04

kHz Plasma Pencil

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Recently several investigators reported on various devices of generating cold plasma jets at atmospheric pressure. A pulsed plasma source developed and reported, the plasma pencil, is one of them. This device is capable of generating a cold plasma plume several centimeters in length using a DC pulsed high voltage source. In this study, kHz alternative current voltage (18 kV−15 kHz) was applied to the electrodes similar to the electrode system of the plasma pencil instead of direct current pulse voltage and a 2−3 cm long plasma jet was produced in an air using the helium gas. This new plasma jet device named as the kHz plasma pencil. The jets produced by the kHz plasma pencil are as cold as room temperature. The optical emission spectrum of the jet of the kHz plasma pencil and the change of the jet length with the gas flow rate have been investigated. Unlike the plasma pencil, the kHz plasma pencil produces jet in two different regimes as filamentary and diffusive and it emits more radiation in the UV range. Preliminary results show that the dynamics of the kHz plasma pencil are also different from the plasma pencil.

Keywords: atmospheric pressure cold plasma jet, kHz, plasma pencil, Emission spectrum.

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Plasma jets at atmospheric pressure without using a transferred arc is named in literature as non-LTE (non-Local Thermodynamic Equilibrium) plasma jets, non-equilibrium plasma jets, non-thermal plasma jets, cold plasma jets or low temperature plasma jets. An extensive overview of those newly developed non-equilibrium plasma jet generation methods was given by Laroussi and Akan in 2007 [1]. One of the main characteristics of Atmospheric Pressure Cold Plasma Jets (APCPJs) is that the plasma generated inside the device (plasma generation region) is launched outside to the external environment or open air in the form of a plume or bullet. The interest in APCPJs lies in their ability to deliver significant densities of reactive species remote from the discharge area and the low gas temperature. APCPJs have received significant attention due to their combination of simplicity, low cost, and wide possibilities for surface treatment and modification in metal and polymer processing and biomedical applications [2]. Because APCPJs perform at temperatures only slightly above room temperature, they offer great potential in a broad range of biomedical applications, such as sterilization and bacterial inactivation, dentistry, wound healing, treatment of cancer cells, genetics, blood, and DNA. Extensive research has also been carried out and reported on applying of APCPJs on food [3], seed [4], textile [5] and water [6].

There are various methods to generate APCPJs, such as microwave discharge, radio frequency discharge, dielectric barrier discharge, and direct current discharge. Although APCPJs are classified according to an ascending frequency range of the power supplies used to ignite and sustain them, their electrode configuration is very important parameter for generation of APCPJs [7]. Laroussi and Lu [8,9] have developed a pulsed device, the plasma pencil, that operates at atmospheric pressure and room temperature. The plasma pencil is an atmospheric pressure plasma jet powered by short high-voltage pulses and that can launch plasma bullets in room air, up to several centimeters away from its nozzle. The plasma pencil is a hand-held plasma jet device that consists of two electrodes, each made of a thin copper ring attached to the surface of a centrally perforated alumina (Al_2O_3) or glass disc. The two electrodes are connected to a high-voltage pulse generator capable of producing pulses with amplitudes up to 10 kV, pulse widths variable from 200 ns to dc, and with a repetition rate up to 10 kHz. The rise and fall times of the voltage pulses are about 60 ns. A review of the use of the plasma pencil is presented in [10]. The plasma pencil has also been used for dental applications [11].

In this work, kHz alternative current voltage was applied instead of direct current pulse voltage to the electrode arrangement, which is the similar electrode design of the plasma pencil. Plasma jet which is several centimeters in length was produced similar to the plasma pencil. This atmospheric pressure cold plasma jet named as kHz plasma pencil was generated by a sinusoidal AC high voltage in 18 kV and at frequency of 15 kHz. The kHz plasma pencil has been produced with flow rate of helium. In this paper, first results on characteristic of the kHz plasma pencil are presented.

18 kV and 15 kHz alternative current voltage are applied between similar to two specially designed electrodes of the plasma pencil through which helium gas is flowing.

