Mapping Local Cavitation Events in High Intensity Ultrasound (HIU) fields

Vinay Raman, Ali Abbas, Sunil Chandrakant Joshi

Presenter: Vinay Raman Indian Institute of Technology Madras, Dept. of Chemical Engineering

Overview

- Introduction
 - Cavitation and acoustic streaming
- Chemical effects
 - Augmentation of chemical reaction rates
- Physical effects
 - Enhanced natural convection heat transfer
 - Enhanced gas-liquid mass transfer
 - Cavitation Erosion
- Finite Element Modeling of HIU fields
 - Numerical Solution and implementation
 - Incorporating bubble dynamics
 - Validation with experimental observations
- Conclusions

Ultrasonic Cavitation

Cavitation

- Local pressure becoming lesser than vapor pressure of water creating cavities
- Acoustically induced cavitation
 - Liquid ruptured apart in the rarefaction cycle
 - Creating cavities
 - Transient bubble collapses
 - Stable cavitation



Cloud of transient cavitation bubbles from Plesset and Ellis (1955)

Acoustic streaming

- Time independent fluid motion generated by sound field
- Two mechanisms
 - Spatial attenuation of wave in free space
 - Friction between medium and solid wall



Laborde et al (2000)

Chemical Effects

Ultrasound

- Initiates reactions
 - Bremmer (1986)
- Augments chemical reaction rates
 - Kristol et al (1981), Cum et al (1988), Lorimer and Mason (1980), Einhorn et al (1991), Javed et al (1995)
 - Saudagar and Samant (1995), Lie Ken Jie (1995)
 - Low (1995), Tuulmets et al (1995), Li et al (1996)
- Changes reactions pathways
 - Dickens and Luche (1991), Ando et al (1984)
- Applications in organic synthesis
 - Homogenous and heterogeneous reactions

Physical Effects

- Enhanced natural convection heat transfer
 - Relationship between heat transfer coefficient and acoustic streaming
 - Cavitation is a reinforcing effect
- Enhanced gas-liquid mass transfer
 - Higher volumetric mass transfer coefficients at higher input ultrasonic power levels and at lower frequencies of operation
 - Cavitation is a dominant mechanism whereas acoustic streaming has only a reinforcing effect
- Cavitation Erosion
- Particle comminution (Vinay Raman and Ali Abbas, 2006)

Enhanced heat transfer



Vinay Raman, Dept. of Chemical Engg.,

IITM

Gas-liquid mass transfer enhancement



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Finite Element Modeling: Overview

- Solving homogenous Helmholtz's equation
 - Spatial distribution of acoustic pressure in the sonochemical reactor
- Cavitation bubble dynamics incorporated
 - Cluster dynamics preferred
 - Calculation of Collapse pressures
- Discussions on
 - Effect of ultrasonic frequency
 - Effect of input ultrasonic power

Homogenous Helmholtz's equation

• Wave equation:

$$\nabla(\frac{1}{\rho}\nabla P) - \frac{1}{\rho c^2} \cdot \frac{\partial^2 P}{\partial t^2} = 0$$

Substituting

$$P(r,t) = p(r) \cdot e^{i\omega t}$$

We get homogenous Helmholtz's equation,

$$\nabla(\frac{1}{\rho}\nabla p) + \frac{\omega^2}{\rho c^2} \cdot p = 0$$

Numerical Solution

- Constraints:
 - Node length

$$\frac{\Delta h}{\lambda} \ll 1$$

- Boundary Conditions:
 - Walls
 - Total reflection (soft boundary conditions)

$$p = 0$$

Hard boundary conditions

$$\frac{\partial p}{\partial n} = 0$$

Numerical Solution

- Boundary Conditions
 - Sides of Sonicator horn
 - Hard boundary conditions
 - Sonicator tip
 - Constant pressure (= maximum pressure amplitude of acoustic wave)

$$p = p_o \qquad I_{US} = \frac{P_{US}}{A} = \frac{p_o^2}{2\rho c}$$

- Air water interface
 - Total reflection (soft boundary conditions)

Implementation

2D plane sliced axially

$$\nabla(\frac{1}{\rho}\nabla p) + (\frac{\omega^2}{\rho c^2} - \frac{k_z^2}{\rho})p = 0$$

Isotropic wave propagation

$$k_x = k_y = k_z = \frac{1}{\sqrt{3}} \frac{\omega}{c}$$







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Optimizing Geometry



Incorporating Cavitation Bubble Dynamics

Cluster dynamics (P. M. Kanthale et al)
Rayleigh Plesset equation (growth phase)

$$r\left(\frac{\mathrm{d}^2 r}{\mathrm{d}t^2}\right) + \frac{3}{2}\left(\frac{\mathrm{d}r}{\mathrm{d}t}\right)^2 = -\frac{\left(P_t - P_v\right)}{\rho}$$

Pressure considerations

$$P(t) = P_0 - P_A \sin(2\pi f t)$$

P_A is the acoustic pressure distribution obtained by FEM modeling using COMSOL Multiphysics (3.2b)

Incorporating Cavitation Bubble Dynamics

Void volume of cluster

$$\beta = 3 \times \frac{\Delta r(t)}{r_0}$$

Rayleigh Plesset equation (collapse phase)

$$r\left(\frac{\mathrm{d}^2 r}{\mathrm{d}t^2}\right) + \left(\frac{3}{2} - \frac{1}{2}(1-\gamma)(1-\beta)\right) \left(\frac{\mathrm{d}r}{\mathrm{d}t}\right)^2 = -\frac{(p_t - p_v)}{\rho\beta}$$

 Incorporating appropriate initial conditions, equations solved in MATLAB, and collapse pressure is obtained as follows:

$$P_{\rm c} = S^2 \rho \beta (1 - \beta),$$

- Termination of simulations
 - Cluster reaches 10 % of initial size
 - Surface instability criteria (Sudarkodi and Kannan)

Validation with experimental results



- Local cavitation intensity using hydrophone measurements
 - Approximately 25% deviation from experimental and numerical solution
 - Limitations in the model
 - Experimental inaccuracies

Conclusions

- Homogenous Helmholtz's equation solved
 - Acoustic pressure field is obtained
 - Sinusoidal variation as opposed to exponential decay obtained by others (V. Saez et al, 2006)
- This is further incorporated in bubble dynamics equation to arrive at collapse pressure
- Experimentally validated with hydrophone measurements
- Mismatch due to limitations in the cavity cluster approach
- Future work
 - Incorporating single bubble theory with Gaussian size distribution of bubbles

Self - References

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