Characterization of Conical Plasma Jet with a Cloth-Covered Nozzle

K. G. Kostov, F. V. P Kodaira, A. C. P. L. Almeida

Department of Physics, Faculty of Engineering, São Paulo State University – UNESP, Guaratinguetá, SP, Brazil

Abstract: In this work, we report on investigation of an atmospheric plasma jet terminating with a 70-mm-diam conical nozzle that is covered by a woven fabric. The device can operate at moderate Ar flow (several l/min) and in a wide range of gap distances producing a stable plasma plume under the entire funnel exit. Polymer samples treated by the plasma jet had their wettability affected in a uniform matter. Therefore, the proposed plasma jet device is suitable for applications that required uniform surface modification over relatively large area.

Keywords: Plasma jet, cold plasma, atmospheric pressure, large area treatment.

1. Introduction

Atmospheric pressure plasma jets (APPJs) are low-cost systems where electric discharge is ignited in a noble gas that flows through a thin dielectric tube and the resulting plasma is ejected into the surrounding environment (usually air). Normally, the APPJs generate several cm-long plasma jets that can be easily adapted to treat irregular 3D objects and internal surfaces of narrow tubes or cavities. Moreover, the gas temperature of the plasma plume can be maintained quite low (under 40 C^{o} in some case), which makes the APPJs suitable for biomedical applications and treatment of thermos-sensitive materials [1]. However, in the most cases the plasma plume diameter is limited by the inner diameter of the dielectric tube thus resulting in a modified surface of few cm^2 [2]. Usually, within the plasma-treated area the degree of material surface modification is not uniform being more pronounce at the center and at lesser extent at the edges [3]. To remedy these disadvantages several approaches, like employing plasma jet arrays, different electrode configurations and larger dielectric tubes with different geometry have been proposed. A common disadvantage of those methods is that they all rely upon an excessively high gas flow rate.

In this work, we report on an APPJ terminating with a conical nozzle with diameter of 7 cm that is covered with a gas permeable cotton cloth. The device was operated with Ar gas using moderate flow rates between 1 and 5 slm. All area below the jet exit nozzle is covered by plasma, which makes the device suitable for applications that require surface modification over big area.

2. Experimental

A schematic drawing of the plasma jet configuration employed in this work is shown in the Fig. 1. It consists of a pin electrode (2.4-mm-thick Tungsten rod) centred inside a 2.5-mm-thick quartz conical funnel, which has inner diameters of 4 mm at the straight part and 70 mm and at the funnel exit, respectively. The device was installed vertically with the exit pointing downward. The bottom of the exit horn was completely covered by a porous 0.5-mm-thick, plain-woven, fabric composed of intertwined (90º) cotton fibres with density of 150 treads/square inch. The cloth possesses many uniformly distributed tiny pores that allow gas passage thus improving the gas flow dynamics and enhancing the discharge homogeneity. Beneath the funnel was placed a grounded metal electrode (Ø 155 mm) covered by a 3-mm-thick glass slab. The distance from the funnel bottom to the target was varied from 0 to 10mm. Argon gas (99.996% purity from AirLiquide, Brazil) was admitted into the system through a Teflon holder, situated on the funnel top end. The gas flow rate was adjusted in the range of 0 – 5 slm by a Horiba model STEC N100 mass-flow controller. Plasma was excited by a commercial AC power supply (Minipuls 6, GBS Elektronik, Dresden, Germany), which was operated in burst mode. The generated voltage waveform was an amplitude-modulated sinewave, i.e., a sequence of N high-voltage oscillations is followed by a voltage off period. The number of high-voltage cycles (N = 12), the signal frequency (25.0 kHz) and the burst repetition period (T_r = 2.0 ms) were kept constant, while the voltage magnitude and discharge current changed depending on the discharge parameters.

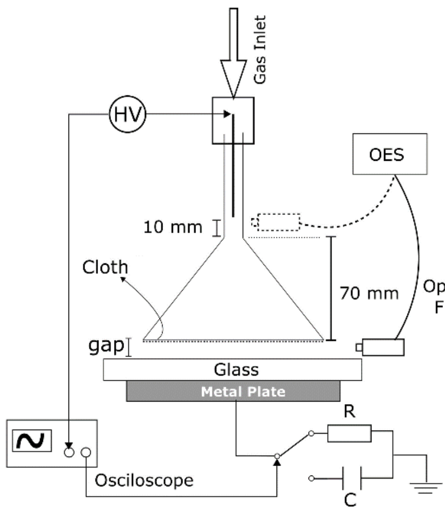


Fig. 1. Experimental setup.