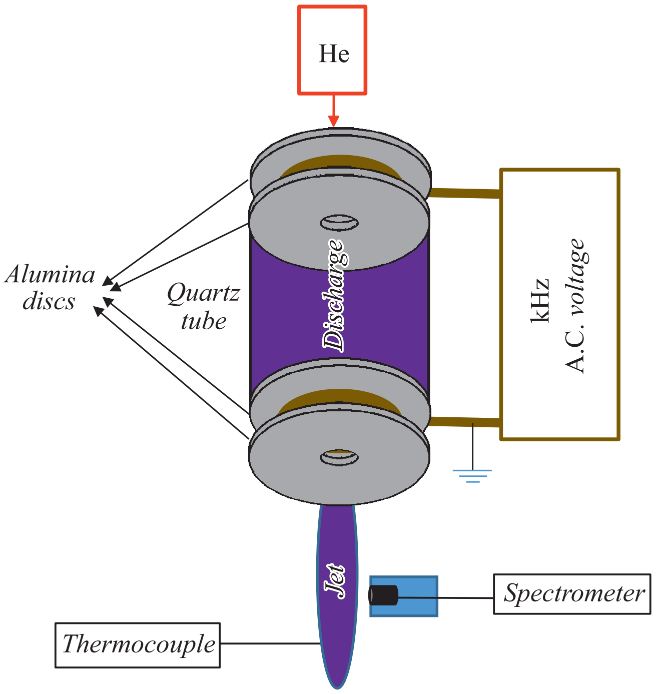

Figure 1. Schematic diagram of the experimental setup of the kHz plasma pencil.

Each of the two electrodes is made of a thin copper ring glued by liquid ceramic (Varian torr-seal) between two centrally perforated alumina (Al_2O_3) disc with thicknesses of 2.46 mm. The diameter of copper ring electrode is about 12 mm, while the inner diameter of the alumina discs is about 5.35 mm and outer diameter of the alumina discs is about 18.1 mm. The two electrodes are attached to top and bottom side of dielectric cylindrical quartz tube with length of 10 mm which has the same diameter as alumina discs. While top side of dielectric quartz tube is attached to other the dielectric tube of the same diameter, plasma jet is launched through the hole of the outer electrode. A schematic diagram of the device is given in Fig. 1.

Helium gas as the working gas (He, 99.95%) is inserted into dielectric (quartz) tube by regulating the gas flow rate in the range of 1–10 L/min. When helium is injected at the top of the dielectric tube and the kHz high voltage are applied to the electrodes, a discharge is ignited in the gap between the electrodes and a plasma jet is launched through the hole of the bottom electrode (nozzle) and in the surrounding room air. The jet (visible) length is measured using a ruler and the length of jet results is documented using a digital camera. The length and type of the jet created by the kHz plasma pencil depends on the helium gas flow. Above 7 L/min flow rates, the jet operates in diffusive mode and the length increases with the flow rate, but eventually levels out at some point. Jet reaches a maximum length of 30 mm when the gas flow rate is 10 L/min (Fig. 2, *b*). Above 10 L/min, the length of the kHz plasma pencil's diffusive jet is virtually independent of the flow rate. At flow rates under 6 L/min, the jet becomes unstable changing filamentary mode, then begins to decrease at lower flow rate values as can be seen in Fig. 2, *a*. A much longer jet can be obtained in filamentary mode up to 50 mm.

Standard K type thermocouple connected to a digital multimeter (Fluke 179) is used for measurement of the kHz plasma pencil's jet temperature. The jet remains at low temperature (28–30°C) when the thermocouple is axial located 2 cm long away from the nozzle of the jet as can be seen Fig. 1. The temperature measurements were repeated for different helium flow rates without any measurable change in temperature. Some of the measurements were carried out a significant time after the discharge was turned on. Therefore, extended operation time does not lead to an increase in temperature. However, when the thermocouple moves closer to the nozzle (about 1 cm), the jet jumps to the thermocouple and makes an arc, then the temperature rises up to 50°C. Therefore, the temperature of the jet was also measured by an IR thermometer (Benetech GM320). The gas temperature was in the (22–24°C) which shows that the jet is cold. The plasma jet of the kHz plasma pencil can be touched by the bare hand or scanned over human skin without establishing a conductive pathway as shown in Fig. 2, *c*.

