Electrode-Embedded Atmospheric Pressure Plasma Jet Device for Humid Environment

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***Abstract*—A newly designed atmospheric pressure plasma jet that can generate plasma without an external power line for use in an inhospitable humid environment is proposed. A four-bore tube is employed as the delivery conduit, and wire electrodes are inserted into two diagonal hollows. As the wire electrodes are completely isolated inside the hollows of the multibore glass tube, there is no contact with the environment at the end of the device where the jet is produced. Two identical plasma plumes can be generated not only in the ambient air but also under water, thereby enabling tissue and wound treatments in a humid environment, such as oral medicine and endodontic care.**

***Index Terms*—Atmospheric pressure plasma device, plasma in liquid.**

AN ATMOSPHERIC pressure plasma jet (APPJ) device consisting of conduit tubes for feed gases and electrodes is a simple means to create nonthermal glow plasmas in ambient air [1]. Since APPJs exhibit nonthermal plasma behavior, even when they contain many charged ions and electrons for treatment purposes, the temperature of the resulting plasmas is low enough to avoid damage to the treated region. Therefore, this particular feature allows atmospheric pressure plasmas to interact with biological applications [2]. Studies on the potential use of APPJs for treating tissues and wounds have already reported that when exposed to the reactive species in a plasma plume, tissues and wounds are sterilized and quickly healed [2]. Notwithstanding, the difficulties related to the use of plasmas for cell and tissue treatments include the precise delivery of the plasma to cellular tissues in the body and the risk of electric shock for the operator and patient due to the use of high voltages. Accordingly, to facilitate the application of plasma in oral medicine and endodontic care, this paper presents a new APPJ device with electrodes embedded inside the plasma delivery tube to avoid operational breakdown in a humid environment.

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Multibore tubes are used as the delivery conduit for the electrode embedding, where the multibore consists of four equal hollows with a 1.5-mm diameter. Two of the bores are used for the nonthermal plasma jets, while the other two bores are used for the electrical feedthrough. The total outer diameter of the four-bore glass tube is 6.35 mm. The ends of two of the four hollows are sealed shut using epoxy glue. Metal wire electrodes with a 1.2-mm diameter are then inserted into the two sealed hollows. The plasma jet device is 20 cm in length and 6.35-mm wide, which ensures that the generated plasma jet and electrical feedline are separated by a spatial distance of 20 cm.

One advantage of the proposed plasma device is that the distance between the two electrodes, which is the most important design parameter as regards igniting and sustaining the discharge, does not change regardless of the length of the plasma device. As a result, the proposed plasma device can be easily fabricated with a shorter or longer length for different treatment conditions. The driving voltage is a sinusoidal waveform with a peak voltage of 5 kV and frequency of 30 kHz, and high-purity helium (>99.997%) is used as the carrier gas. Due to the small inner diameter of the hollows, the gas flow rates are required to be fairly low at ∼4 slm (standard L/min). As a result, the device produced two equal plasma plumes of 2.5 cm, as observed in Fig. 1(a).

Another advantage of the proposed configuration is that it allows the device to operate stably in adverse environments. Since the ends of the two hollows containing the electrodes are sealed shut, the risk of unwanted electrical breakdown is essentially eliminated. Thus, the proposed plasma jet device can be submerged in water, as shown in Fig. 1(b) and (c). In experiments, although the plasma plumes extending beyond the confines of the hollows were shortened to 1 mm under water, the plasma device was still able to continue operating in a stable state. The reason that plasma jet length was shorter in water than in air is caused by the different density of media. In this plasma device, a helium discharge ignited between two electrodes inside the hollows of the glass tube and the flowing afterglow of atmospheric pressure plasma came out through two nozzles to the outside due to the neutral helium gas flows. When an outside medium is quite dense like water, by the way, the flowing afterglow of plasma has trouble in going out of the plasma device, resulting in the short plasma plume length in water. Even if the plasma jet length shortened to 1 mm, numerous chemical species still existed in plasma medium and came out through the device with helium bubbles. On the contrary, when the outside is a sparse medium (<760 torr),

