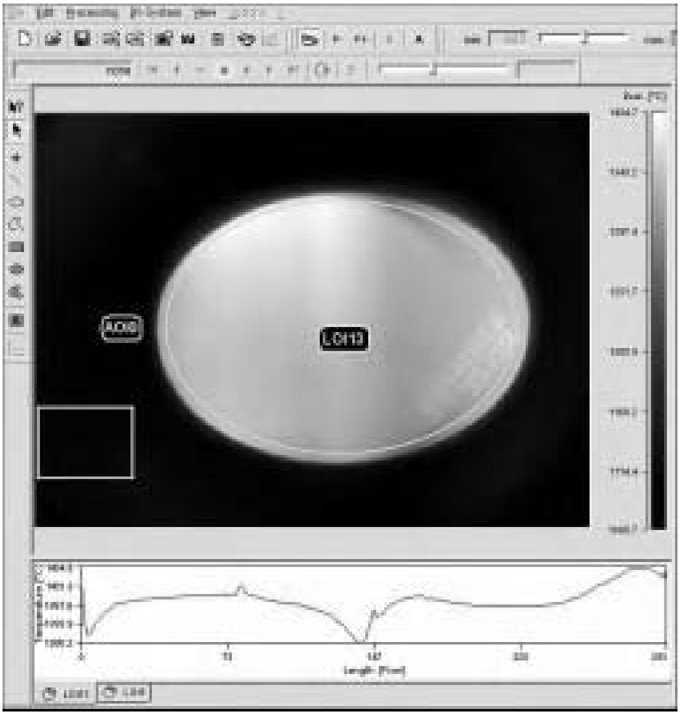


**Fig. 14.15** Temperature image (320 × 240 pixels) taken with an FLIR IR SC500 array camera.

## 14.3 Process control systems

### 14.3.1 The environment

For optimal process control, the aim is to supply all process parameters to the microwave process controller. The main process parameters very often are temperatures, moisture level, forward and reflected microwave power, and load conditions of the applications for products in continuous systems or weight losses in batch systems.

In the design phase, the focus is not only on the main process parameters; attention is also given to the indirect process parameters. Indirect process parameters are, for example, ambient temperature, ambient humidity, supplied dried air conditions for microwave dryers, etc. The philosophy should be to collect as much useful information as possible for controlling and maintaining a stable process and safe operation of the microwave plant. A risk analysis and a process analysis are necessary for evaluating all relevant data.

One has to take into consideration the environment in which the microwave plant is operated. High ambient humidity changes have a tremendous influence on a microwave dryer. To operate microwave plants in clean room conditions has an impact on plant design. Some industries, such as pharmaceuticals, require special regulations and validations such as cGMP for the process and plant design and GAMP for the PLC and automation components.

Production plants worldwide have changed and advanced over the years. Processes are getting more complicated and advanced nowadays. The use of industrial microwave plant is also more complex internally as opposed to the conventional heater and dryer. Operators today are trained to handle SOPs (Standard Operation Procedures) and often do not have much background knowledge of the process. With fewer personnel assigned to more machinery, process control has thus increased tremendously in its responsibility.

One of the future trends will be *Smart and Intelligent Microwave Machines*, which can be operated with minimum user interaction as they can adapt themselves to changes within the process.

Within the concept phase of a project it very important to test different design approaches. Based on the process requirements and environment, different concepts have to be compared to each other to find the best final solution. Figure 14.16 is intended to show within a block diagram the different areas of interest.

### 14.3.2 Instrumentation for process control

The qualities of sensor signals have a considerable effect on process control. Many sensors such as light beams and infrared cameras have to operate under higher electromagnetic emissions than specified. Therefore these devices ought to have good EMC stabilities. For sensitive analogue signals, good earthing and shielded wiring is necessary. Bus systems such as RS232/RS485/CAN/Profibus, etc., for sensitive signals have advantages as there is no risk of signal losses.

As temperature measurement is a widely used parameter, three different measurement systems are available:

- Infrared temperature measurement
- Fibre optical measurement
- Metal shielded thermocouples.

### 14.3.3 The PLC as the core component

The PLC has to cover different tasks:

- To ensure a stable process
- To offer an easy to use and clear human interface
- To ensure the safety of the means of operation of the microwave plant
- To provide full and quick access to all relevant information.

The basic design rules of industrial microwave plants should ensure that all tasks are as easy as possible for both the operator and the process engineer. The philosophy is that the design should meet all user and process requirements. A clear user interface, as in Fig. 14.17, with access to all process parameters means better process control. The results are better process stability and higher product quality.

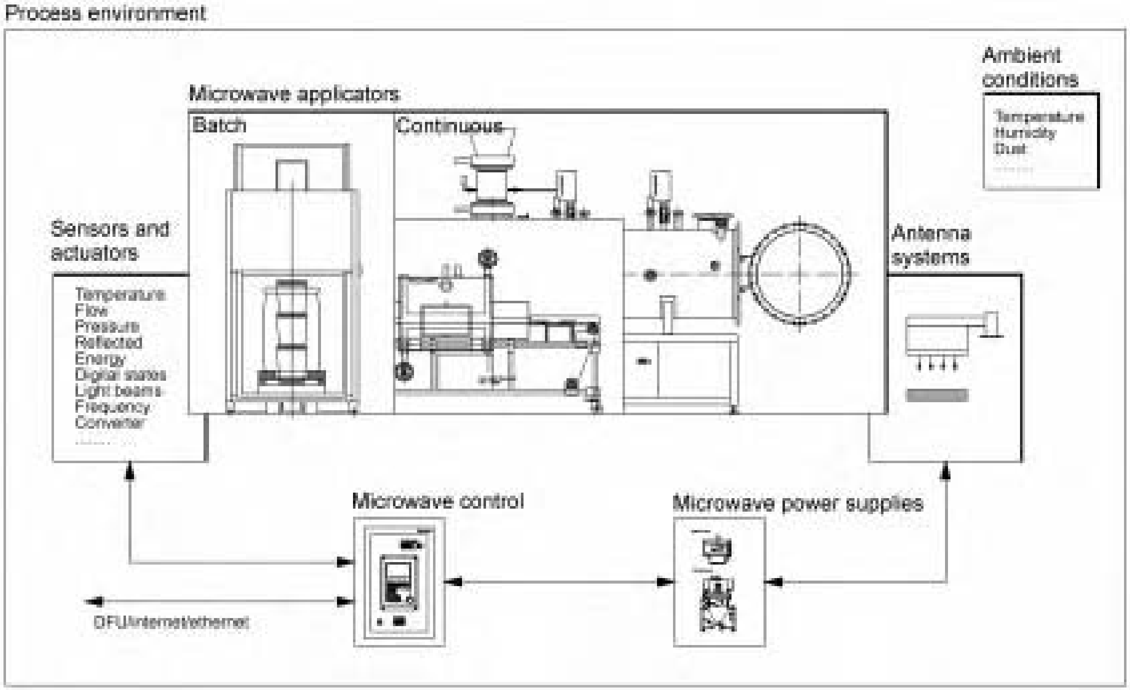


**Fig. 14.16** Block diagram of different components for building up an industrial microwave plant.

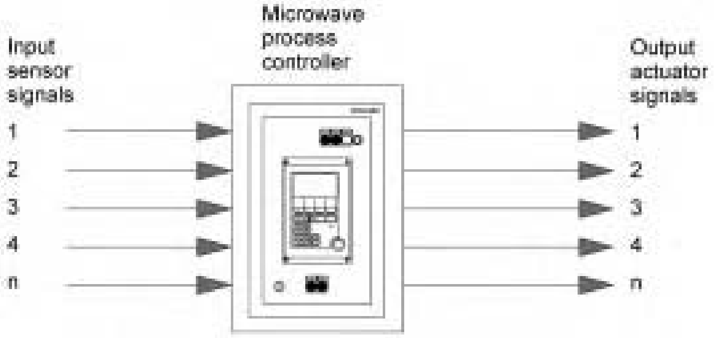


**Fig. 14.17** General microwave PLC with user interface and input and output signals.

### 14.3.4 Different view from operator and process engineer

The requirements of the operator and process engineer are different due to their differing responsibilities. As the normal operator is responsible for production, the requirements for the operator are that the system should:

- Be easy to use and operate
- Provide clear text messages in case of alarms, warnings and cautions
- Have minimum settings to control the process (just start and stop philosophy)
- Provide easy access for changing set values with minimum user interaction
- Need minimum attention for the machine (stable operation)
- 'Talk' the operator's language.

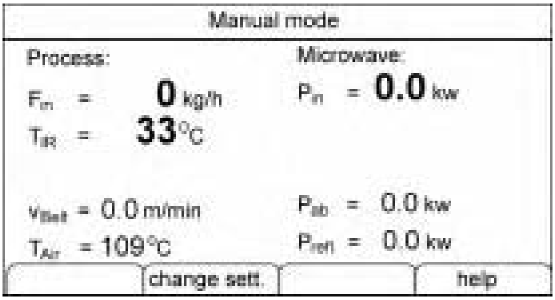
The requirements of the process engineer are:

- Easy access to all parameters
- Easy to change process settings and process control
- History of alarms, settings and user interactions
- Forecast if product out of specifications
- Easy to judge stable process.

From the above-mentioned points the front-end command panel and the implemented user interface are of great significance in the successful installation of an industrial microwave plant. The menu of the display has to have a clear structure, starting with the most important process parameters, such as in the example shown in Fig. 14.18.

*Easy access to all process parameters*

As a result of using Windows PCs, people are used to the 'windows' philosophy and to changing settings by mouse pointing and clicking. A similar mouse-like device is a rotary knob, which has introduced an unprecedented level of simplicity in setting parameters. One hand and three simple steps (select – adjust – confirm) are all the user needs, as shown in Fig. 14.19.



Manual mode

Process:

$F_{in}$ = 0 kg/h

$T_{IR}$ = 33°C

$v_{Belt}$ = 0.0 m/min

$T_{Air}$ = 109°C

Microwave:

$P_{in}$ = 0.0 kw

$P_{ab}$ = 0.0 kw

$P_{refl}$ = 0.0 kw

**Fig. 14.18** Main window with main process parameters.

### 14.3.5 Process visualizing

As static data gives only snapshot information, the process parameters should be available as trends, which will give more information about the actual process stability. To judge the long-term stability of a process, trend data monitoring is essential. Figure 14.20 shows an example of trend data of a continuous microwave dryer.

- The microwave set, forward and reflected power are displayed in the top trend window of the screen. With 12.1 kW forward and 3.4 kW reflected power, the product absorbed 8.7 kW while flowing through the drying channel.
- For a continuous dryer, a constant feed of product is essential in order to achieve constant drying results. Therefore the dryer has a gravimetric feeding system. The set and actual measured values are shown in the window below.
- The next important process parameter is the product temperature. An infrared camera is placed at the outlet of the drying channel to measure the temperature.
- The next parameter is the pressure in the drying channel. As the pressure conditions of the site exhaust have a big influence on the microwave drying process, the pressure is measured.

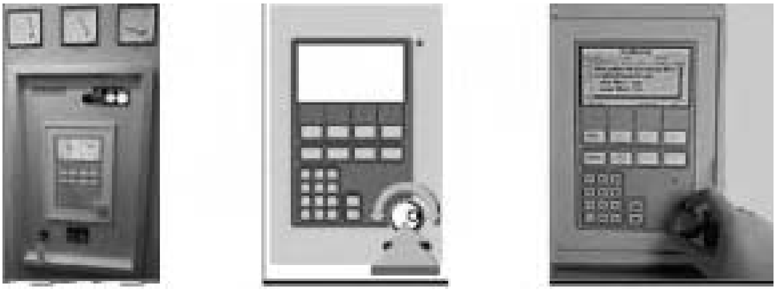


**Fig. 14.19** Example of a command panel (left) with user interface 'turn and push' (centre) and human interface with PLC (right) of a microwave plant.

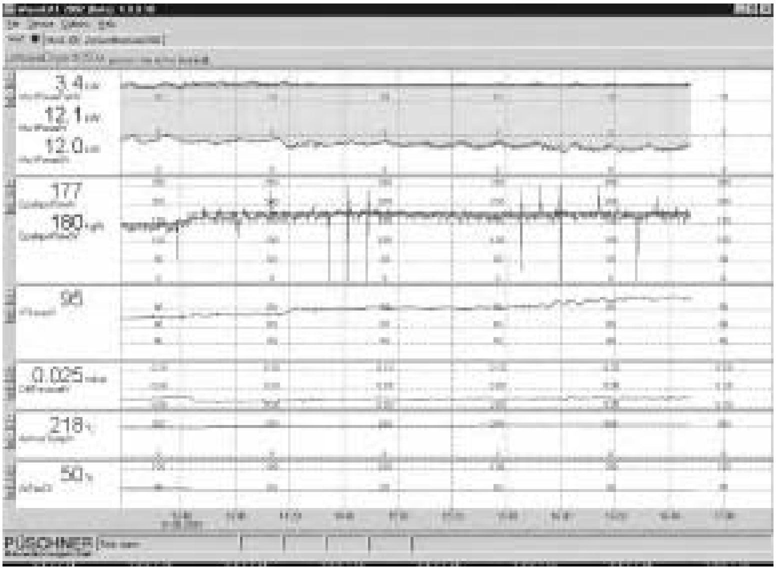


**Fig. 14.20** Trend data monitoring of the main process parameters of a microwave dryer.

- The heated air supplied to the drying channel is also important for the drying process, as well as the airflow controlled by a frequency converter-driven fan that is set to 50% in the example of Fig. 14.20.

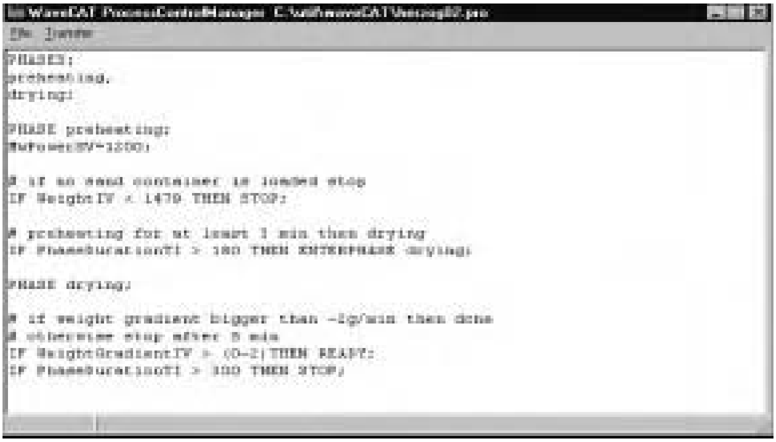
Stable conditions of the dryer can be identified clearly by constant levels of the process parameters. With one quick look at the trends, the operator has an impression of the process conditions. Besides showing the trends and monitoring the data, all critical values have alarm limits. The alarm is triggered when the actual values exceed the set alarm value.

### 14.3.6 Open system for process control

Most microwave applications require settings to be proven at the initial trials. Upon installation these settings have to be optimised, or products have to be adapted to new settings. In some advanced applications the process engineer may have to deal with 100 set values, especially when plants have a lot of sensors and single microwave systems. Therefore a process control language is very useful and allows the process engineer to run a process automatically and change process parameters easily.

A simple example of a drying program is given in Fig. 14.21. The application is to dry a filter cake with variable weight and variable moisture content. The product has to remain below 0.1% residual moisture using a small 1.2 kW/2450 MHz microwave batch oven.