Axial Optical Emission Spectrum (OES) of the kHz plasma pencil with resolution of 2 nm in the optical range from 200 to 1000 nm has been applied for characterization of the plume (jet). Emission spectra of the jet in Helium when applied voltage is 18 kV and frequency is 15 kHz and gas flow rate is 10 L/min, taken by an Ocean Optics mini-spectrometer USB 2000+XR1-ES are shown in Fig. 3. The probe of the optical fiber of spectroscopy device, which is inserted in a movable holder with a hole to protect it from electric arc with the jet, were positioned about 1 cm from the kHz plasma pencil jet and the integration time was set to 100 ms. The OES measurements were taken 1 cm below the nozzle (bottom electrode). Very intensive molecular bands (vibrational transitions) of the N_2 second ($C^3\Pi_u$–$B^3\Pi_g$) positive system (315, 337, 353, 357, 375, 380, 399, 405 nm), molecular ions N_2^+ first ($B^2\Sigma_u^+$–$X^2\Sigma_g^+$) negative system (391, 427, 470 nm) and the OH hydroxyl radical ($A^2\Sigma^+$–$X^2\Pi$) system (309 nm) are observed. The emission spectrum is dominated by N_2 excited states and also by N_2^+ ions. Atomic oxygen O ($3p^5P$–$3s^5S^0$ and $3p^3P$–$3s^3S^0$) lines (777 and 845 nm) are also present. The jet produces a significant UV radiation which belongs to transitions of the OH band. The appearance of this band in the spectrum is due to the process of dissociative excitation of water molecules that are present in air. The other most important features correspond to the Helium which are located at 587 nm ($1s3d^3D_{1,2,3}$–$1s2p^3P^0_{0,1,2}$) and 728 nm ($1s3s^1S_0$–$1s2p^1P^0_1$). Apart from the electric field and charged particles various plasma agents such as UV radiation, reactive oxygen and nitrogen species (RONS) play important roles in all plasma-surface interactions, especially with biological cells and tissues.