The charge transferred to the target and the discharge current were obtained by measuring the voltage drop across a serial capacitor of 10 nF or a serial resistor of 100 Ω, respectively. The high-voltage signal applied to the pin electrode was measured by a P6015A Tektronix voltage divider (1×1000). The signals were monitored on a digital oscilloscope (Tektronix TDS3032C model). To determine the plasma jet mean power, we used the Q-V Lissajous method, which was adapted for amplitude-modulated voltage signals as reported in a previous work [4].

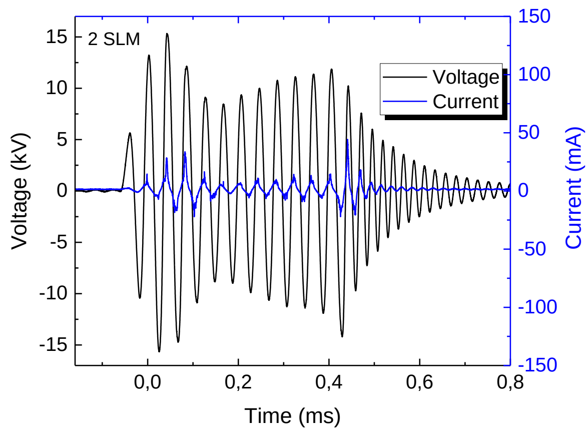
For all operation conditions, the plasma was generated in the form of randomly distributed filaments that emerged from the pin electrode, and propagated down the quartz funnel until reaching the cloth (see the photo in the Fig. 2(a)). Since the latter has a matrix structure with regularly distributed small holes, many tiny plasma jets are ejected from the fabric in direction to the target. Also, some long-living reactive species produced by the discharge inside the quartz funnel are driven by the gas flow through the holes in the cloth and can reach the target. A photograph of the conical plasma jet in operation is shown in Fig. 2. The distance to the target was 5 mm and the gas flow rate was 4.0 slm. As can be seen the emission coming beneath the cloth is much more intense compared to the light radiated from space inside the funnel, which indicates the presence of much more excited species. To identify the exited species produced by the plasma an Avantes spectrometer model AvaSpec-ULS-RS-TEC was used. The spectra were acquired at two different positions as indicated in Fig. 1.

Fig. 2. Photo of the plasma jet for gas flow of 4.0 slm and 5.0 mm gap.

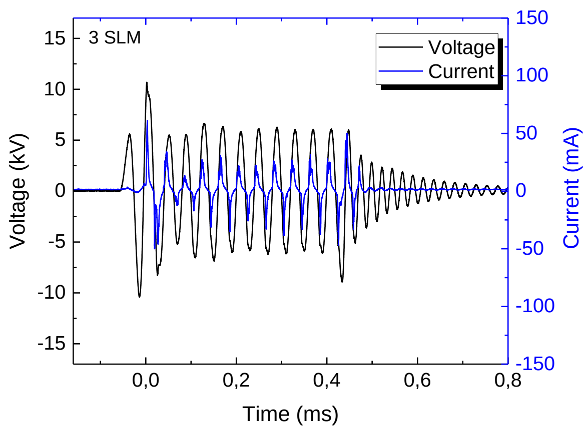
The visually uniform plasma produced under the entire funnel exit can be employed for surface modification of materials. It is known from the literature that treatment of polymers by atmospheric plasmas results in enhanced wettability and adhesion, properties that are very much desirable for coating, printing, painting, and dying [5]. All these applications require plasma sources that can generate uniform plasma over large area. For initial tests, we employed Polyethylene (PE) as a common engineering polymer. The plasma treatments were performed on 1-mm-thick commercial PE. The samples were cut in rectangular shapes with 50 × 20 mm size. Before plasma treatment, all samples were first ultrasonically cleaned in distilled water for 15 min and after that in isopropyl alcohol for 10 min to remove organic contaminants and finally left to dry at room temperature for 1 h. To assess the surface modification of polymer samples induced by the conical plasma jet we employed water contact angle (WCA) measurements. They were performed using the sessile drop method on a Rame-Hart goniometer (300 F1) with automated drop dispenser. Deionized water was used as a test liquid and the volume of each drop was set as 1.0 μl. For each sample a sequence of equidistant droplets was deposited on the sample surface to determine the treatment area and the radial distribution of the WCA. The WCA measurements were performed within 10 min interval after the plasma treatment. Polymer surface modification and its distribution were assessed by a series of water contact angle measurements performed along the sample. Depending on jet's operating conditions, such as jet-sample distance, and gas flow rate, uniform surface modification over the entire area covered by the horn can be achieved.