The drying program consists of the two phases *preheating* and *drying*. First the microwave will be switched on in phase *preheating* using the statement



```
PHASES:
preheating,
drying;

PHASE preheating;
MwPowerSV=1200;

# if no used container is loaded stop
IF WeightIV < 1479 THEN STOP;

# preheating for at least 3 min then drying
IF PhaseDurationTI > 180 THEN ENTERPHASE drying;

PHASE drying;

# if weight gradient bigger than -2g/min then done
# otherwise stop after 5 min
IF WeightGradientIV > (0-2) THEN READY;
IF PhaseDurationTI > 300 THEN STOP;
```

**Fig. 14.21** Example of a drying program.

```
MwPowerSV=1200;
```

The set value is 1200 W. The statement

```
IF WeightIV < 1479 THEN STOP
```

checks whether the PTFE container is on the scale pan. The weight of the used PTFE container can be varied. If the weight exceeds 1479 g the program continues with the statement

```
IF PhaseDurationTI > 180 THEN ENTERPHASE drying;
```

This statement means that after 3 minutes of preheating the drying phase is entered. In the drying phase the statement

```
IF WeightGradientIV > (0-2) THEN READY;
```

means that drying will continue as long as the gradient is less than −2 g/min. When the gradient of −2 g/min is reached, the process is stopped regularly. As a general time-out statement the last line is defined:

```
IF PhaseDurationTI > 300 THEN STOP;
```

If the gradient is not reached after 5 minutes then the process stops irregularly.

A drying curve controlled by the above program was driven and monitored and the result is shown in Fig. 14.22.

### 14.3.7 Web enabled microwave engineering

As a matter of fact all machines of a production line are linked using bus or network connections. Ethernet is becoming a standard for network hardware using TCP/IP as a common protocol standard. Connecting machines to the Internet gives many advantages. As production lines consist of many single

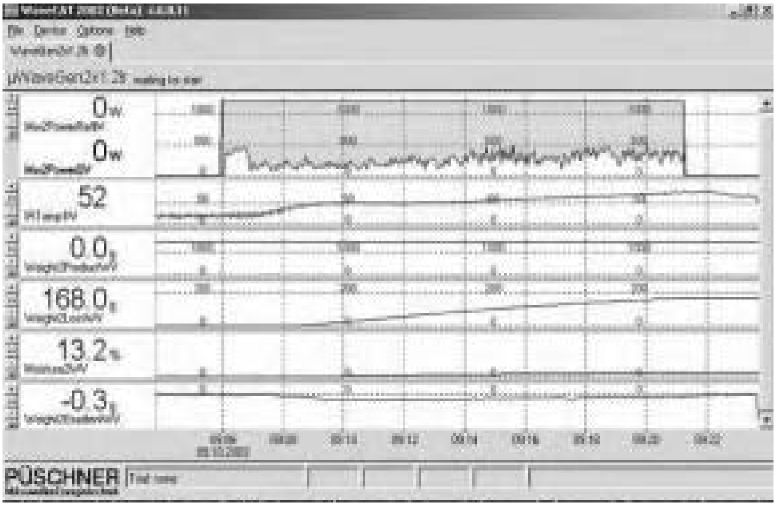


Fig. 14.22 Trend data monitoring of a simple drying process controlled by a script file.

modules, they have to be linked in a powerful network together with a process control computer with all process information in order to ensure stable and reproducible production results (see Fig. 14.23). To meet ISO standards and FDA regulations, quality process control will become a big issue in the coming years.

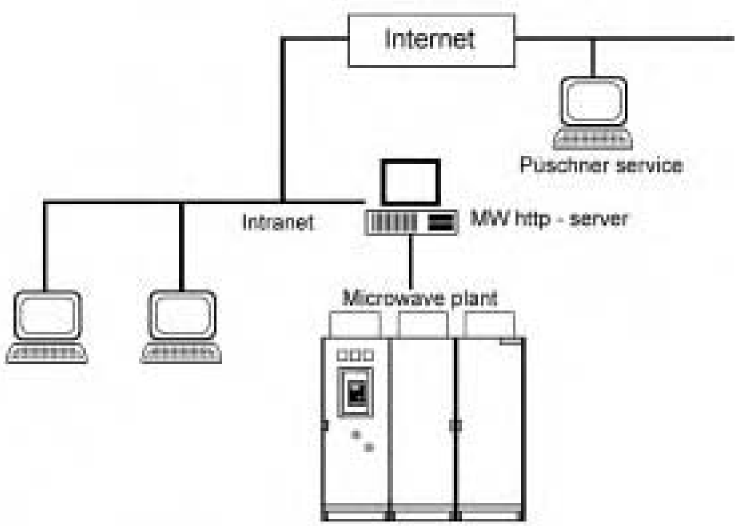


Fig. 14.23 Microwave plant linked to intra-/Internet.

## 14.4 Examples of process control systems in food processing

### 14.4.1 Batch vacuum drying

For integration of microwave components into a vacuum system, some important high-frequency specific items have to be taken into consideration. These are in particular:

- Dielectric properties
- Installed transport systems
- Product throughput rate
- Drying parameter
- The vacuum used, in particular the depth of the vacuum.

A homogeneous microwave energy distribution over the cross-section of the product bed is a significant requirement. Especially in applications of end drying or using products with poor dielectric losses, special microwave antenna systems are required in order to achieve an even temperature and drying results.

In addition, peaks in the electric field strength have to be avoided using high-quality linear regulated microwave power supplies, because the breakdown field strength is reduced by the vacuum as shown in Fig. 14.24. If the breakdown field strength is exceeded, the results are sparks and plasma.

The process parameters as well as the microwave applicator or microwave antenna system have to be evaluated using microwave vacuum trial plants. Figure 14.25 shows a microwave trial plant, which can be equipped with different applicators or antenna systems. Using an infrared and fibre-optical temperature measurement system, core and surface temperatures can be

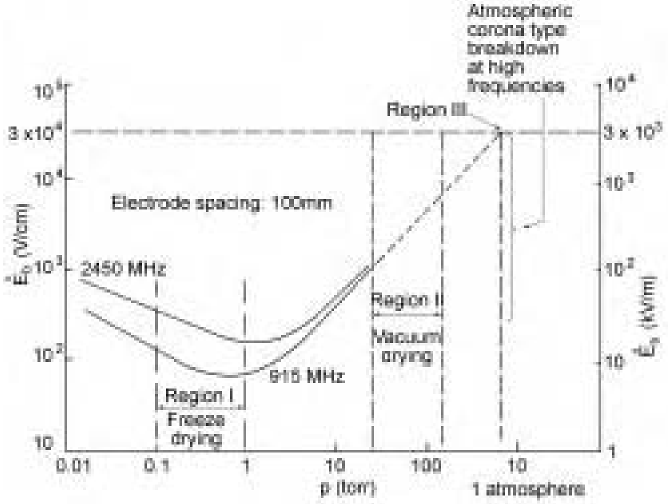


**Fig. 14.24** Typical breakdown electric field responses in air (peak values) as a function of pressure for two frequencies.[4]

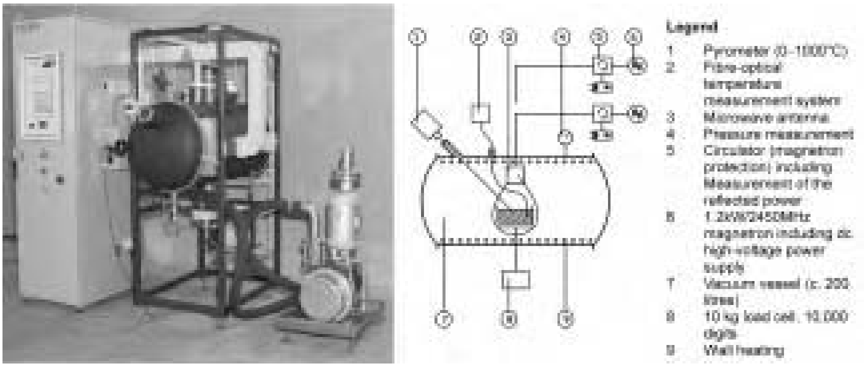


**Fig. 14.25** Microwave vacuum trial plant.

measured. In addition the weight loss, pressure and absorbed microwave energy can be measured also.

In order to perform trials for evaporation of solvents, the vacuum vessel can be rendered inert by using nitrogen. The procedure of applying nitrogen is observed with an oxygen measurement device.

Based on the results of these trials, the drying kinetics of a process can be investigated. Based on the dependence of the drying performance on the microwave energy distribution and the vacuum level, an estimated calculation can be made for designing a production plant. The estimated rating for a continuous production process has to be validated with a continuous pilot plant as shown in the next example.

### 14.4.2 Continuous vacuum drying

Using a conventional vacuum dryer the product is heated using contact heating within several heating zones. Heated plates are used as a heat transfer medium using pressurised water, steam, oil or electrical sources. Compared to such conventional heating systems, microwave is the better alternative. Microwave vacuum belt dryers are used for the continuous and automatic drying of temperature-sensitive products with low thermal conductivity, such as herbal extracts, foods, pharmaceutical and chemical products. The drying process is adapted to the desired dry product quality in terms as final solids content, solubility, density and other factors.

Feeding of solid substances is effected by means of a suitably designed attached feeding device, with product-orientated metering and distribution setup in the dryer. When feeding wet product a metering pump and an oscillating feeder are allocated. The throughput of this feeder is adjustable during operation, allowing easy optimisation.

Pumpable products are normally in a highly viscous and sticky form when passing through the drying phase. Towards the end of the drying phase and influenced by the steam bubbles, a dry cake is formed. This cake is brittle and is broken at the end of the belt and, if required, granulated.

The vacuum belt dryer consists of a casing with built-in conveyor belt. The belts are made from selected PTFE-coated glass fibres. For the continuous and automatic operation of such a plant, a belt control device that runs reliably for a long period is imperative.

To achieve a certain product quality, the heating temperature during drying is of essential importance. In the traditional vacuum belt dryer, the belts normally run through three or four heating zones followed by a cooling zone at the end. These are fed with hot water, steam or thermal oil. In microwave heating, the microwave system shown in Figs 14.26 and 14.27 has been carefully designed, with variable power and homogeneous E-field distribution, to ensure optimum and even energy transfer into the product. The temperature profile may be selected to the needs of the product. The product temperature is controlled by infrared thermometers installed on top of the dryer. When the product temperature reaches a critical value, the microwave power will be reduced automatically. The generators used in microwave heating systems are normally in the range of 1–6 kW/2450 MHz.

The normal working vacuum pressure for drying is in the range of 10–50 mbar abs. The outlet sluice chamber can also be used as a product buffer hopper. The material is discharged in a cyclical way during continuous operation. The vacuum for the inlet and outlet sluice chamber is provided by a separate vacuum system.

The complete microwave vacuum dryer is controlled by a PLC system. Data recording and process visualising as well as active process diagrams can be managed with a Windows PC.

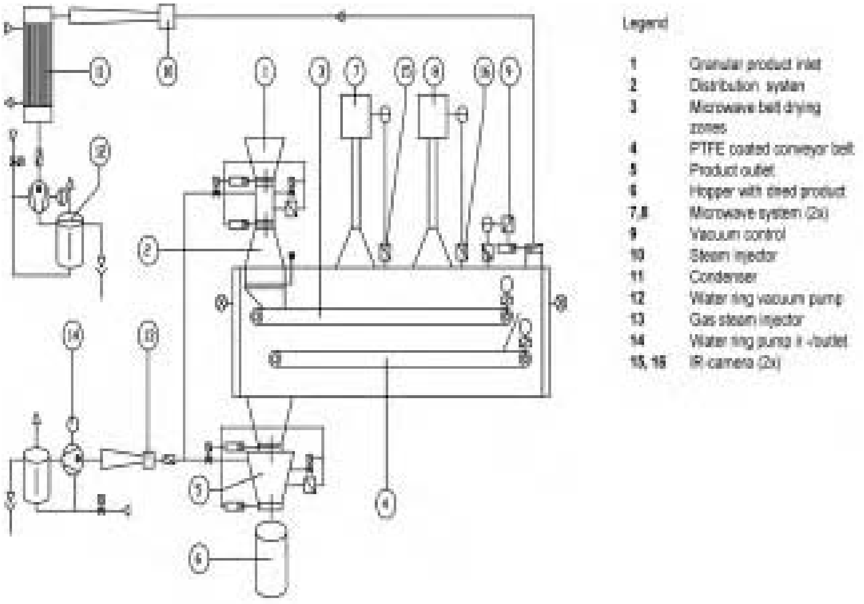


**Fig. 14.26** Process flow diagram.

**Fig. 14.27** 12 kW/2450 MHz double stage continuous belt dryer.

Standard protocol interfaces based on RS232 or Ethernet are available. As an http-server the microwave plant can be set up in a TCP/IP network and allow *web enabled engineering* as well as remote control access via an intranet and the Internet.

For cleaning, two options are available:

- Integrated cleaning
- External cleaning by removing the complete transport system.

The continuous microwave vacuum dryer provides optimal settings in order to achieve best drying results. The following parameters can be adjusted:

- Flow rate for granular or for viscous products
- Nozzle section, nozzle distance to belt, charge width of viscous products
- Foam of the product whilst charging the belt
- Closed product foam
- Inlet cycle time and product rate for granular product at the inlet sluice chamber
- Belt speed
- Vacuum
- Microwave power
- Outlet cycle time.

### 14.4.3 Process under ex-protection

For drying of solvents in pharmaceutical products the microwave vacuum dryer in Fig. 14.28 was developed. As a 2.4 qm disk dryer (containing a stack of disks with a total area of 2.4 $m^2$) it can be used with circulating air heating as well as with vacuum. In view of the requirement for protection against explosion, a redundant oxygen measurement system is used to control the procedure of applying nitrogen to render the atmosphere inside the vacuum vessel inert.

The evaporation of a solvent, e.g. ethanol, is measured with an online infrared measurement system in order to avoid critical gas concentrations within the vacuum vessel. A PLC system is used to control the drying process with an inbuilt online load cell, infrared and a fibre-optical temperature measurement. The microwave vacuum dryer fulfils the requirements of cGMP.

A flexible PLC with a process control language guarantees that each batch is reproducible. In end-drying the absolute deviations from all product positions on all disk layers are smaller than 0.2%. A typical drying curve is shown in Fig. 14.29.

### 14.4.4 High pressure

The disposal of moist organic wastes with a moisture content of typically 75–85% poses a severe problem. Various thermal treatment methods have been established. These, however, require preliminary drying of the wastes, which can be very energy consuming.

**Fig. 14.28** Microwave disk dryer for combined air circulation and vacuum mode under explosion protection.

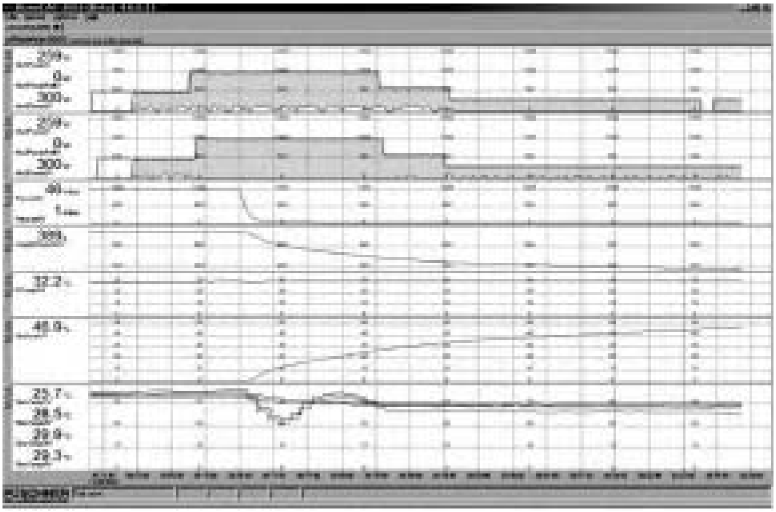


Fig. 14.29 Visualised drying curve of a thermo-sensitive pharmaceutical solvent raw materials.