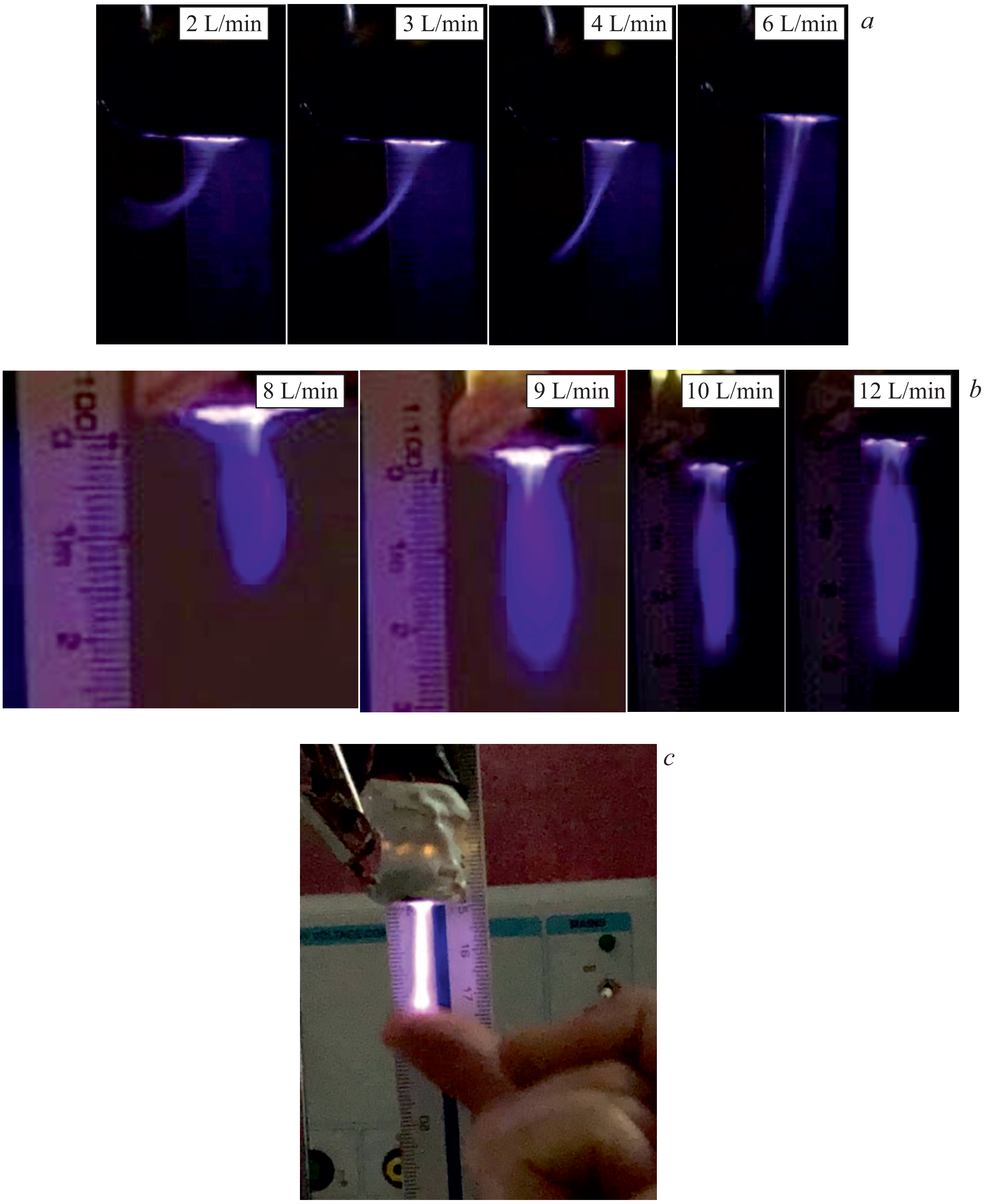

Figure 2. Photographs of the Helium kHz plasma pencil's jet for various gas flows. *a* — filamentary regime of the kHz plasma pencil; *b* — diffusive regime of the kHz plasma pencil; *c* — bare hand (T. Akan) in contact with the jet of the He kHz plasma pencil.

Emission spectra of the plume of the plasma pencil were reported in [8 and 12]. Its emission spectrum is dominated by the presence of excited nitrogen, helium, and nitrogen ions. In addition, highly reactive radicals such as hydroxyl OH and atomic oxygen are detected. While the emission spectrum of the plume of the plasma pencil is dominated by N_2^+ $(B{-}X)$, the emission spectrum of the jet of the kHz plasma pencil is dominated by N_2 $(C{-}B)$ excited states as can be seen in Fig. 3. In addition, radiation in the UV range produced by the kHz plasma pencil emit more intense and in different wavelengths compared to the radiation in the UV range produced by the plasma pencil. Due to recombination and attachment, the electron density rapidly decreases with distance from the nozzle. Negative and positive ions will be found at larger distances from the nozzle due to their lower recombination rate. Excited species and reactive species will survive longest and can interact with materials at a distance of up to a few centimeters, depending on the lifetime of the radicals.

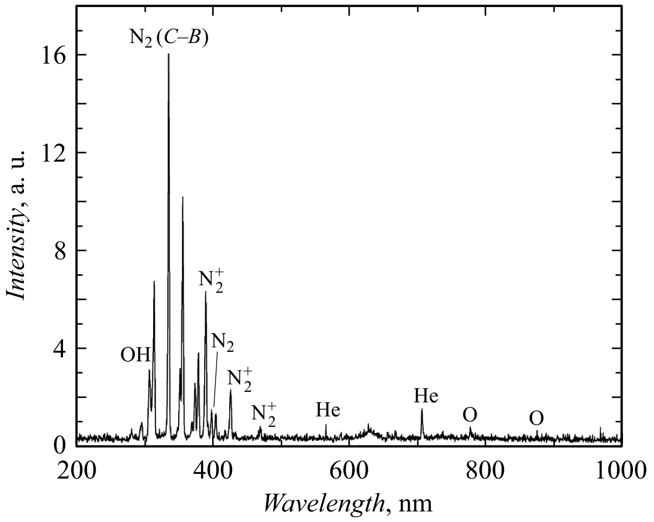

Figure 3. Emission spectrum from the Helium kHz plasma pencil's jet in ambient air.

APCPJs produce plasma plumes with lengths from a few millimeters to more than ten centimeters. The dynamics of plasma plumes appears to be continuous visually and it propagates at a high-speed resembling a bullet. Previous reports point to that plasma plumes generated by APCPJs are generally electrically driven. However, a model based on photoionization is used to explain the propagation kinetics of the plasma bullet produced by the plasma pencil under low electric field conditions [9]. When the grounded copper plate is placed close to the plasma jet of the kHz plasma pencil (but not in direct contact), the plasma jet bends towards the copper plate and stops propagating. It can be explained by that the plasma jet produced by the kHz plasma pencil is electrically driven. The grounded copper plate close to the plasma jet affects the electric field distribution and consequently propagation of the plasma jet.

An atmospheric pressure plasma jet called the kHz plasma pencil similar to the plasma pencil but with different features was produced. While the kHz plasma pencil operates in filamentary regime at low gas flow rates, it operates diffusive regime at high flow rates. Although the emission spectrum is similar to the plasma pencil, more the UV emission and more intensive N_2 excited atoms lines are observed at the jet of the kHz plasma pencil. In addition, the kHz plasma pencil also produces jets at room temperature like the plasma pencil. The model proposed for the plasma pencil assumes that the local electric field and photoionization play an important role in the propagation and plasma propagation was inhibited if the ratio of air molecules to helium atoms exceeded a certain value. First results for the kHz plasma pencil show that the gas flow has not a significant effect on the length of the plasma jet when it operates in diffusive regime and it seems that the propagation is electrically driven.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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