3. Results and Discussion

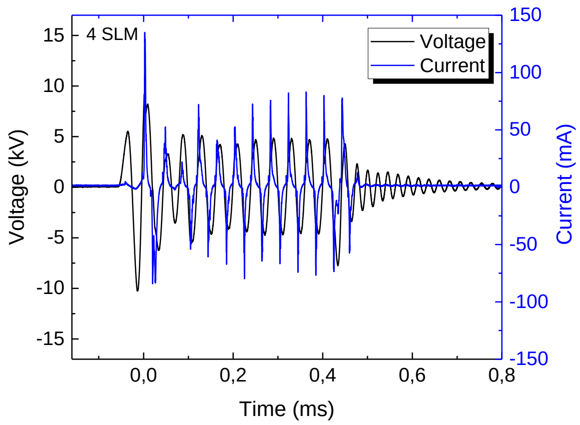
The porous fabric at the funnel exit greatly improves the gas dynamics as well as discharge homogeneity allowing device operation over a wide range of gas flow rates (1–5 slm) and distances (0–10mm). Only in extreme cases, like the combinations of the largest gaps with very low Ar flows, the discharge is not stable. The distance to the target as well as the gas flow rate can affect the plasma jet operation and more specifically its current waveform and mean power. Typical current/voltage waveforms at different gas flow rates are shown in the Fig.2 (a-c) for 5 mm gap distance. As can be seen in the Fig. 3 the current amplitude increases with the Ar flow, while conversely the voltage magnitude first decreases rapidly and after that, it tends to saturate ah high flows.



(a)



(b)



(c)

Fig. 3(a-c). Current/voltage waveforms for 5 mm gap and different gas flow rates.

The effect of the gap distance on the *rms* value of the discharge current and the mean power for three different Ar flows can be seen in the Figs. 4 and 5, respectively.

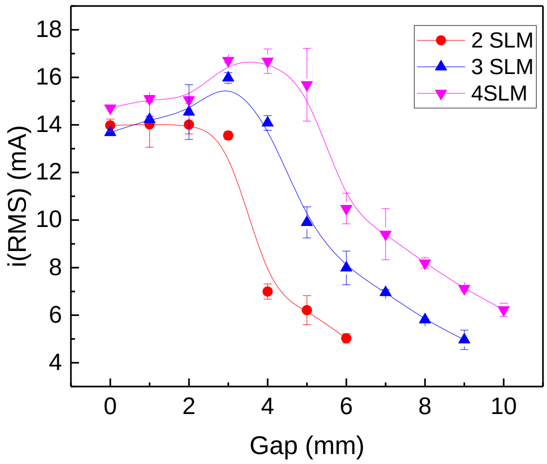


Fig. 4. Rms discharge current vs gap distance.

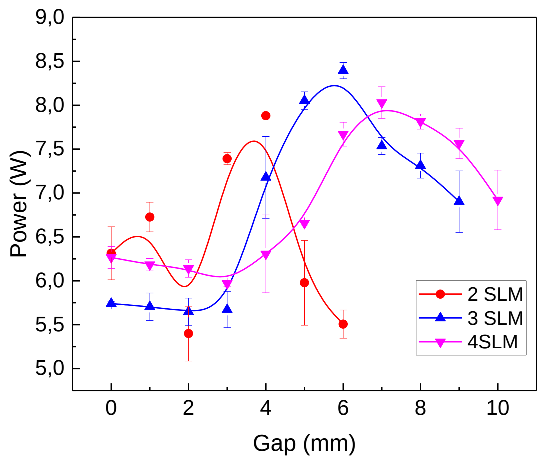
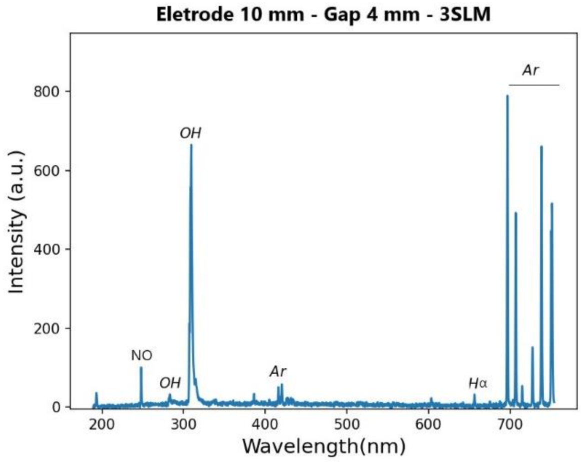