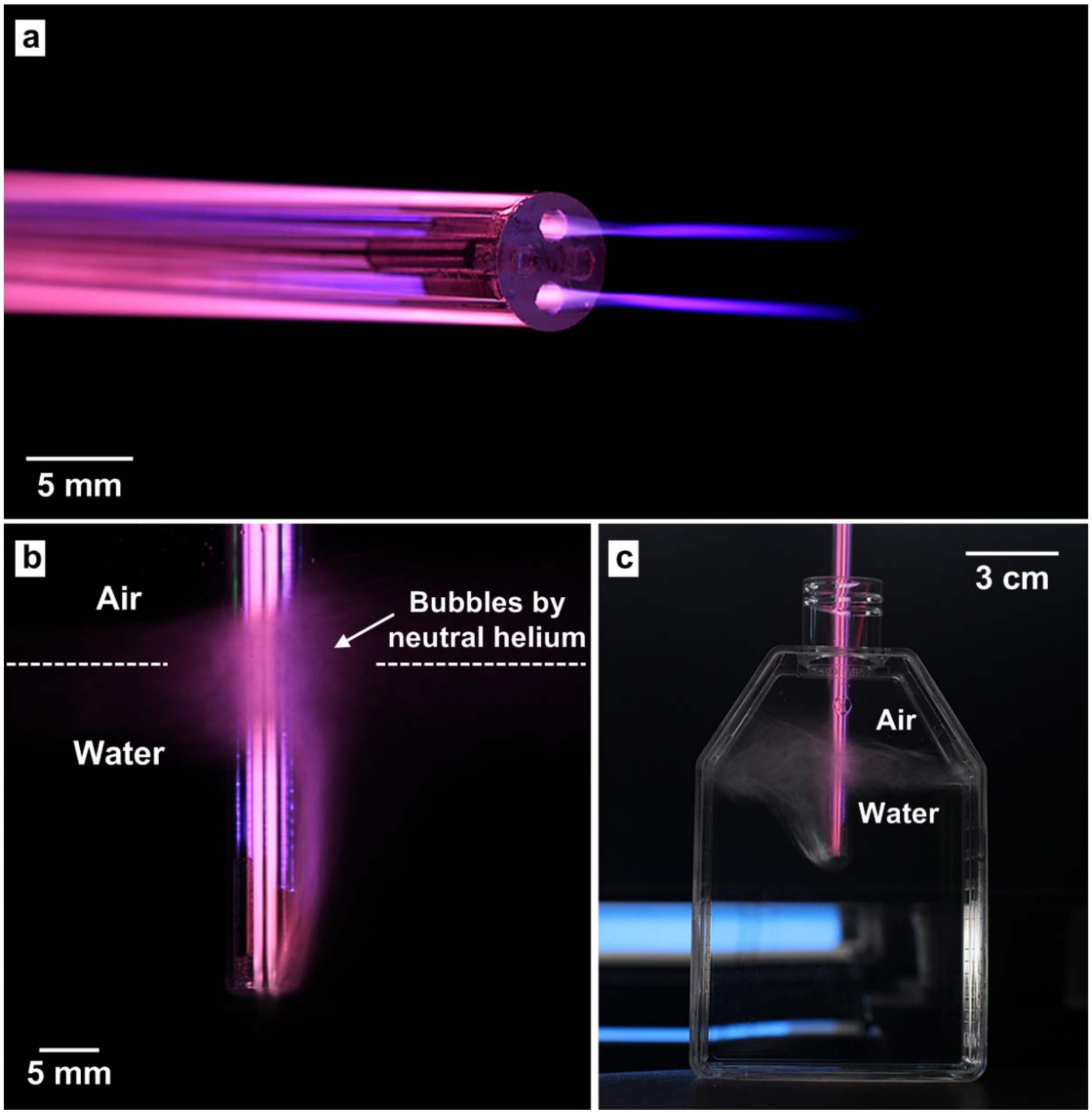

Fig. 1. (a) APPJ device with two electrodes embedded in embedded in a multibore tube. Two of the bores are used for the plasma jets, while the other two bores are used for thin wire electrodes. (b) Enlarged plasma image of helium plasma generated in water and (c) original plasma image in a cell culture flask with water. Two wires are isolated inside of the four-bore tube, thereby not allowing contact with the adverse environment at the end of the device where the jet is produced. To make good exposure, the camera shutter speeds for (b) and (c) were adjusted to 5 and 0.8 s, respectively. In these exposure times, the helium bubbles were blurred in the plasma image due to the rapid movement of bubbles. The pictures were taken using the digital single-lens reflex camera with macrolens (Canon EOS 700D camera with Canon EF 100-mm f2.8 Macro USM lens).

the flowing afterglow of plasma has a diffusive shape, as reported in [3].

This ability is crucial when using plasmas in the moist atmosphere of the human mouth for oral medicine and endodontic care. Finally, the proposed plasma jet design configuration also eliminates the need for both an external electrical supply connection and packaging material to protect the device. As a result, the atmospheric pressure plasma device can be smaller and more compact for precise biomedical treatments.

References

[1] X. Lu, Q. Xiong, Z. Tang, Z. Jiang, and Y. Pan, "A cold plasma jet device with multiple plasma plumes merged," *IEEE Trans. Plasma Sci.*, vol. 36, no. 4, pp. 990–991, Aug. 2008.

[2] D. B. Graves, "The emerging role of reactive oxygen and nitrogen species in redox biology and some implications for plasma applications to medicine and biology," *J. Phys. D, Appl. Phys.*, vol. 45, no. 26, p. 263001, 2012.

[3] W.-C. Zhu, Q. Li, X.-M. Zhu, and Y.-K. Pu, "Characteristics of atmospheric pressure plasma jets emerging into ambient air and helium," *J. Phys. D, Appl. Phys.*, vol. 42, no. 20, p. 202002, 2009.