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An 11 cm long atmospheric pressure cold plasma plume for applications of plasma medicine

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In this letter, a room temperature atmospheric pressure plasma jet device is reported. The high voltage electrode of the device is covered by a quartz tube with one end closed. The device, which is driven by a kilohertz ac power supply, is capable of generating a plasma plume up to 11 cm long in the surrounding room air. The rotational and vibrational temperatures of the plasma plume are 300 and 2300 K, respectively. A simple electrical model shows that, when the plasma plume is contacted with a human, the voltage drop on the human is less than 66 V for applied voltage of 5 kV (rms). © *2008 American Institute of Physics*. [DOI: 10.1063/1.2883945]

Atmospheric pressure plasmas have recently received increased attention because of several applications.[1–13] However, due to the relative high breakdown voltage of working gases at atmospheric pressure, the discharge gaps are normally from few millimeters to several centimeters, which limit the size of materials to be treated for direct treatment. If indirect treatment (remote exposure) is used, some short lifetime active species, such as oxygen atom, charge particles may already disappear before reaching the object to be treated.[14]

To address these concerns, low temperature atmospheric pressure plasma jet devices have recently been attracting significant attention.[15–22] The plasma jet devices generate plasma plumes in open space (surrounding air) rather than in confined discharge gaps only. Thus, they can be used for direct treatment and there is no limitation on the size of the object to be treated.

In this letter, a special designed plasma jet device is reported. Figures 1(a) and 1(b) show the schematic of the device and photograph of the plasma plume. The high voltage (HV) wire electrode, which is made of a copper wire with a diameter of 2 mm, is inserted into the 2 cm long quartz tube 1 with right end closed. The inner and outer diameters of the quartz tube 1 are 2 and 4 mm, respectively. The ground electrode, which is attached to the outer surface of the quartz tube 2, is made of an aluminum foil. The inner and outer diameters of the tube 2 are 8 and 10 mm, respectively. The distance between the tip of the HV electrode and the ground electrode is about 2 cm. When helium is injected from the left end of the tube 2 and 40 kHz ac HV is applied to the electrodes, a homogeneous plasma is generated between the two electrodes and a long plasma plume reaching lengths of up to 11 cm long is launched through the other end of the tube 2 and in the surrounding room air, as shown in Fig. 1(b). This is the longest cold plasma plume in surrounding air ever reported. The length of the plasma plume can be adjusted by the gas flow rate and the applied voltage. Besides helium, gases including argon, nitrogen, or even air could be used.

As we know, the human body is a mixture of resistance and capacitance in both parallel and series orientations. A simplest biological equivalent model is a single resistor R_{human} and capacitor C_{human} in parallel. The typical R_{human} and C_{human} of a human are approximately 1 MΩ and 60 pF,[23] respectively. When a human is contacting with the plasma plume, a simple electrical model can be used, as shown in Fig. 2(a). The $C_{\text{tube 1}}$ is the effective capacitance of the tube 1. It is estimated to be about 1 pF. Therefore, for the applied voltage of 40 kHz, its reactance is about 5 MΩ. The $C_{\text{pla-in}}$ and $R_{\text{pla-in}}$ are the capacitance and resistance of the plasma inside the tube 2, respectively. The C_{plume} and R_{plume} are the capacitance and resistance of the plasma plume in the surrounding air. The $C_{\text{tube 2}}$ is the effective capacitance of the tube 2. In the worst case, $R_{\text{pla-in}}$, R_{plume}, and $C_{\text{tube 2}}$ are all equal to zero. For the frequency of 40 kHz, the total reactance of a human is about 66 kΩ, which is much less than the reactance of the tube 1. For the applied voltage of 5 kV, the voltage drop on the human is about 66 V. In reality, the effective reactance of the plasma inside tube 2 and the plasma plume in the surrounding air is in megaohm range. Therefore, the voltage drop on the human is even lower.

In addition, as observed from the experiment, the optical emission from the plasma between the two electrodes is much stronger than that of the plasma plume. Therefore, it stands to reason that the main part of the discharge current probably goes through the $C_{\text{tube 2}}$ rather than the human. So the potential drop should be mainly between the electrodes and the potential drop on the human is further lowered. It is noticed that a human can touch any part of the plasma plume

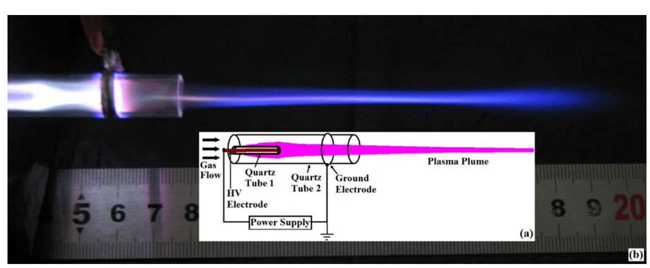

FIG. 1. (Color online) (a) Schematic of the experimental setup. (b) Photograph of the plasma plume with applied voltage of 5 kV (rms), frequency of 40 kHz, and helium flow rate of 15 l/min.