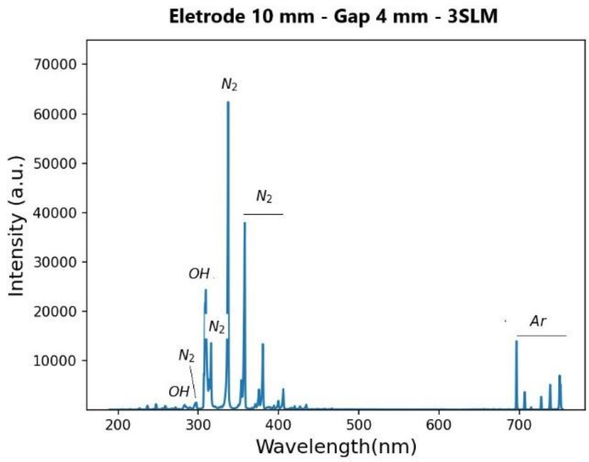
Fig. 5. Mean discharge power vs gap distance for different gas flow rates

For each gas flow rate, there are gap distances that maximizes both the rms current and the mean discharge power. However, the maximums of the *rms* current and the mean power are somehow shifted, probably due to the nonmonotonic behaviour of the applied voltage signal at different gaps.

The results of optical emission spectroscopy are presented in the Fig 6. As can be seen in the Fig 6(a) the emission inside the quartz funnel is dominated by the exited Ar atoms and OH radical, which is due to the presence of water vapours in our gas lines. On the other hand, the spectrum, which was taken under the cloth, is dominated by the emissions of the exited N_2 molecules that is typical finding for atmospheric plasma jets. In addition, it is worth noting that the absolute intensity of the plasma emission under the cloth is much higher



(a)



(b)

Fig. 6. Optical emission spectra of the plasma jet at: (a) from the quartz funnel at 10 mm below the pin electrode and (b) under the woven fabric.

The abundant reactive species produced by the plasma jet that were evidenced in the Fig. 6(b) can affectively alter surface properties of materials. In this work, the PE samples were centred under the plasma jet exit and then plasma treated for 1.0, 3.0 and 5.0 min using 4.0 slm Ar gas flow and 5.0 mm gap distance. The untreated PE exhibits hydrophobic characteristics with WCA of 98º. After the plasma processing, the sample's WCA was measured along its longer dimension and the results are presented in the Fig. 7. As can be seen, the plasma exposure resulted in a uniform enhancement of the polymer wettability. By increasing the treatment time, the WCA decreases approaching saturation value at treatment time longer than 3 min. In addition, the uniformity of the WCA distribution tends to improve with the time of plasma exposure.

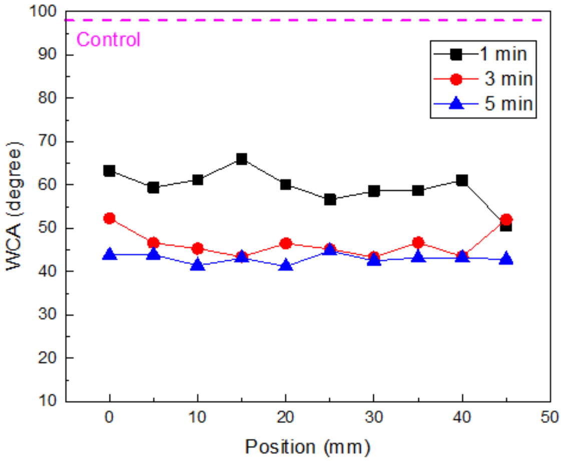


Fig. 7. Distribution of PE water contact angle

4. Conclusions

The proposed conical plasma jet with exit nozzle covered by woven fabric exhibited a stable operation over wide range of gas flow rates and gap distances. Depending on the operating conditions, the device mean power and rms current can be maximized. The cloth that covers the funnel exit permits operating at moderate gas flow rates and big distances to the target. The cloth also helps optimizing the gas flow dynamics, thus generating plasma over the entire area covered by the funnel nozzle. The plasma jet device has very simple construction, but it is able to promote a uniform surface modification over relatively large area.

5. Acknowledgments

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6. References

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