A high-pressure thermochemical conversion, which originated from the HTU (Hydrothermal Upgrading) process developed by Shell Laboratories under the name of STORS (Sludge to Oil Reactors System), was applied to sewage sludge. Figure 14.30 schematically illustrates the conversion process. Due to their high degree of moisture, biomass wastes are suitable for microwave treatment, which offers the following major advantages:

- No deposits on the inside of heated walls
- Fast and homogeneous volumetric heating
- Moderate heating conditions, with no local temperature peaks
- Fast process control through immediate cut-off of energy supply.

These features lead to the conclusion that, for the same throughput, microwave reactors can be made smaller than conventionally heated reactors, thus requiring less investment and also less operation costs. An experimental setup of the continuous high-pressure microwave reactor is shown in Fig. 14.31.

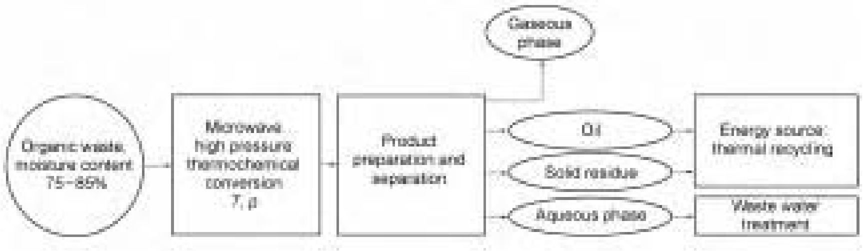


Fig. 14.30 Scheme of the microwave thermochemical process.

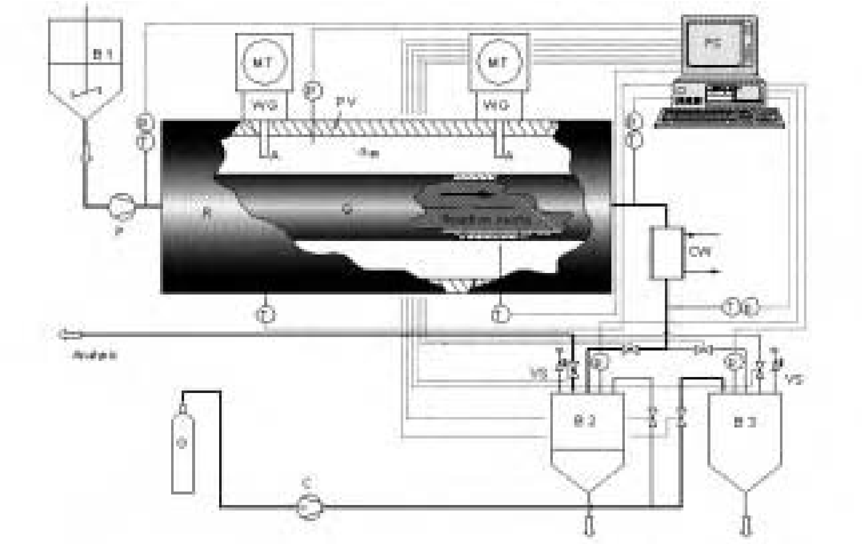


**Fig. 14.31** Continuous high-pressure microwave reactor.

The thermochemical conversion of moist sewage sludge under high pressure yields a product mixture of aqueous and gaseous phases as well as the economically relevant product oil and solid residue. On average, added yields of both fractions were 40.5% (waf). After centrifugation the product mixture contains sediment $e_{\text{sediment},50\%} = 5.69\,\text{MJ/kg}$ specific energy as opposed to sludge $e_{\text{sludge},19.9\%} = 1.96\,\text{MJ/kg}$.

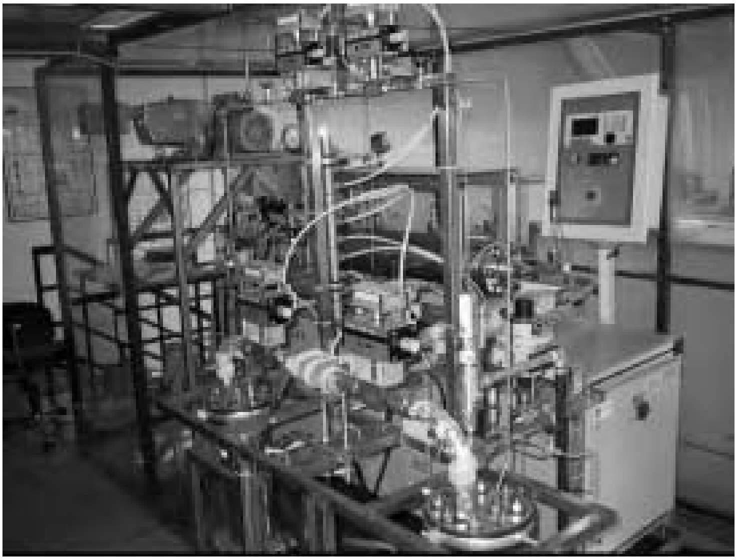


**Fig. 14.32** 2 × 2 kW/2450 MHz pilot plant at the TU-Berlin, Institute of Biotechnology.

The application of a novel thermochemical conversion process employing microwave energy can be regarded as an economic alternative to conventional disposal methods such as incineration or pyrolysis. There are two main aspects: first, the extent to which otherwise necessary costs for drying are reduced, and secondly, how product separation and recovery are achieved, thus the conditions in which products are provided. The application was realised in conjunction with TU-Berlin (Fig. 14.32).[5]

In general, the continuous high-pressure microwave reactor offers a wide field of application:

- Chemical reactions
- Adsorption/desorption process
- Extraction process
- Sterilisation/homogenisation in the food industry.

## 14.5 Future trends

The worldwide trends to 6 sigma qualities stimulate efforts to achieve better quality and to develop new process technology. Microwave volume heating can be used for new processes as well as to speed up heating and drying processes in existing production lines with better quality results. *Smart microwave heating and drying plants* have the potential to fulfil future requirements for better product designs. To install suitable microwave plants means to combine process understanding with optimal microwave design knowledge as well as to build robust and self-controlled intelligent machines.

## 14.6 Further reading

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# 15

# Improving the heating uniformity in microwave processing

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## 15.1 Introduction

This chapter is an overview, focusing on methods for making microwave heating distribution as uniform as possible, with examples given of some selected applications. Since the space is limited, this overview cannot be extensive; instead, some important theoretical remarks will be made, where methods for improving the uniformity in microwave heat distribution are exemplified or referred to. This chapter provides a starting point; the interested reader can find more information on the details in the references.

In Sections 15.2–15.4, the problem of non-uniform heating is described, exemplified and discussed. References are given to previous works, and in Sections 15.5–15.6 some selected methods and tools are mentioned which are helpful when designing food products intended for microwave heating. The techniques referred to in this chapter are possible for use in improving microwave heating uniformity in many applications. Such applications may be e.g. heating in household or institutional microwave ovens or different types of industrial microwave heating appliances. More on this can be found, for example, in Section 15.7. Finally, a section on future trends is given, followed by sources of further information and advice (Sections 15.8–15.9).

## 15.2 Heat distribution and uniformity in microwave processing

Microwaves are defined as electromagnetic waves of a frequency in the range between 300 MHz and 300 GHz, with corresponding wavelengths from 1 m to 1 mm. The frequency is, however, limited for food applications to the ISM (Industrial and Scientific Medical) band of 2450 ± 50 MHz. In the United States, another recognized ISM frequency is 915 ± 15 MHz. In European countries except for the UK, the latter frequency is not generally available.

Over the years, microwave heating of foods has sometimes been connected with uneven heating, due to the 'hot and cold spots' which may be present in the food product after heating. The temperature distribution in microwave heated foods is determined by the thermo-physical properties of the food product as well as of the distribution of the absorbed microwave energy. The microwave heating distribution in the food is, in turn, determined by the electric and the magnetic fields (the latter ones by inducing displacement currents, which may contribute to the heating pattern to a smaller or larger extent depending on the load impedance) inside the microwave cavity or applicator, by the dielectric properties of the food but also by the microwave frequency. The electromagnetic field pattern can be controlled by the oven design (e.g. size and shape of the cavity or applicator), including the design of the waveguide system, but heating uniformity is also influenced by composition, position and geometry of the food as well as of the package during heating. This will be dealt with further in Section 15.2.1.

More on the principles for microwave heating can be found in the literature. The subject has been described by several authors, e.g. Bengtsson and Risman (1971), Ohlsson (1983), Walker (1987), Buffler (1993), and Ohlsson and Bengtsson (2001).

### 15.2.1 Factors influencing microwave heating uniformity

During microwave processing, several interacting factors influence the heating result in a complex way. Factors which are affecting the heating uniformity are among others the design of the waveguide or applicator system and of the cavity, the geometry, size, and dielectric as well as thermal properties of the food material. Additionally, the composition and geometry of the package will influence the heating result, as will the spacing between neighbouring products if several items are heated at a time. Furthermore, not only electromagnetic field pattern, heat conduction, radiation as well as convection of heat, but also water transport in the food may influence the overall temperature distribution. The microwave oven mode properties, related to cavity volume modes and trapped surface waves (Risman, 1994), play a dominant role for heating from above and below, respectively.

For multi-component ready meals, additional factors like the geometry, size, and placement of the included components will also be important for the heating result. So will the distance between neighbouring components. More on this subject is discussed in Section 15.4.1.

### 15.2.2 Heating phenomena which influence uniformity

Examples of phenomena related to microwave heating uniformity are *edge overheating* caused by strong electric fields parallel to an edge of a food load, *run-away heating* in frozen foods, and *standing wave patterns* in food items.

*The run-away heating phenomenon*

In frozen foods, most of the water content is found as ice crystals within the food item; pure ice has very low dielectric properties as compared to thawed foods. However, approximately one tenth of the water remains unfrozen as a strong salt solution inside the food, which explains why frozen foods do absorb microwave energy at all (Ohlsson and Bengtsson, 2001). Since the regions which will thaw first have much higher loss factors $\epsilon''$ they will heat very rapidly in comparison to still frozen regions. This is called thermal runaway heating (Buffler, 1993).

*Edge and corner overheating*

When thawing and heating frozen foods, edges and corners thaw first, due to the so called edge (or corner) overheating effect (see Fig. 15.1). Edge overheating is caused by scattering phenomena. It can be explained by the fact that at the boundary between the food item and the surrounding air, one of the boundary conditions when solving the electromagnetic problem leads to the continuity of the parallel component of the electric field. Edge overheating is strongly influenced by the polarization and incident angle of the incident field, the angle and curvature of the edges, the presence of other scatterers close to the edge, and the permittivity of the heated food materials (Sundberg, 1998a). For food items, where loss mechanisms due to ionic conduction as well as dielectric relaxation are present, the effective loss factor $\epsilon''_{\text{effective}}$, where both types of loss are included, is often used (Metaxas, 1996).[1] The relative effective loss factor is then described by:

$$\epsilon''_{\text{effective}} = \frac{\sigma}{\omega\epsilon_0} + \epsilon'' \qquad [15.1]$$

where $\sigma$ is the electrical conductivity in S/m, $\omega$ is the angular frequency in radians/second, $\epsilon_0$ is the absolute permittivity of free space, and $\epsilon''$ is the loss factor. The dissipated time-averaged power density $p_{\text{diss}}$ (W/m$^3$) in typical food products is proportional to the square of the electric field,

$$p_{\text{diss}} = \frac{1}{2}\text{Re}\{\vec{E}\cdot\vec{J}^*\} = \frac{1}{2}\omega\epsilon_0\epsilon''_{\text{effective}}|\vec{E}|^2 \qquad [15.2]$$

where $\epsilon''_{\text{effective}}$ is the relative effective loss factor of the food material, $|\vec{E}|$ is the amplitude (peak value) of the electric field intensity (V/m), and $\vec{J}^*$ is the complex conjugate of the electric current density (A/m$^2$). In eqn 15.2, it has been

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[1] For applications related to microwave heating of foods, the loss factor refers to two types of losses into heat: the dipole relaxation and the ion conductivity. At other frequencies, however, other mechanisms may be more dominant (Hasted, 1973).

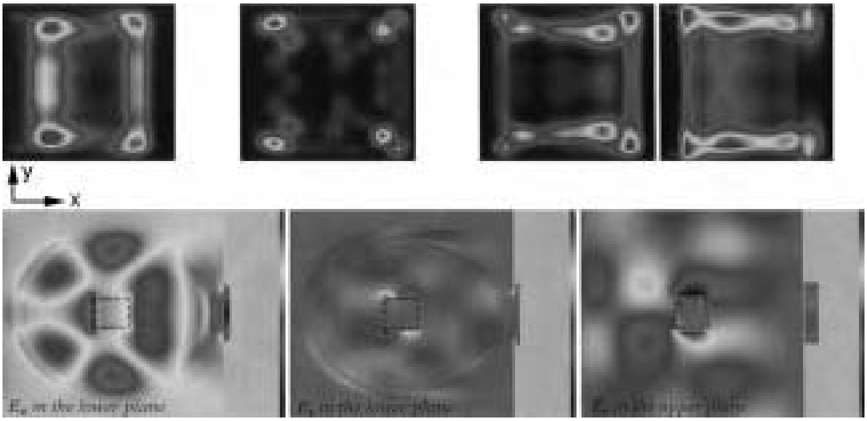

**Fig. 15.1** The upper part of the figure illustrates microwave heating of one rectangular block (50 mm × 60 mm × 60 mm) in a model microwave oven with a sinusoidal waveform excitation and rectangular $TE_{01}$ excitation field (Wäppling-Raaholt and Janestad, 2003). From left to right: heating patterns in lower plane (5 mm from the lower surface of the block), middle plane (at 30 mm height), and upper planes (10 mm and 5 mm respectively, as measured from the upper surface). The corners and vertical edges are overheated. So are the horizontal edges in the $x$ direction at the upper surface, and the horizontal edges in the $y$ direction at the lower surface. The lower part of the figure indicates the strong electric field components in parallel with the edges. The contours of the load are marked with a dotted black line. The electric field components, $E_x$ and $E_y$ in the lower plane and $E_y$ in the upper plane (5 mm from the upper surface) are shown.

assumed that the food is magnetically close to vacuum, i.e. the relative complex permeability $\mu$ is assumed to be 1.

At the edges of the food item, microwaves approach the food from two directions. Furthermore, electric fields of two polarisations are parallel to a surface at the boundary. The continuity boundary condition of the parallel electric fields explains the resulting concentration of the energy distribution to the sharp edges. This is one of the dominating heating uniformity problems in rectangularly shaped foods. Analogously, for corners, the corresponding will be the case for electric fields of three polarisations, resulting in an even more pronounced heating at the corners. In many cases, more than 15% of the microwave energy which is absorbed by the food sample is lost by the edge overheating phenomenon (Risman, 1992). An investigation of the edge overheating effect for high-permittivity dielectrics is found in (Sundberg, 1998a). Furthermore, resonances between food items in the near vicinity of each other are illustrated in Fig. 15.2.

*Centre overheating*

For foods with convex surfaces, e.g. spheres and cylinders, the power distribution is concentrated to the geometrical centre for certain diameters (Ohlsson and Risman, 1978), due to refraction and reflection phenomena. This centre overheating is influenced by different geometries, sizes, and complex permittivities. In Fig. 15.3 the phenomenon of centre overheating is exemplified.