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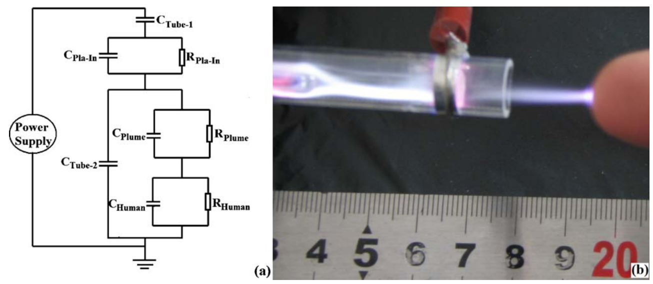

FIG. 2. (Color online) (a) A simple electrical model of the discharge circuit. (b) Photograph of a human finger contacting with the plasma plume near the end of the discharge tube [Operating conditions are same as that of Fig. 1(b).]

without any feeling of electrical shock. Figure 2(b) shows another photograph when a human finger is contacting with the plasma plume near the end of quartz tube 2 without any harm. There is no feeling of warmth at all even though the contacting area of the finger with the plasma plume looks very bright.

The rotational and vibrational temperatures of the plasma plume are determined by comparing the simulated spectra of the $C^3\Pi_u - B^3\Pi_g$ ($\Delta\nu = -2$) band transition of nitrogen with the experimental recorded spectra. A spectrometer is used to measure the emission of nitrogen second positive system. Figure 3 shows the simulated spectrum and the experimental spectrum for the ac frequency of 40 kHz, applied voltage of 5 kV (rms), and helium flow rate of 15 l/min. The power delivered to the plasma is estimated to be about 10 W. It is clear that the simulated spectrum at $V_{rot} = 300$ K and $V_{vib} = 2300$ K give good fit to the experimental spectrum. Therefore, the gas temperature is practically room temperature, which can be easily verified by touching the plasma plume with a finger or by a thermometer. The vibrational temperature of 2300 K is much higher than the rotational temperature. In other words, the plasma plume is under nonequilibrium condition, which is favorable for enhanced plasma chemistry. It has been noticed that the measurement does not depend on the operation time of the device. This stable low-temperature operation is very important for applications such as plasma medicine where microorganisms, cell, etc., are very sensitive to the temperature.

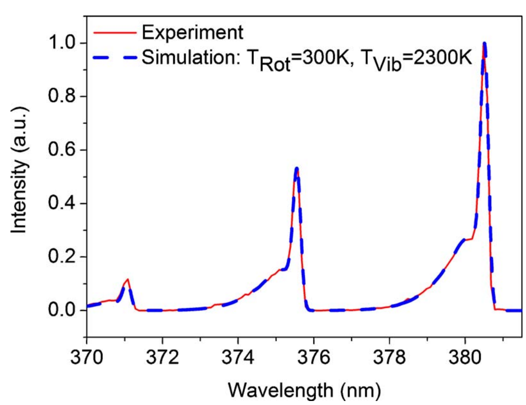

FIG. 3. (Color online) Experimental and simulated spectra of N_2 second positive system 0-2 transition.

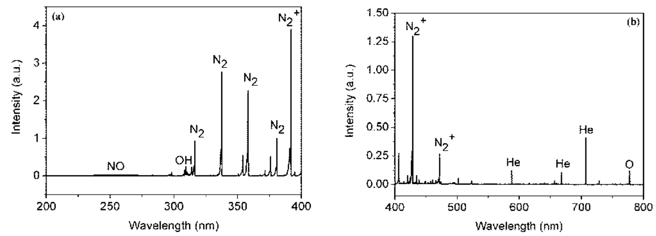

FIG. 4. Emission spectra of the plasma plume from (a) 200–400 nm and (b) 400–800 nm.

To identify the various reactive species generated by the plasma plume, optical emission spectroscopy is applied. For all the recorded spectra, the ac frequency is 40 kHz, the applied voltage is 5 kV (rms), the helium flow rate is 15 l/min, and the operational parameters of the spectrometer are unchanged (grating: 1200 g/mm, slit width: 100 μm). Figures 4(a) and 4(b) show the emission spectra from 200 to 800 nm. It clearly indicates that excited O, OH, N_2, N_2^+, He, and NO exist in the plasma plume.

In short, this device meets all the requirements for the applications of plasma medicine, which are no risk of arcing, operating in room air, good safety, low gas temperature, hand held, and rich of active species.

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