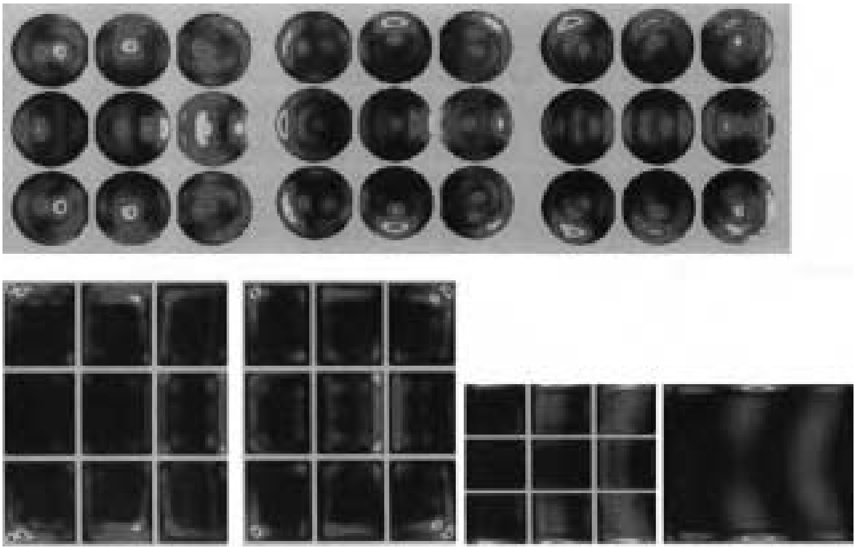

**Fig. 15.2** The dissipated power in food loads located close to each other, heated in a model microwave oven with a sinusoidal waveform excitation, and rectangular $TE_{01}$ excitation field (Wäppling-Raaholt and Janestad, 2003). Resonances between cylindrically shaped food items in the near vicinity of each other are illustrated in the uppermost figures. The lower part of the figure: the corresponding situation for several rectangular blocks (9 blocks close to each other; the leftmost figure shows the result for the middle horizontal plane, while the second figure from the left shows dissipated power 5 mm from the upper surface of the same blocks). The two rightmost figures illustrate that the heating pattern in 9 blocks will show similarities to the corresponding result for a single large block, having the same volume as the packs of nine.

### *Standing wave patterns in microwave heated foods*

There are several different types of standing wave phenomena in foods during microwave heating (Ryynänen *et al.*, 2004). Standing waves may appear *between* plane upper and lower surfaces, *at* larger surfaces, *at edges* of larger surfaces (which in turn is partly due to the edge overheating effect, partly due to surface wave phenomena), and finally *within* certain thicker loads. The latter phenomenon is due to internal resonances, i.e. standing waves.[2]

The standing wave patterns of absorption and reflection (i.e. internal ‘hot and cold spots’) can be quantified by modelling in simplified scenarios, as described by Ryynänen *et al.* (2004) by using an extension of the transverse resonance method (Harrington, 1961) in order to include the behaviour of all TM and TE waveguide modes propagating in the vertical direction. A rectangular metal cavity is modelled, with a cavity height of a real microwave oven. Its horizontal dimensions are selected in order to obtain the wave pattern and heating distribution only in the vertical direction. The model includes horizontal load layers which extend completely to the vertical walls.

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[2] It should be noted that external resonance phenomena, like the exploding egg effect, is not a standing wave phenomenon.

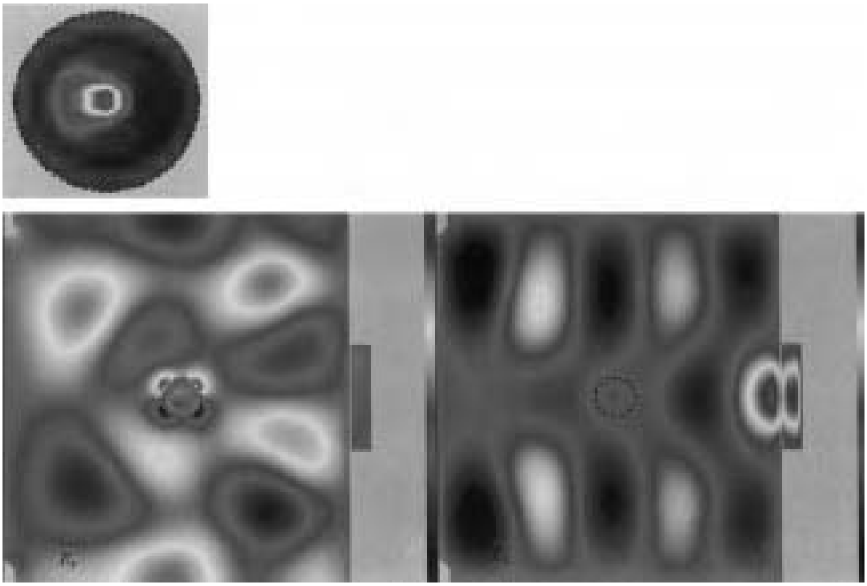

**Fig. 15.3** Centre overheating in cylindrically shaped meatloaf, placed with the circular bottom area at the turntable in a microwave oven. The load has thawed during heating (relative permittivity 52-j20 at 20 ºC). The radius of the cylinder was set to 20 mm, and the height of the cylinder was selected to be much larger than the radius, so that the heating in the centre of the cylinder at half its height would not be affected too much by heating effects at the edges. The upper figure shows the dissipated power in the cylinder at the middle horizontal plane (total height of cylinder = 160 mm). The next two figures illustrate the electric field pattern in the oven cavity and in the load, with the cylinder placed in the middle, for the *y* and the *z* electric field components, in the middle horizontal plane. The cylindrical load is marked with a dotted black line.

There are also other kinds of phenomena occurring when heating foods, e.g. those which are related to different penetration depths[3] for different kinds of food materials (see Section 15.4.1, where this is described for multi-component foods).

## 15.3 Heating effects related to uniformity

New microwave products have been developed on existing labels and elsewhere. In several cases good results have been achieved, but some food products do not perform well from a food quality point of view in microwave cooking, reheating or thawing. Quality variations related to heating uniformity are differences in temperature and moisture distribution in microwave heated foods as compared to conventional cooking. Higher moisture levels in the surface areas of

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[3] For a definition of the penetration depth in this context, the reader is referred to Risman (1991).

microwave heated foods may result in less development of desirable flavours for cooked foods and in variations in product appearance, which may lower sensory quality.

Ingredients especially designed for modification of microwave heating characteristics have been suggested to partly solve the problems encountered. Suggestions of such ingredients are flavours and salts; other examples are sweeteners and starches (Grimwood, 1989; Katt, 1991). Emulsifiers and suggestions of ways to increase the water content are mentioned by Miller and Hoseney (1997). Water and salt content are major factors in affecting the dielectric properties of a material. These in turn describe to what extent and how a material will absorb microwave energy and convert it into heat, how much the microwave wavelength will be reduced in the material, as well as how strong the reflection and refraction phenomena will be.

Non-even temperatures in microwave heated foods attracted much interest from the mass media, reaching a culmination in the early 1990s. Reports and articles on formation of undesirable components during microwave heating of instant milk formulas or said risks of microwave heated foods compared to 'natural' open fire cooking gained much publicity, which confused and worried some consumers and microwave oven users. In spite of the fact that these alarming reports have been shown not to be based on proper scientific investigation, there have been periods with a weak doubt remaining in the public mind regarding the safety of microwave heating and microwave heated foods. It should be noted that at the same time food nutritionists agree on the nutritional advantages of microwave cooking, e.g. in terms of improved retention of vitamins and minerals in vegetables (Ohlsson and Åström, 1982; Ohlsson, 1989).

Uniform heating is important also from a microbiological perspective. A subject of much publicity, particularly in the UK, has been concern about insufficient inactivation of food-poisoning bacteria in microwave heated foods. The risk that sufficiently high temperatures are not reached everywhere in the foods during microwave processing was discussed especially in the early 1990s (e.g. Walker *et al.*, 1991). Among others, Cole *et al.* (1991) evaluated survival of *Listeria monocytogenes* during microwave heating. When a temperature of 70 ºC is reached and maintained for at least two minutes throughout a food product, there is a substantial reduction in the numbers of *L. monocytogenes* (Walker *et al.*, 1991). However, such risks with microwave heating do not differ from those of traditional heating. Both types of heating methods require that foods are cooked throughout to the desired temperatures in order to inactivate pathogenic bacteria that may be present in the food (Ohlsson, 1991). Efforts towards solving the problem by improvement of the manufacturer's reheating instructions are reported e.g. by George *et al.* (1995), where an investigation into the reheating of lasagne meals, a multi-component product by that time known to be difficult to heat uniformly in a microwave oven, is described. Reheating instructions on the product label were, where necessary, further developed to allow a minimum of 70 ºC for two minutes to be achieved in the samples of commercially available lasagne. The new instructions incorporated longer heating times, rest periods, a 90° turn and retention of a pierced film lid throughout reheating.

Much of the discussion on safety and quality of foods is characterised by limited understanding of the qualitative and quantitative importance of factors related to heating uniformity. Since the early 1990s, improved heating uniformity of microwave ovens, improved cooking instructions, and novel methods for designing food products in a way which gives as high a level of uniformity after microwave heating as possible, have resulted in a solution to many of the previous concerns. Today, methods are available which can serve as valuable tools in design of microwaveable foods, with the aim to improve uniformity in heating patterns (Wäppling-Raaholt *et al.*, 1999, 2001; Wäppling-Raaholt, 2000). More on this can be found in Sections 15.4.1 and 15.6.

## 15.4 Examples of applications related to heating uniformity

### 15.4.1 Household and institutional microwave heating

Today's methods for achieving a more uniform microwave heating distribution may often assist in avoiding previous problems with non-uniform heating patterns (Wäppling-Raaholt *et al.*, 1999, 2001; Wäppling-Raaholt, 2000). As a first step, the factors which are relevant for the present application are sorted out, using a fractional factorial scheme applied on modelling of microwave heating of the food product in question. Next, a suitable selection of the relevant factors is studied further, and the optimal settings of values for these factors are found by optimising the heating uniformity with respect to the selected factors. It is possible to influence the heating distribution favourably, and in many cases it can be controlled towards the desired heating uniformity. At the same time, the heating times can often be significantly reduced. By optimising the design of the food product, based on the mentioned methods, it is possible to avoid uneven temperatures. It should be pointed out that, for a successful result, electromagnetic modelling and mathematical optimisation methods should be used as tools *in combination with* knowledge on microwave engineering and food science. Analogously, the method for optimising heating uniformity can also be used as an aid in oven design (Wäppling-Raaholt and Risman, 2000).

Microwave heating of multi-component foods in a multimode oven, such as household microwave ovens with a ceiling stirrer, may often be problematic due to non-uniform energy absorption. There are several reasons behind this. As in other microwave heating applications, the oven design will of course influence the electromagnetic field distribution and thus the temperature distribution in the food item (Risman, 1998). Furthermore, the different dielectric and thermophysical properties of the components will affect the heating result, as will microwave reflections caused by the boundaries between different components (Mudgett, 1986). The latter phenomenon is a result of the fact that each component will differ in microwave penetration depth $d_p$, due to the different relative permittivities between various components. Furthermore, the microwave reflections at the interfaces between air and food material will depend on permittivity for each component, frequency, as well as on the microwave oven mode properties. Several different *selective heating phenomena* like edge overheating, centre overheating, and runaway heating will also play a role. Such phenomena are described further in Section 15.2.2.

Methods for evaluating temperature distribution and heating uniformity have been developed, e.g. for the IEC standard works (IEC publication 60705, 1999). Such measurements must always be related to the performance in heating of actual food products (Ohlsson, 1981). Heating uniformity in microwave heated foods of different geometry has been studied experimentally using temperature measurements and infrared thermography as well as numerical modelling of the electromagnetic fields. In a study of composition of a layered product, a hamburger, and microwave heating uniformity, results by Ryynänen *et al.* (2004) suggest that uneven heating is difficult to improve by recipe modifications, and the resulting changes in dielectric properties alone.

However, factors of relevance for the microwave heating uniformity can be found by methods based on numerical modelling (Wäppling-Raaholt, 2000), which with the development towards today's faster computers serve as a tool in the product development of microwavable foods. Numerical modelling can assist in reducing the previous need for empirical work during product development, with a resulting shortening of the time from product idea to market. As an additional competitive advantage, the improved heating uniformity may often result in a decreased heating time.

### 15.4.2 Industrial microwave heating

The phenomenon of uneven temperatures in foods has been described for industrial applications by several authors. Here follows a selection of some examples on industrial microwave heating where heating uniformity is discussed. In some of these examples solutions for solving the problem are suggested. For a more complete picture of industrial microwave heating applications, than the limited space here allows for, the reader is referred to Ohlsson and Bengtsson (2001).

In multi-applicator tunnel ovens, the dominating causes of non-uniform heating are load diffraction phenomena in combination with the applicator heating pattern (Sundberg *et al.*, 1995). Among possible industrial applications of such ovens are: drying of wood (Antti, 1997), drying of various foods (Funebo and Ohlsson, 1997), as well as pasteurisation and sterilisation of foods (Sundberg *et al.*, 1996). Since in the latter application the packaged ready meals on the conveyor belt are moving under (or over) the applicator, its momentaneous overall microwave efficiency will often vary significantly, which sometimes results in an even more pronounced heating non-uniformity. On the other hand, irregular fields in the feed direction will be evened out by the continuous movement of the food on the conveyor, similar to the function of the rotating turn table in a household oven. In addition, the non-linear behaviour of magnetron sources complicates the overall efficiency problem. If circulators are used, this problem will be reduced.

An industrial unit operating under «steady state conditions», may give better load matching and larger power efficiency. In general, industrial microwave applications often show a more even field and temperature distribution (Ohlsson and Bengtsson, 2001). Sundberg (1998b) studied the analysis and design of industrial microwave tunnel ovens, and suggested a quantification of heating uniformity in multi-applicator tunnel ovens (Sundberg *et al.*, 1998). More details are found in Section 15.6.

Single mode applicators will often allow for the use of very high field strengths, if designed to give a uniform field inside the food material. For a specific food and a specific application, such applicators have to be carefully tailored since the introduction of the food material into the applicator affects the electromagnetic field distribution considerably. Risman and Ohlsson (1975) described a tubular $TM_{020}$ applicator, which was designed for continuous microwave processing of pumpable liquid or semi-liquid foods. By choosing a suitable tube thickness, the heating profile can be controlled towards a compensation of the centre heating by the higher centre velocity of the food stream due to the flow profile (Ohlsson, 1993). Inspired by a patent by Risman (1997), Isaksson *et al.* (2002a) used numerical modelling to design an applicator for continuous microwave heating of pumpable foods, with the aim to enable the design to permit larger workload radii with as small an axial field variation as possible, also at 2450 MHz, by superposition of two single modes. The design of the feed system as well as of the circular cavities are both important for a successful heating result. In order to get the desired heating pattern associated with each specific mode, a proper design is important, especially for applications with microwave heating of high loss loads.

## 15.5 Modelling of microwave processes as a tool for improving heating uniformity

### 15.5.1 Background

Modelling plays an important role as a tool to give an increased knowledge and understanding of microwave heating of foods. This knowledge may be used to optimise the process with regard to certain quality means, such as increased heating uniformity which in turn also improves the quality from a microbiological as well as a sensory and nutritional point of view.

The mechanisms behind the general behaviour in an empty cavity are described in several textbooks (e.g. Kok and Boon, 1992). However, in the case of microwave heating of a food item, the situation generally becomes much more complex. An analytical or exact solution of Maxwell's equations is unfortunately extremely difficult, or impossible for all but the simplest product geometries and cavity configurations. A valid alternative is to use numerical modelling; a survey of computational methods for electromagnetics and microwaves is given by Booton (1992). Among such methods are the finite difference time domain approach, first described by Yee (1966), the finite element method (e.g. Silvester and Ferrari, 1983), and method of moments (Harrington, 1968). Furthermore, hybrid methods, combining the finite difference time domain scheme and the finite element method for Maxwell's equations have been described and tested (Rylander and Bondeson, 2000).

Modelling of microwave processes involves solving for the electromagnetic fields, described by Maxwell's equations (Maxwell, 1892), coupled to the heat transfer problem. SIK has a long tradition within modelling of microwave heating, with work starting already in the 1970s (Ohlsson and Bengtsson, 1971; Ohlsson and Risman, 1978). With the development of modern computers towards increasing power, numerical modelling of electromagnetic fields in the ovens and foods during heating has become a valuable tool when designing microwave heating units as well as microwaveable food products and packages. For microwave processing of foods, the electromagnetic problem can be solved numerically by several methods. The most common ones are: the finite difference time domain FDTD method (Yee, 1966; Taflove, 1980; Lau and Sheppard, 1986; Gwarek, 1988; Sundberg *et al.*, 1996), the finite element method (FETD) (Dibben and Metaxas, 1994), and the Method of Moments (MM) (Yamashita, 1990). Furthermore, hybrid methods like the stable FEM-FDTD method (Rylander and Bondeson, 2000) have been developed. Several commercial software packages are now available, which have offered increased opportunities to use modelling as a tool to find the optimal solutions for microwave processing, with regard to design of food products but also oven design.

By coupling electromagnetic models to heat transfer models, it is possible to predict the temperature distribution within the processed foods. As was described by Wäppling-Raaholt (2000), Fu and Metaxas (1994) included coupling of the electromagnetic to the thermal process using the method of lines (Fu and Metaxas, 1993). Ma *et al.* (1995) suggested a combined electromagnetic and thermal FDTD model, however with time steps in the two algorithms of very different order of magnitude. Torres and Jecko (1997) suggested the use of a time-scaled form of the heat transfer equation in order to overcome this difficulty. In both papers, temperature dependent thermal properties were included in the model, though only to a limited extent due to the complexity of the numerical model. However, the thermal properties of the microwave heated dielectrics were held constant by these and other authors, and microwave-only heating was modelled (i.e. no convective boundary conditions were included). Zhang and Datta (2000) also studied a microwave-only heating process, using a finite element (FE) frequency domain software for the microwave part, and a separate FE software for the heat conduction part. Variations of dielectric properties and weak convection were taken into account. However, they assumed constant thermal properties and did not include any surface evaporation. Wäppling-Raaholt *et al.* (2002) modelled and validated combined microwave and forced air heating of foods in a microwave combination oven, using the FDTD method, taking into account the temperature dependence of the thermo-physical properties, convective heat transfer at the boundaries and evaporation in the product.

Recent developments are modelling of microwave defrosting of foods in three dimensions (Wäppling-Raaholt and Janestad, 2003), taking into account the strong enthalpy and temperature dependence of dielectric and thermal properties.

### 15.5.2 Modelling as a tool in product development

Today's knowledge in coupled electromagnetic and heat transfer modelling (Wäppling-Raaholt *et al.*, 2002; Wäppling-Raaholt and Janestad, 2003) can, in combination with knowledge and experience in food science give enhanced opportunities to improve design of microwaveable food products. This has been demonstrated by Wäppling-Raaholt *et al.* (1999), Wäppling-Raaholt (2000), and Wäppling-Raaholt *et al.* (2001). Since then, several projects where these methods have been used have been performed successfully. Figure 15.4 illustrates the predicted power distribution as a result of numerical modelling of microwave heating of a compact ready meal.

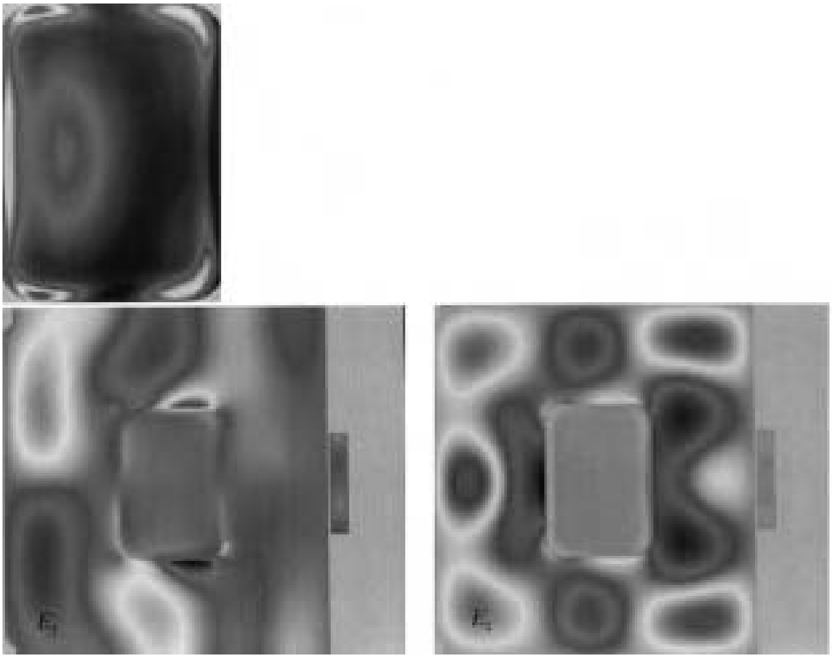

**Fig. 15.4** The predicted power distribution as a result of numerical modelling of microwave heating of a compact ready meal (the top part of the figure). In this example, the meal is a rectangularly shaped load with rounded corners. The top figure illustrates the result for the horizontal cross-section located 5 mm below the upper surface if the load. At that plane, overheating occurs at the corners and at the left edge. The electric field components in the $y$ and $z$ direction in the cavity and load are illustrated in the lower part of the figure. Model oven as in Wäppling-Raaholt and Janestad, 2003, with a sinusoidal waveform excitation, and rectangular $TE_{01}$ excitation field.

## 15.6 Techniques for improving heating uniformity

Heating uniformity in microwave processing can be improved in different ways. Among such techniques can be mentioned the modification of relevant food or package parameters in order to optimise the heating uniformity based on modelling and suitable schemes for describing and evaluating the selected optimisation parameter (Wäppling-Raaholt *et al.*, 1999, 2001; Wäppling-Raaholt, 2000). These tools are today important in food product development. The same concept may also be used in microwave oven design (Wäppling-Raaholt and Risman, 2000). Other complementary aspects related to techniques for improving heating uniformity are, on the other hand, oven devices like rotating turntables in household microwave ovens or moving conveyor belts in industrial appliances, but also mode stirrers which may often result in improved uniformity. There are also several different patents and solutions for exciting the microwaves in a way which results in a more uniform field pattern, one of which will be mentioned in this section.

The introduction of a mode stirrer in several types of oven will assist for a selection of the possible modes to exist in the cavity, as determined by the rotational speed of the mode stirrer. Alternatively, or as a combination, movement of the food through the field on a rotating turntable at the bottom of the cavity makes it possible for temperature differences to be partly levelled out, since the field pattern will be affected accordingly. Even if rotating turntables and mode stirrers may to some extent often result in more levelled out heating patterns, the need for a proper design of the food and package, as well as of the relevant oven parameters is still obvious.

As mentioned in the previous section, modelling of microwave processes may serve as a tool to learn more about a process, and for improving the heating uniformity by finding the optimal values of relevant food and package parameters, or alternatively relevant oven parameters. In many practical situations it can also be used to reduce the number of experiments needed to find the best design of a food product. The previously empirically based product development of microwave foods has been replaced by numerical modelling, followed by validation, computer simulations and optimisation.

For analysis of industrial microwave ovens, Sundberg *et al.* (1998) suggested the introduction of the concept of cost functions in order to classify the performance of a specific oven design. The cost functions assign a figure of merit to the field distribution within the oven, and serve as a measure of how close the field generated by the oven comes to the requested field distribution. Sundberg introduced two different cost functions, one that will give as uniform heating as possible in the load (eqn 15.3), by minimising the difference between the hottest and coldest part of the food, and one that will suppress the horizontal component of the electric field in order to minimise overheating of the edges of closely positioned food packages, transported on a conveyor belt (eqn 15.4).

$$f_1(a,b,c,X) = \max|\vec{E}|^2 - \min|\vec{E}|^2 \qquad [15.3]$$

$$f_2(a,b,c,X) = \frac{\sum |E_x|^2 + \sum |E_y|^2}{\sum |E_z|^2} \qquad [15.4]$$

where the sums are taken over all points included in the set of data. Sundberg further suggests the use of 'simulated annealing' (Press *et al.*, 1992), as a suitable optimisation method. The reason for this is the presence of many local minima, due to the strong variation of the field inside the cavity and within the food load.

In a patent by Risman (1997), a technique for exciting pure $TM_{0n0}$ and $TM_{1n0}$ modes is described, together with on the one hand a method to superimpose these modes to enable larger work load radii, and on the other hand a principle for enlarging the cavity length. Isaksson *et al.* (2002a) used the same concept for achieving uniform heating by combining selected modes for a microwave process where meat is continuously heated, as briefly described in Section 15.4.2.

The penetration depth $d_p$ is considerably higher (approximately 2.5 times larger) for microwave frequencies of 915 MHz than at 2450 MHz, under the assumption of similar permittivities at both frequencies. This has been used, for example, in applications with continuous tubular microwave heating, in order to overcome the disadvantage of limited penetration depth for the 2450 MHz (Nykvist and Decareau, 1976; Isaksson *et al.*, 2002b). However, at lower frequencies, the temperature dependence of the complex permittivity becomes stronger (Ohlsson *et al.*, 1974), which has to be taken into account in the electromagnetic modelling. This results in more time-consuming 3D simulations than in other cases. A simple and fast tool, based on a semi-analytical method for solving the eigenmode problem and for estimation of the heat profile, in order to get a quick view of the behaviour of the process, was developed and suggested by Isaksson (2002a). The system of equations for the electromagnetic axial fields is given by Jin (1993). Under the assumption of an axially uniform field, and no azimuthal variation of $\epsilon$ and $\mu$, the modes become TE (transverse electric) and TM (transverse magnetic). For TM modes, this leads to the radial solution to Bessel's differential equation

$$\frac{1}{r}\frac{\mathrm{d}}{\mathrm{d}r}\left(r\frac{\epsilon}{k_t^2}\frac{\mathrm{d}E_z}{\mathrm{d}r}\right) - \frac{\epsilon m^2}{k_t^2 r^2}E_z + \epsilon E_z = 0 \qquad [15.5]$$

where $\omega$ is the angular frequency, and $k_t$ is the transverse wave number. This approach has several advantages, especially in the estimation of the heat profile for scenarios with markedly strong temperature dependence on the dielectric properties.

Wäppling-Raaholt *et al.* (1999, 2001) and Wäppling-Raaholt (2000) suggest a statistical criterion for a quantitative measure on the heating uniformity, namely the standard deviation of the dissipated power distribution normalized by the mean value, for representative planes of the food load. Practical examples on results for improving the heating uniformity of real food products are given in, for example, Wäppling-Raaholt *et al.* (1999, 2001) and Wäppling-Raaholt

(2000). As described in Wäppling-Raaholt *et al.* (1999) an error norm to control the grid computational accuracy was defined, as given in eqn 15.6:

$$ERROR = \frac{\sqrt{\sum_{(i,j,k)\in M} (P^{\Delta x}(i,j,k) - P^{0.9\Delta x}(i,j,k))^2}}{\sum_{(i,j,k)\in M} |P^{\Delta x}(i,j,k)|} \leq \epsilon \qquad [15.6]$$

where $M$ is a set of points in the food load, epsilon is a given error parameter, $P^{\Delta x}(i,j,k)$ and $P^{0.9\Delta x}(i,j,k)$ denote the power density at a point $((i+\frac{1}{2})\Delta x, (j+\frac{1}{2})\Delta y, (k+\frac{1}{2})\Delta z)$ for grids with cell sides $\Delta x$ and $0.9\Delta x$, respectively. A corresponding error norm to control the convergence of iterations was defined, as given in eqn 15.7:

$$ERROR = \frac{\sqrt{\sum_{(i,j,k)\in M} (P^{n+1}(i,j,k) - P^{n}(i,j,k))^2}}{\sum_{(i,j,k)\in M} |P^{n+1}(i,j,k)|} \leq \epsilon \qquad [15.7]$$

Several examples of successful results in design of food products, intended for microwave heating, have been given since then. Three such examples are given in Figs 15.5 and 15.6 (see Section 15.7). Furthermore, Figs 15.7 and 15.8 illustrate the possibilities to use modelling as a tool for predicting the microwave heating pattern for another two food products.

## 15.7 Applications to particular foods and processes

Today, methods are available (Wäppling-Raaholt *et al.*, 1999, 2001) and Wäppling-Raaholt (2000) which give the opportunity to design microwaveable food products with improved microwave heating characteristics. This is demonstrated for three types of ready-meals, meat loaf (Wäppling-Raaholt *et al.*, 1999), lasagne and a multi-component ready meal (Wäppling-Raaholt *et al.*, 2001), and illustrated in Figures 15.5 and 15.6. The corresponding heating results for two additional food products are illustrated in Figs 15.7 and 15.8.

Among industrial applications designed to give uniform heating a continuous microwave process of liver paste can be mentioned. Based on a technique for achieving uniform heating by combining selected modes (Risman, 1997), Isaksson *et al.* (2002a) use the same concept for a microwave process where meat, which is transported in the axial direction of a circularly cylindrical tube geometry, is uniformly heated. In the process, two single-mode circularly cylindrical cavities are involved, each carrying a different mode ($TM_{010}$ and $TM_{120}$ mode). This combination of modes allows for uniform heating if designed properly. Isaksson analysed the heating by a simplified one-dimensional

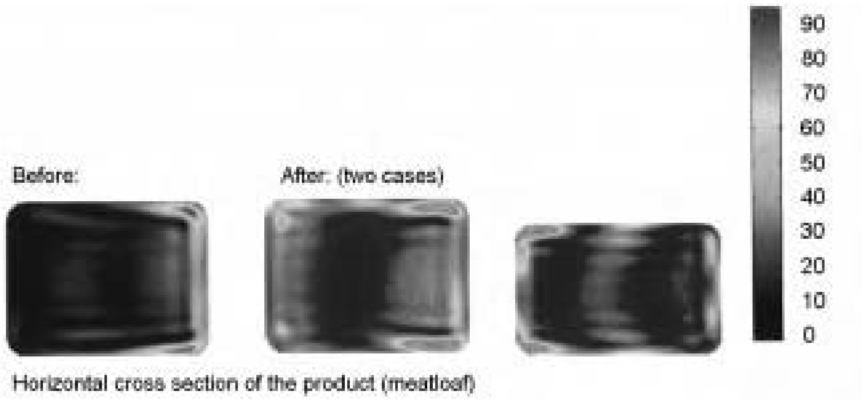

**Fig. 15.5** Microwave power distribution in meatloaf, as a compact ready meal, before (left) and after (the two figures to the right) optimisation. After optimisation, the geometry and dimensions of the package were changed. In the optimised cases, the overheated and underheated areas are less pronounced.

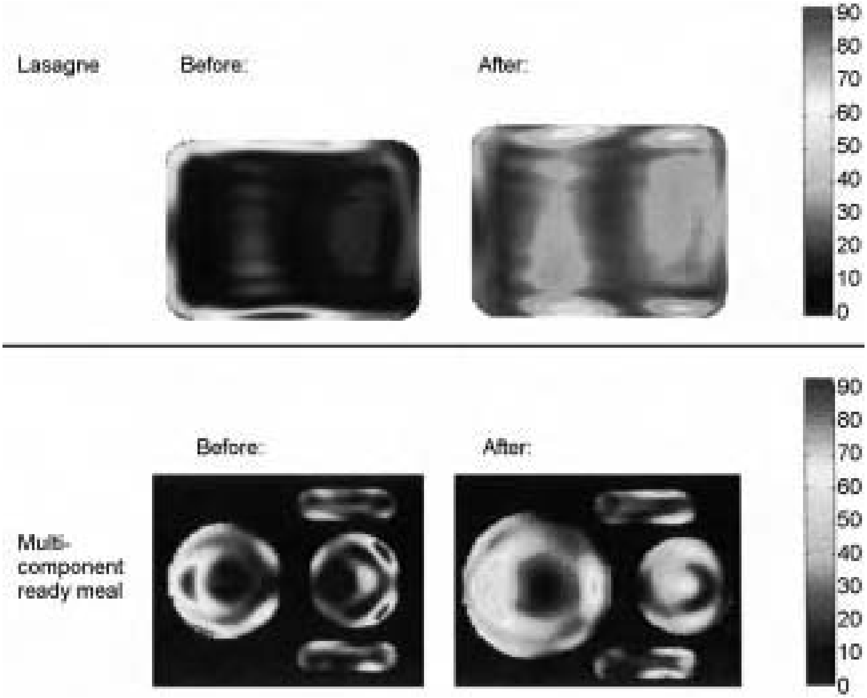

**Fig. 15.6** Dissipated power in lasagne and in a multi-component ready meal, before and after optimisation. The multi-component meal consists of a meat patty, mashed potatoes and carrots. In both cases, the same volume of the meal is maintained after optimisation. Geometries, dimensions and placement of the individual components were changed. The optimised meals have a more levelled out heating distribution.

**Fig. 15.7** Predicted dissipated power in a multi-component ready meal. The meal is heated from frozen, and consists of mashed potato (the larger component), two meat patties (at the bottom), and pieces of parsnip (upper left), and Swedish turnip (middle right). The heating uniformity would be more levelled out if the product were designed in a way which would allow a quicker thawing of several of the components and a more levelled out heating distribution between the components.

analysis, extended by introducing temperature dependent dielectric properties. The validity of the one-dimensional results was evaluated by full-geometry finite difference time domain simulations, which showed good agreement. This approach allows for analysis also at lower frequencies, where the dielectric properties show a stronger temperature dependence. The study was demonstrated on microwave processing of liver paste at 2450 MHz. A photograph of the experimental plant for continuous microwave heating of pumpable foods is shown in Fig. 15.9.

**Fig. 15.8** Predicted microwave heating pattern in a multi-component ready meal, consisting of two sausages, two components of mashed potato and pieces of blanched vegetables. From left to right: three different planes through the ready meal, lower, middle and upper planes, located 5 mm from each other. The lower plane is located 5 mm above the bottom of the meal. The overheated areas and the non-uniformity between different components indicate the need for optimisation of the product, similar to the solutions for the previous cases (see Fig. 15.7 and compare with Figs 15.5 and 15.6).

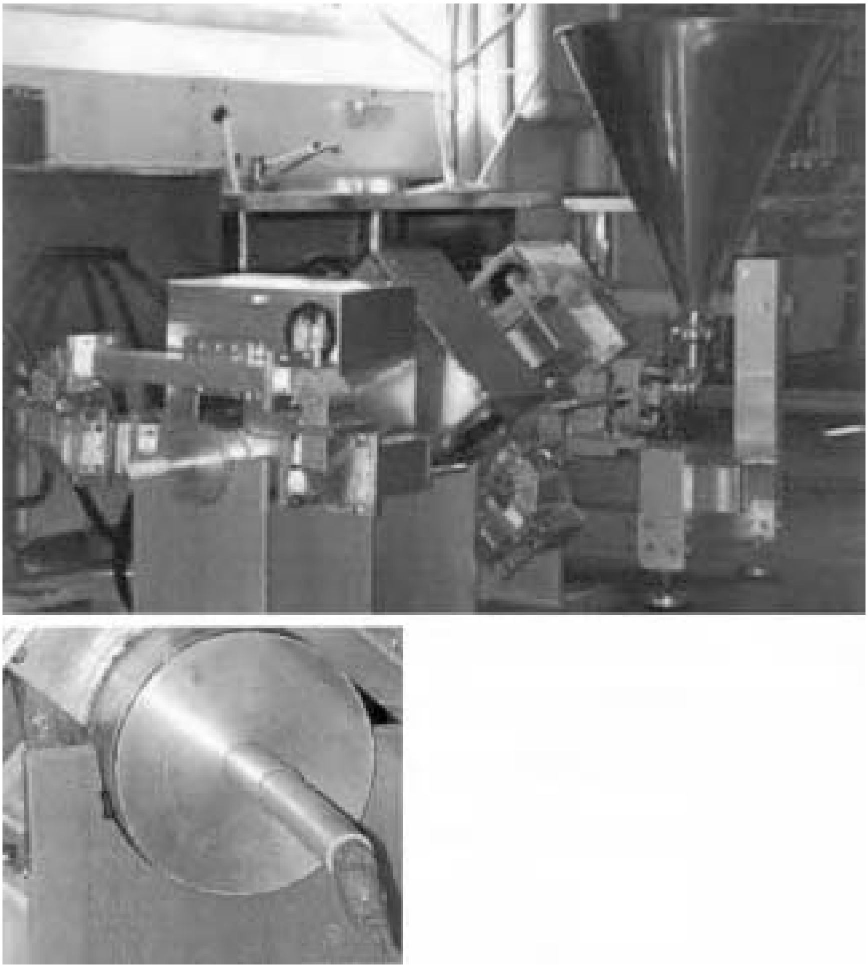

**Fig. 15.9** A pilot plant for microwave processing of liver paste at 2450 MHz, for continuous heating of pumpable foods.

## 15.8 Future trends

Household microwave ovens have become more and more common in many countries, with a saturation level in the kitchens in the UK and Northern Europe exceeding 80%, while in Australia, the United States and Japan the saturation level has for several years been well over 100% (Ohlsson and Bengtsson, 2001). The market for household microwave ovens is expected to grow world wide, although in a few countries, like Australia and the United States, almost all households already have one or more microwave ovens.

The increasing knowledge on electromagnetic field distribution during microwave heating and the interactions between the factors which influence the heating results, will gradually improve oven performance. Furthermore, the ongoing international standardization of performance and testing methods will lead to improved heating performance.

Modelling based product development in combination with packaging development (including different materials, shielding, susceptors, geometry etc.) has increased rapidly in the food industry during the last five years.

Furthermore, improvements in oven components, such as solid state components, will lower size, oven weight, and production cost. The number of combination ovens, combining microwave heating with convection or radiative heating is expected to grow continually at least in Europe.

Industrial microwave processing has been considered very promising for decades, but practical application has previously developed slowly. There are several reasons for expecting an increasing growth in the future:

Today's microwave heating units have a reliability which is well comparable to that of alternative processing equipment, which makes microwave heating with its special advantages more attractive.

There is a trend in the food industry towards continuous processing lines and on-line process control. Thus, there will be an accelerating need for microwave heating as a unit operation for very rapid and in-depth heating. The advent of more sophisticated applicators, giving more uniform power distribution and improved process control will be a contributing factor; both for the tubular heating of pumpable foods, and for the continuous heating of food packages on conveyor belts.

Tempering, pasteurisation, drying and snack production will probably also be the dominating applications in the future, but with a steadily increasing number of applications. With 915 MHz as a generally recognised ISM frequency, it will be important for industrial processing, because of its advantages in penetration depth and generator power and efficiency. However, properly designed 2450 MHz systems will also in the future be a strong alternative for many applications.

Further developed modelling tools will be invaluable tools for modern product design of microwaveable foods. By combining today's optimisation tools with knowledge on microwave engineering and food science, unique possibilities for optimising and developing microwave food products are generated. These tools will also enable modelling of combination processes, where microwaves are combined with other heating techniques. The tools will reduce the time from product development to market for food products within the microwaveable segment, with enhanced possibilities to meet the increased requirements from consumers and respond to market needs.

## 15.9 Sources of further information and advice

One of SIK's research areas of interest within microwave engineering is since many years improvement of heating uniformity in foods during microwave heating. Much of this work has previously been published. Parts of the present research will be submitted as papers to scientific journals, and presented continuously on SIK's web site: www.sik.se.

An introduction to the subject is found in Bengtsson and Ohlsson (1974). For further information on dielectric properties and their consequences for heating uniformity, the reader is referred to Ohlsson and Bengtsson (2001]. The subject of the principles for microwave heating is described by several authors, for example, Bengtsson and Risman (1971), Ohlsson and Risman (1978), Ohlsson (1983), Walker (1987), Buffler and Standford (1991, 1995), Buffler (1993), and Ohlsson and Bengtsson (2001). For a review of the fundamental aspects on electromagnetics and numerical modelling, see, for example, Dibben (2001).

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# 16

# Simulation of microwave heating processes

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## 16.1 Introduction

In the early days of microwave processing, but also up to the present day, the product and process development was essentially a trial-and-error procedure. Due to the lack of powerful computers and the complicated interactions of electromagnetism with heat- and mass transfer, it was nearly impossible to calculate realistic temperatures or even electromagnetic field distributions within microwave applicators, especially when products were involved.

The reason for this is the number of coupled partial differential equations, describing the physical problems of electromagnetism, heat- and mass transfer, which have to be solved in a parallel manner. Meanwhile for the separated problems, numerical software packages are available and there is also progress in the solution of the coupled problem, which best describes real processes.

The governing equations of electromagnetism, Maxwell's equations, have been already described in the physical principles' chapter (1), together with the wave solutions for the simple one-dimensional plane wave example. The resultant exponentially damped wave within a material with dielectric losses has also been often used for the three-dimensional case, in order to simply estimate the power distribution within products. More sophisticated approaches calculating more realistic solutions should be presented later in this chapter, first the governing equations for heat- and mass-transfer and the coupling to the electromagnetism should be introduced.

Starting from the continuity equation, the thermal energy equation and Fick's law, a general equation for the heat transfer can be described by:

$$\rho c_p \frac{\partial T}{\partial t} - \nabla \cdot (k \cdot \nabla T) = -\nabla \cdot q_R - \sum_i h_i I_i + Q_{em} \qquad [16.1a]$$

(For a complete list of symbols, the reader is referred to Section 16.5.)

Whereas the left side of this equation is well known from the traditional heat conduction equation, the terms on the right side have to be added for heat transfer by radiation and by a mass sink or source (e.g. phase change of water or due to diffusion or convection) and for the heat source by the dielectric losses, respectively (Metaxas, 1996).

If the product consists of a moist solid material, the radiative term has only to be taken into account at surfaces to gaseous materials yielding additional boundary conditions and the mass sink and source can be replaced by the moisture content changing:

$$\rho c_p \frac{\partial T}{\partial t} - \nabla \cdot (k \cdot \nabla T) = \epsilon_V \rho h_{\text{evap}} \frac{\partial M}{\partial t} + Q_{em} \qquad [16.1b]$$

Especially for the case of drying this equation is coupled to the mass transfer equation, here written for the moisture content *M*:

$$\frac{\partial M}{\partial t} = \nabla \cdot \left( \alpha_m \left[ \nabla M + \delta_T \nabla T + \delta_p \nabla p \right] \right) \qquad [16.2]$$

This equation becomes even more difficult, when a product porosity has to be taken into account with its capillary forces and the possible shrinkage.

The equation, describing the behaviour of the total pressure can also be found in (Metaxas, 1996):

$$\frac{\partial p}{\partial t} = \alpha_p \Delta p - \frac{\epsilon_V}{c_a} \frac{\partial M_l}{\partial t} \qquad [16.3]$$

The above equations and the electromagnetic equations are coupled in two ways: explicitly by the values of the temperature, the moisture content, the pressure and the electromagnetic heat generation (eqn 16.1) but also implicitly by the temperature and moisture dependency of the material properties. In general these material properties have also a directional dependency, which has to be expressed by tensor properties. This is especially valid for inhomogeneous natural material, as a well known example the variation of mass transfer coefficient along and orthogonal to the predominant fibre orientation can be mentioned.

Additionally these equations are already simplified by the assumption that there would be no volume change of the solid material structure. Indeed volume shrinkage can often be observed during heating because of drying. At the product surface, boundary conditions come into operation to take into account the external heat-, mass- and pressure-transfer, respectively.

Although there is a fast development of numerical calculation power, a complete calculation could not be done without some simplifications, up to now. Those simplifications have to be established, that neglect some of the above mentioned dependencies.

For the case of pure electromagnetics, commercial numerical software packages are available. A comparison of their potential for microwave heating has been addressed by (Yakovlev, 2000, 2001a, b; Komarov, 2001). Nevertheless also some home-built software codes are described in literature. Most of them originate from the telecommunication area but are developed further on to microwave heating applications, with their special demands. General to all numerical techniques is the discretion between the partial differential equations or their corresponding integral equations together with the suitable boundary conditions on a calculation grid.

In practical use most spread are the method of finite differences time domain (FDTD), the finite integration method (FIM), the finite element method (FEM), the method of moments (MOM), the transmission line matrix method (TLM) and the boundary element method (BEM), but also methods using optical raytracing codes. Again, we have to refer to special publications (Metaxas, 1996; Lorenson, 1990), for a more detailed overview. Some approaches should be mentioned here, together with the articles, where the interested reader may find more information.

For short times and high microwave power densities, the heat transfer, which is in this case much slower than the microwave heat generation itself, can be neglected. Whereas the one dimensional example has been already addressed in Chapter 1 analytically, which has educational value, of course, for more realistic problems two or three dimensions are needed. The temperature rise in a defined volume is then directly proportional to the microwave heat generation rate, which can be inferred from the effective electric field value and the dielectric loss factor. Some results using this approximation can be found for example in (Fu, 1994; Liu, 1994; Sundberg, 1998; Dibben, 1994; Zhao 1997).

Only in a few papers the electromagnetic model is already coupled to a thermal model, examples including the heat conduction can be found in (Torres, 1997; Ma, 1995; Knoerzer, 2004a; Kopyt, 2002, 2003, 2004). Additional to the heat conduction, heat transport by radiation may be addressed by a raytracing algorithm (Haala, 2000). Since for most food applications the temperatures are more moderate in comparison to ceramics sintering, where the latter software code originates from, this radiation seems to be more negligible than heat transport by convection or evaporation.

Whereas in one publication (Zhang, 2000) the heat transfer from the product surface by free convection in a microwave oven is addressed by the corresponding boundary condition, both ways of heat and mass transport within the product are taken into account only in more phenomenological studies: Either the microwave heating phenomen is simplified by using Lambert's or Mie's equations for special geometries (Lian, 1997; Jun, 1999), or the heat and mass transport is modelled by the use of non-local balances (Erle, 2000; Zhou,1995). Generally, it has to be concluded, the published model calculations are most limited to special cases or to very similar ones, where they have been applied successfully.

One example of a microwave heating simulation, incorporating thermal conductivity and also free convection (Knoerzer, 2004a), should be shown in detail in this chapter, in order to present the typical proceeding in microwave modelling. However, after model calculations, the verification of the simulation is also a very important task, that is in the case of microwave applications not at all simple. The electromagnetic fields are not easily measurable without changing them by the measurement procedure itself. The same has to be stated for the measurement of temperature distributions. A relatively old bibliography of different temperature indication methods in microwave ovens can be found in (Ringle, 1975). A more up-to-date comparison (focused on magnetic resonance imaging thermography) is given in Chapter 13.

## 16.2 Modelling techniques and capable software packages

### 16.2.1 Review of the suitable numerical methods

As already mentioned in the introduction to this chapter, partial differential equations (PDE) are the basis of the physical models that describe microwave heating. Analytical solutions of PDEs are not easy to derive in case of multidimensional problems, in scenarios with realistic boundary conditions or in case of complex shape of boundaries. Aspects like these are typically easier to handle with the help of numerical methods.

The two main numerical models typically used to solve PDEs in case of electromagnetism and heat and mass transfer problems are the finite differences time domain and the finite element method:

- *Finite Differences Time Domain Method (FDTD)*. The main idea of solving PDEs with a finite-difference based method is to replace spatial and temporal derivatives of the equation with their discrete approximations, that means breaking up one large problem into many smaller (and easier) problems. A grid of points (nodes) is placed on top of the geometry being modelled. The governing equations of the system under investigation are solved for each node at each time point in an iterative fashion until the final time point is reached. The approximations of the derivatives are obtained with Taylor series expansion. The governing equations can be very complicated when applied to the entire system as a whole, but can be written as a system of algebraic equations when applied to each node individually. A more detailed survey about finite difference time domain methods can be found in (Kopyt, 2002).
- *Finite Element Method (FEM)*. The finite element method is an approximation for solving partial differential equations by replacing continuous functions with piecewise approximations defined on polygons, which are referred to as elements. Usually polynomial approximations are used. The finite element method reduces the problem of finding the solution at the vertices of the polygons to that of solving a set of linear equations. This task may then be accomplished by a number of methods, including Gaussian

elimination, the conjugate gradient method and the multigrid method. In its variational formulation the accurate approximation of the solution is obtained through minimization of a certain function. For example in heat conduction the heat flow that occurs is such that the entropy is minimal. Solving a problem with the FEM method usually leads to formulation of large matrices with a time-consuming inversion. Even when iterative methods are used for matrix inversion the time needed for finding the solution is often longer than in the case of finite differences. Nevertheless it is a method often used because of its possibility to deal with complex shapes through proper choice of finite elements.

### 16.2.2 Advantages of finite difference methods

Besides the faster calculation, finite difference methods have a number of other advantages over finite element methods: finite difference methods are computationally more effective for electrically large structures, the calculations converge faster for lossy structures, what is essential for heating problems and the methods are directly applicable to nonlinear and time-varying circuits (Yakovlev, 2003). Furthermore finite difference time domain algorithms are not sensitive to round-off errors and thus applicable with low-precision arithmetic, another possibility to reduce computer resources (Yakovlev, 2003). Another advantage is the predictable simulation time and the possibility to observe intermediate (non-converged) results. In FEM, it is extremely difficult to predict the computing time and it is impossible to obtain preliminary results before the end of the computation.

### 16.2.3 Available software packages: electromagnetics and thermal solvers

Only few of the commercial simulation software packages for microwave power engineering allow an approach of a coupled electromagnetic and thermal problem by taking the process of heat transfer effects into account. Most applications are limited to either electromagnetic or thermal solutions. A possible approach is to couple electromagnetic and thermal solver to get an improved accuracy of calculations for microwave heating processes.

### 16.2.4 Electromagnetic solvers

The suitability of different commercial codes for electromagnetic simulation for development and design of industrial systems of microwave thermal processing have been addressed by (Yakovlev, 2000). To reduce the number of available codes, the codes for low frequency electromagnetics and the one dealing just with 2D approaches and open problems, such as antenna models etc. have been neglected. The remaining packages were exposed to the criteria on the software capabilities. The characteristics determined by numerical methods can be listed in order of increasing complexity:

- Lossy materials; phase and attenuation; eigenfields; power density;
- Fields excited by the given source;
- Dissipated power of the excited fields;
- Level of coupling;
- Specific absorption ratio (SAR) patterns.

Table 16.1 includes vendors and names of the full-wave 3D codes that passed the selection criteria. Further details can be found in (Yakovlev, 2000) and on the websites of the software vendors (see Table 16.1).

**Table 16.1** Commercial electromagnetic software in microwave power engineering (based on Yakovlev, 2000)

| Vendor | Code |
|---|---|
| Ansoft Corp.<br>http://www.ansoft.com | Ansoft HFSS 9.0 |
| ANSYS, Inc.<br>http://www.ansys.com | ANSYS/EMAG |
| CRC Research Institute, Inc.<br>http://www.crc.co.jp | MAGNA/TDM |
| CST GmbH<br>http://www.cst.de | CST Microwave Studio 5<br>MAFIA 4 |
| ElectroMagnetic Applications, Inc.<br>http://www.electromagneticapplications.com/ | EMA3D 3.0 |
| G.I.E. EADS CCR<br>http://www.aseris-emc2000.com | ASERIS-FD<br>EMC2000-VF |
| FEMLAB GmbH<br>http://www.femlab.de | FEMLAB 3.1 |
| IMST GmbH<br>http://www.imst.de | EMPIRE 4.1 |
| Infolytica, Corp.<br>http://www.infolytica.com | FullWave |
| The Japan Research Institute<br>http://www.jri.co.jp | JMAG-Works |
| Remcom, Inc.<br>http://www.remcom.com | XFDTD 6.2 |
| QWED<br>http://www.qwed.com.pl | QuickWave-3D 3.0 |
| Technical University of Hamburg-Harburg<br>http://www.tu-harburg.de/~tebr | CONCEPT II 12.5 |
| Weidingler Associates, Inc.<br>http://www.wai.com | EMFlex |
| Zeland Software, Inc.<br>http://www.zeland.com | FIDELITY 4.0 |

**Table 16.2** Most famous commercial thermal solvers applicable to microwave power engineering

| Vendor | Code |
|---|---|
| inuTech GmbH<br>http://www.diffpack.com/ | Diffpack 4.0 |
| FEMLAB GmbH<br>http://www.femlab.de | FEMLAB 3.1 |
| Fluent, Inc.<br>http://www.fluent.com | FLUENT 6.2 |

### 16.2.5 Thermal solvers

Among the large quantity of thermal solvers, in Table 16.2 only the solvers known as applicable to microwave power engineering and already used in literature are listed. Kopyt (2003) investigated the coupling of QuickWave-3D with Diffpack, (Knoerzer, 2004a) the coupling of QuickWave-3D with FEMLAB. With both approaches good agreements between measurement and simulation could be obtained.

## 16.3 Example of simulated microwave heating

The following part of this chapter will show an example of a microwave heating problem simulated by using a coupled one-way QuickWave-3D – FEMLAB model. No theory of electromagnetics, heat transfer and coupling method will be explained, just the sequence from the problem to its solution using this method will be described.

Figure 16.1 shows the graphical user interface of the MATLAB-script which controls the simulation process as it appears on start-up (in some input fields default values are pre-inserted). Before starting the simulation four steps have to be fulfilled:

*Step 1*

Software (QuickWave-3D and FEMLAB) locations, model path and results folder has to be defined.

*Step 2*

The models have to be created. By pressing the corresponding buttons (see Fig. 16.1) the requested simulation software can be started.

Figure 16.2 shows a typical QuickWave-Editor surface. Displayed is a waveguide with a cylindrical sample (model food (Knoerzer, 2004b), constant dielectric properties) and a water load below. Microwaves are introduced at the top of the waveguide (frequency 2.45 GHz, sinusoidal excitation, defined power). Not absorbed microwaves leave the waveguide on the bottom. This

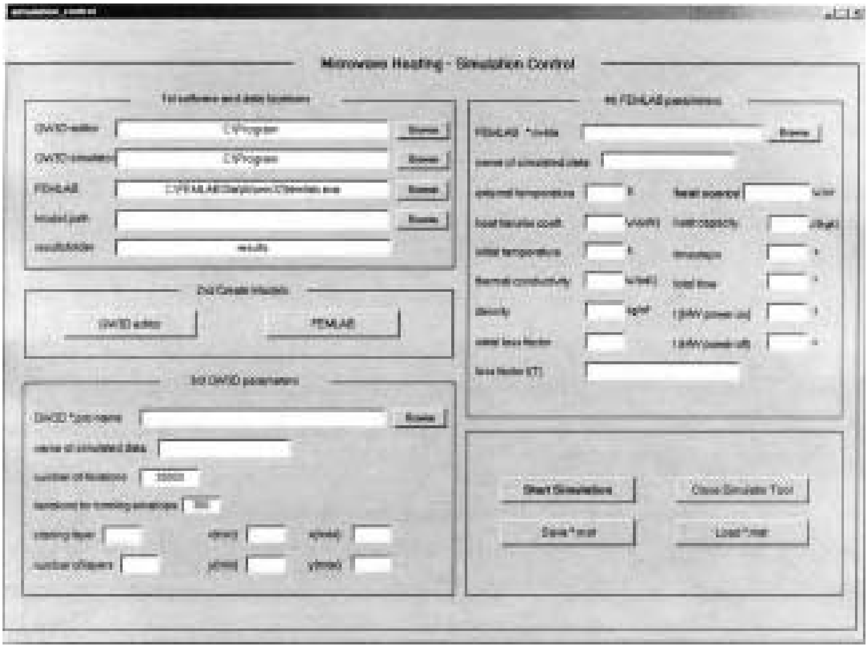


**Fig. 16.1** Graphical User Interface (GUI) of 'Simulation Control', a MATLAB-script for controlling the simulation process.

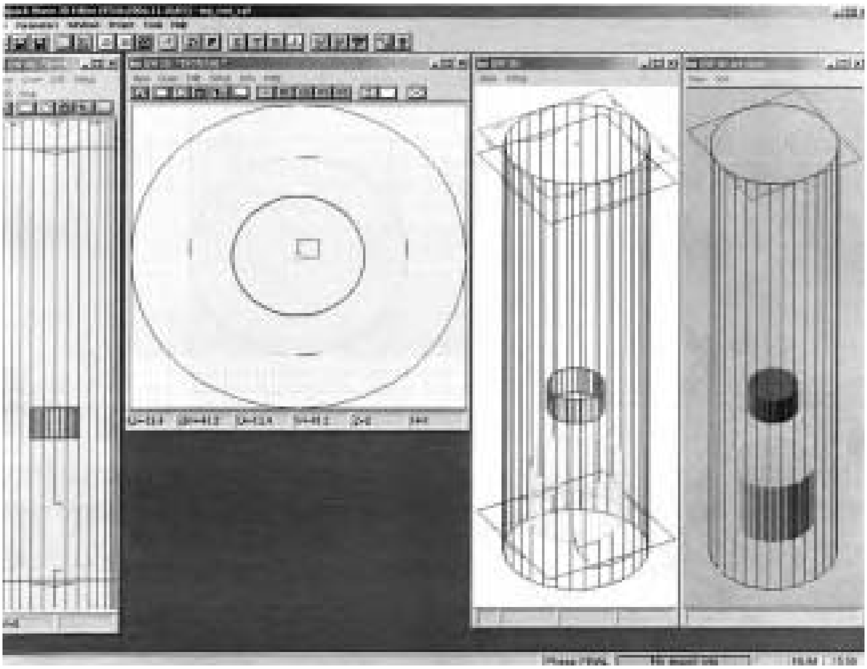


**Fig. 16.2** Typical surface of QuickWave-3D editor for building the electromagnetic model.

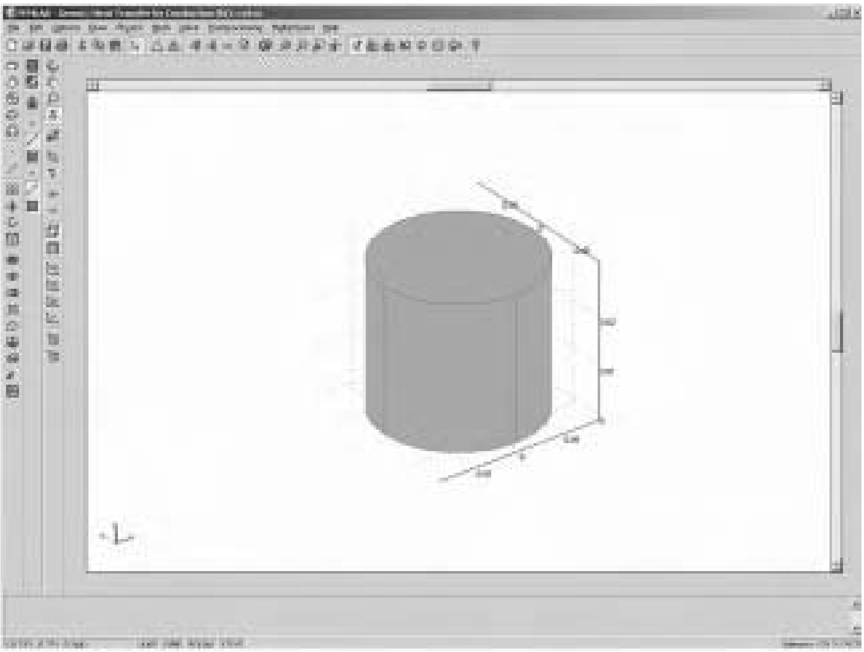


**Fig. 16.3** FEMLAB-GUI for building the heat transfer model.

geometry was selected for simulation, because such a device was already developed for measuring temperature distributions inside a sample during microwave processing (see Chapter 13).

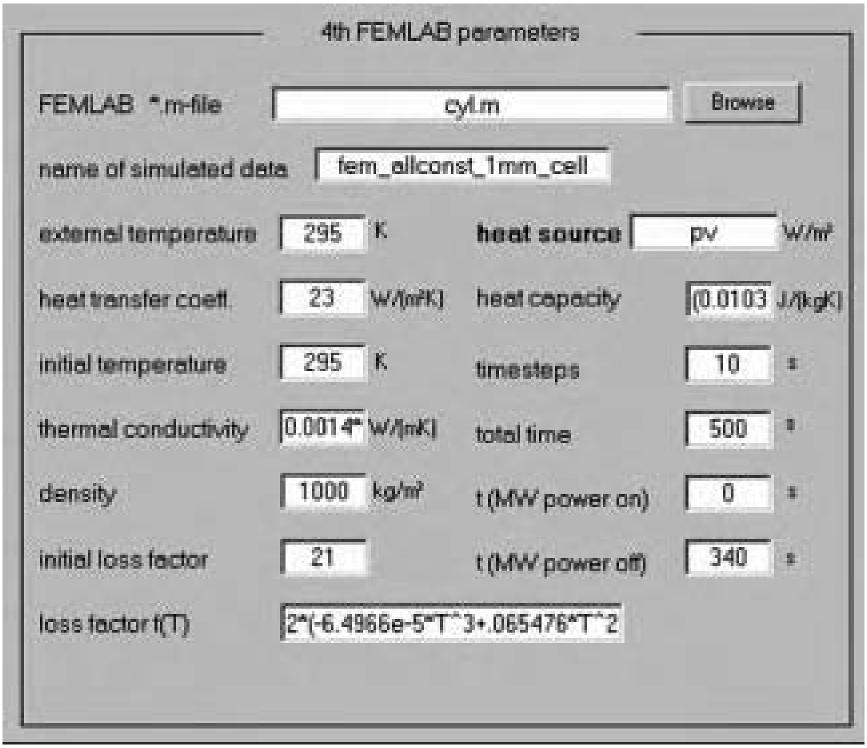
Figure 16.3 shows the creation of the FEMLAB-model. In this step the only thing to do is to create the model of the sample (all physical properties are defined in step 4). The geometry of the oven is neglected, due to the chosen boundary conditions (given heat transfer coefficients and external temperature) at the product's surface.

*Step 3*

In this step, parameters for the QuickWave-simulator has to be defined. These are: the name of the QuickWave-model (defined in step 2), the name of the simulated data (which will be stored in the results folder (see step 1), the number of iterations after that steady-state is reached (this has to be checked before manually), iterations for forming the envelope (average power density in the sample), the starting layer (z-coordinate of the bottom of the sample), the number of layers (height of the sample) and if necessary (that means if the sample is off-centered), the x- and y-values of the sample location.

*Step 4*

Definition of FEMLAB-parameters (see Fig. 16.4). These are: the name of the FEMLAB-model (defined in step 2), the name of the simulated data (stored in



FEMLAB *.m-file cyl.m
name of simulated data fem_allconst_1mm_cell
external temperature 295 K
heat transfer coeff. 23 W/(m²K)
initial temperature 295 K
thermal conductivity 0.0014* W/(mK)
density 1000 kg/m³
initial loss factor 21
loss factor f(T) 2*(-6.4966e-5*T^3+.065476*T^2
heat source pv W/m³
heat capacity (0.0103 J/(kgK)
timesteps 10 s
total time 500 s
t (MW power on) 0 s
t (MW power off) 340 s

**Fig. 16.4** Definition of FEMLAB parameters.

the results folder), the external temperature (inside the oven/waveguide, outside the sample, with the possibility to vary as a function of time), the heat transfer coefficient at the boundary between sample and air (constant or a function of temperature/time) the initial temperature of the sample, thermal conductivity (constant or a function of temperature) inside the sample, the density of the sample, the heat capacity of the sample (constant or a function of temperature), the heat source, which is the simulated QuickWave data (average power density as a function of the location (in Cartesian coordinates)), the timesteps of the FEMLAB simulation, the total time of the experiment, the time when microwave power was switched on, the time when microwave power was switched off and the initial loss factor of the sample. Furthermore, to improve the simulation results, the loss factor of the sample as a function of temperature can be introduced. This function will be implemented according to the following equation:

$$p_{\text{dissipated}} = \pi \cdot f \cdot E^2 \cdot \epsilon_0 \cdot \epsilon'' \tag{16.4}$$

that means:

$$p_{\text{dissipated}}(T,x,y,z) = p_{\text{dissipated,Quickwave}}(x,y,z) \cdot \frac{\epsilon''(T,x,y,z)}{\epsilon''_{\text{initial}}} \tag{16.5}$$

By pressing the button ‘Start Simulation’ (see Fig. 16.1) the simulation with the parameters defined before (step 1 to step 4) is started.

When the simulation is finished, the simulated microwave heating can be analyzed using different self-developed MATLAB codes. The possibilities are:

- showing the simulated three-dimensional temperature distribution at a certain time.
- showing one axial slice of the simulated temperature distribution at a certain time.
- creating a movie of the three-dimensional temperature distribution.
- displaying a curve of the temperature in one selected point (function of time).
- displaying the scattering of the temperatures in all points, the relative frequency and the relative cumulative frequency.
- creating a movie of the scattering of the temperatures, the relative frequency and the relative cumulative frequency as a function of time.

As mentioned in the introduction to this chapter, the validation of the simulated data is also an important task. The possibilities of temperature measurement are described in detail in Chapter 13. In this study the method of magnetic resonance imaging (MRI) was used to obtain (analogous to the simulated data) three-dimensional temperature distributions inside the microwave heated sample.

Figure 16.5 shows the graphical user interface of the MATLAB-script, developed to compare the simulated microwave heating with the measured temperature distributions. Two validation methods are possible. The first possibility is to observe the temperature curve in one single spot. Therefore first the corresponding slices have to be selected in the simulated and in the measured sample and then corresponding points (stemming from the same location) have to be chosen in both 2D-matrices (see Fig. 16.6). The result of one experiment is

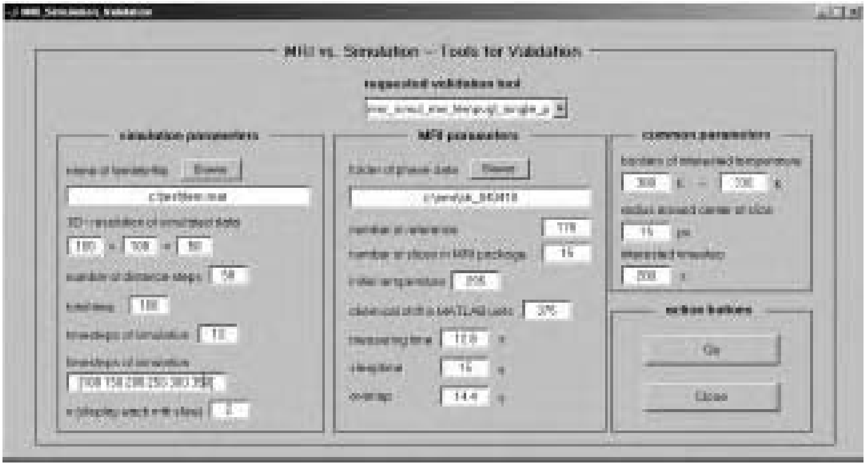


**Fig. 16.5** Graphical User Interface of ‘MRI vs. Simulation – Tool for Validation’, a MATLAB code for comparing simulated and measured (MRI) temperature distributions.

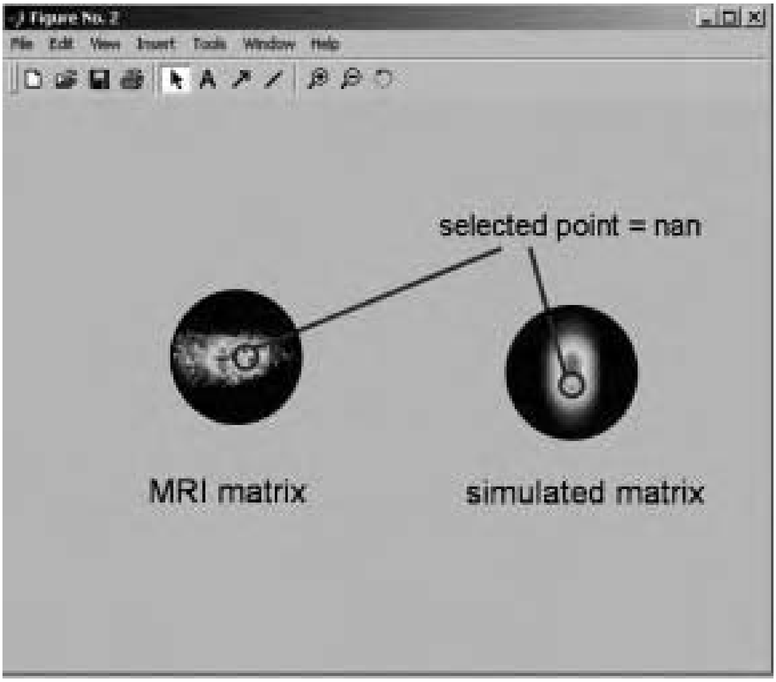


**Fig. 16.6** Two corresponding slices (left: measured MRI temperature distribution, right: simulated temperature distribution) with marked spots for comparing the temperature curves.

shown in Fig. 16.7. As obvious, a good agreement is obtained. Another possibility is to compare whole slices of the sample. As in the first method, first the corresponding slices have to be selected. The second step is to rotate the MRI temperature matrix by selecting two equal points in both matrices (see Fig. 16.8). Then each spot in the simulated slice is compared with the corresponding spot in the measured slice by displaying a diagram with simulated against measured temperature. Ideally the points are located along the bisecting line of the graph. Figure 16.9 shows the result of this validation method and again a good agreement could be obtained.

## 16.4 Future trends

### 16.4.1 Optimization problem

An important aspect of computer-aided design of microwave thermal processing is the optimization of variable parameters, e.g. the geometry of the oven, the location of the heated products or the locations of the microwave feed. The task of an optimization in microwave processes is for example the increase of the efficiency of the energy coupling into the product or, maybe even more important, the improvement of temperature homogeneity.

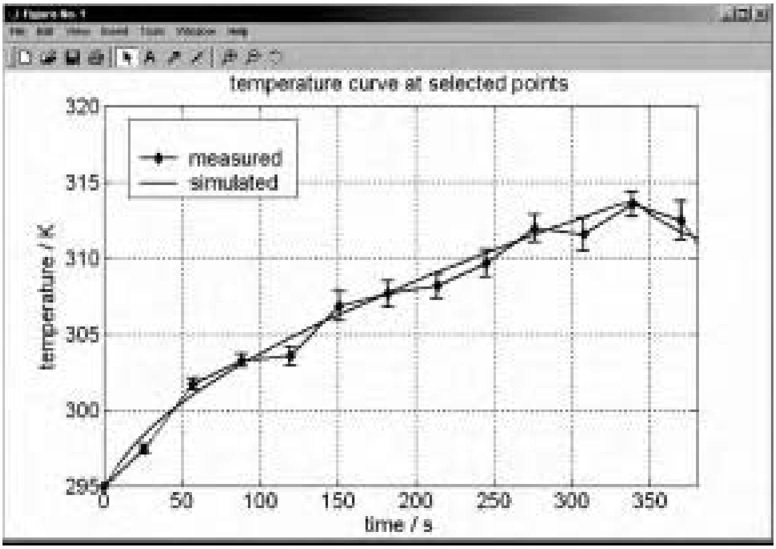


**Fig. 16.7** Temperature curves of simulated (solid line) and meausred (solid line with diamond markers) data in the selected spots (see Fig. 16.6).

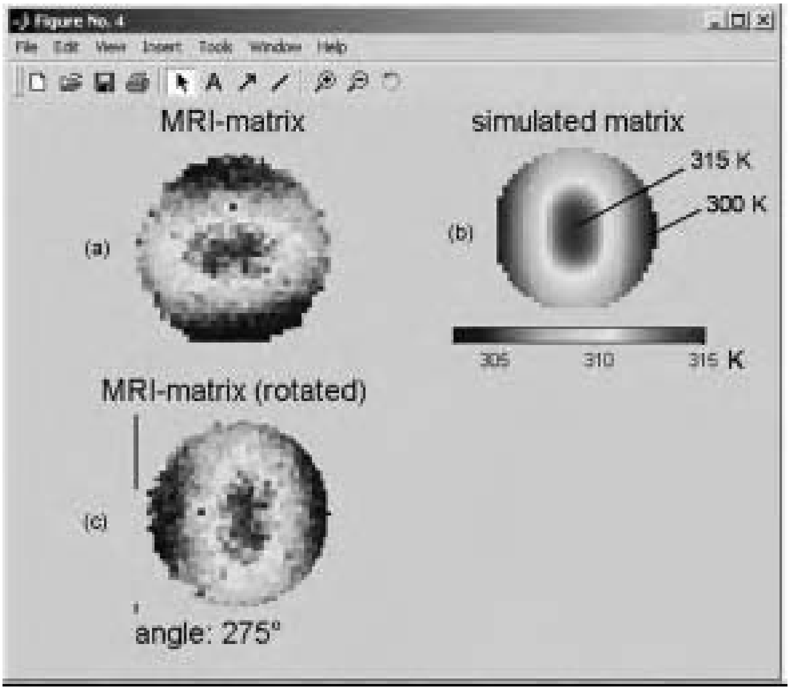


**Fig. 16.8** (a) and (b): Two corresponding slices (left: measured MRI temperature distribution, right: simulated temperature distribution). (c) Rotated MRI temperature matrix for quantitative comparison of measured and simulated temperature distribution.

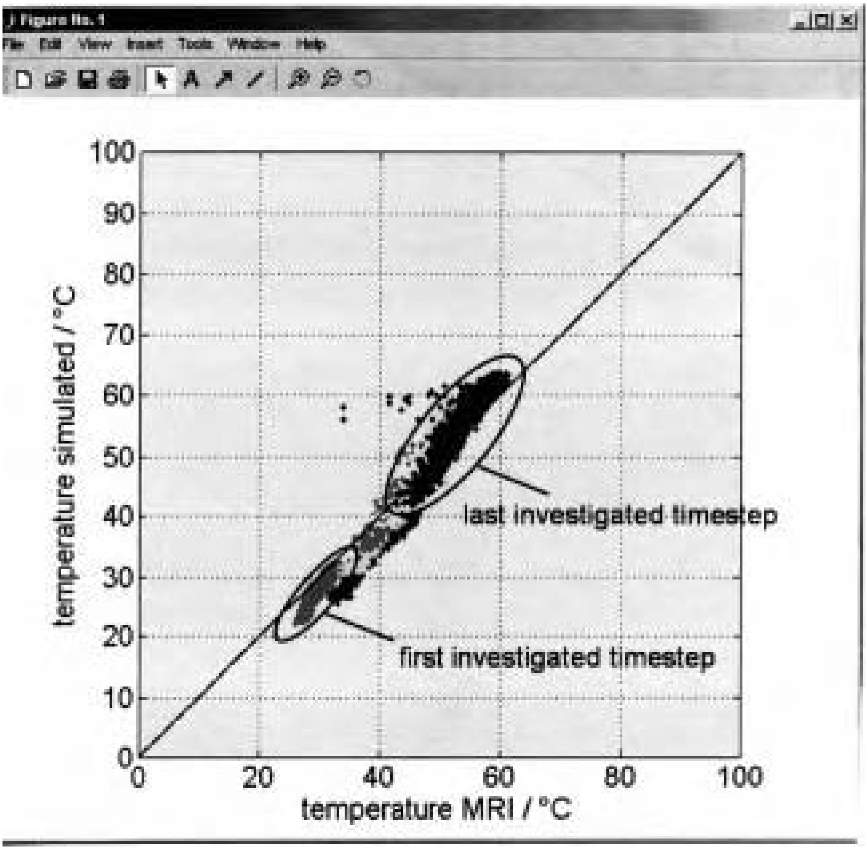


**Fig. 16.9** Quantitative comparison of simulated and measured temperature distribution. Each spot of the simulated slice is compared with the corresponding (stemming from the same location) spot of the measured slice.

While the first task is already accomplished nowadays by implementing an algorithm based on MATLAB's neural network toolbox (Mechenova, 2004) in a QuickWave-3D model, the second one is still at its beginning (see Chapter 15). Considerations of possibilities led to the conclusion, that also an algorithm based on neural networks mentioned above could be implemented in the coupled model described in this chapter. For the optimization the peaks of the relative frequency (obtained with the previously mentioned MATLAB-script) just have to be as narrow as possible.

### 16.4.2 Microwave sterilization/pasteurization

Although microbial reduction by microwaves, i.e. pasteurisation and sterilisation has been studied in a large number of experiments and on many types of food (for a review see Rosenberg, 1987), up to now only a few industrial microwave sterilisation processes have been in use. This is due to the problems of rather inhomogeneous temperature- and thus inactivation-distributions, which cannot be predicted easily in the case of microwave heating due to the complex interactions of electromagnetism, heat (and mass) transfer.

Whereas the stand-alone simulation of microwave heating (see above) and of microbial inactivation (Pardey, 2004) has been accomplished successfully, the coupling of the two models is a novel concept to be executed.

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## 16.6 Appendix: notation

| | |
|---|---|
| $c_a$ | specific moisture capacity of vapour phase |
| $c_P$ | heat capacity (constant pressure) |
| $\vec{E}$ | electric field |
| $f$ | frequency |
| $h_{evap}$ | evaporation heat density |
| $h_i$ | enthalpy of phase $i$ |
| $I_i$ | mass sink or source density of phase $i$ |
| $k$ | thermal conductivity |
| $M$, $M_l$ | moisture content, liquid moisture content |
| $p_{\text{dissipated}}$ | dissipated electromagnetic power density |
| $p$ | pressure |
| $Q_{em}$ | electromagnetic heat production density |
| $q_R$ | radiative power flux density |
| $t$ | time |
| $T$ | absolute temperature |
| x,y,z | local vector |
| | |
| $\alpha_{\mathrm{M}}$ | mass diffusivity |
| $\alpha_{\mathrm{p}}$ | pressure diffusivity |
| $\delta_{\mathrm{p}}$ | pressure gradient coefficient |
| $\delta_{\mathrm{T}}$ | thermal gradient coefficient |
| $\epsilon_0$ | dielectric constant of vacuum |
| $\epsilon = \epsilon' - i\epsilon''$ | relative permittivity |
| $\epsilon_{\mathrm{V}}$ | ratio of vapour flow to total moisture flow |
| $\rho$ | mass density |

## 16.7 Annotation

The use of trademarks, trade names etc. without any special labelling in this chapter should not lead to the assumption, that these names are free concerning the legislation of protection of trademarks.

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