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Influence of a sample surface on single electrode atmospheric plasma jet parameters

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ABSTRACT

The article reports on reciprocal influence between the sample surface and atmospheric plasma jet. This correlation is important since it changes plasma parameters and plasma itself, depending on the sample-material surface, presence of liquid or treatment distance. However, in experiments and treatments of surfaces with atmospheric plasma jets, this relationship is usually disregarded. In order to investigate reciprocal influence, we implemented electromagnetic and optical emission spectroscopy characterization of atmospheric plasma needle jet. Characterization was performed during treatment of various samples. We have shown that sample material and its distance from the tip of the electrode have a pronounced influence on atmospheric pressure plasma jet electromagnetic and optical characteristics, such as jet length, shape, color, voltage, current, power, electromagnetic field and concentrations of plasma species. It was shown that for a given flow there is a critical distance (≈15 mm) between the tip of the wire and the sample surface for which jet emission intensity, especially ionic, is at maximum.

1. Introduction

Low temperature, non-thermal plasmas are nowadays widely used for biomedical applications in fields including surface treatment of biomedical devices and sterilization [1–7]. The most commonly used cold plasmas are low pressure inductively coupled plasmas, where plasma is created in a discharge tube with a radio frequency (RF) field induced inside an excitation coil [8–10].

However, since some treatments cannot be made in vacuum, the atmospheric low temperature non-thermal plasma jets have been developed [11,12]. Because the temperatures of the cold plasma jets are near room temperature, they can be used for treatment of delicate material, biomedical applications [13–16], therapeutic techniques such as wound sterilization [17–21] and cancer treatment [22–26].

Currently, there are a lot of different designs of cold atmospheric pressure non-equilibrium plasma jets, which can be grouped into four different categories: dielectric-free electrode (DFE) jets, dielectric barrier discharge (DBD) jets, DBD-like jets and single electrode (SE) plasma jets [27]. DFE jets are driven with RF power source and they consist of a powered inner electrode and grounded outer electrode. In DBD jets there is a dielectric between high voltage electrode and working gas [28]. DBD-like plasma jets usually consist of two electrodes; the high voltage electrode in contact with the working gas, and grounded ring electrode separated with dielectric from the working gas. Single electrode jets, also known as plasma needle jets, are similar to DBD-like jets except that there is no grounded ring electrode on the outside of the dielectric tube. In order to keep low plasma temperature, most of these jets are used with noble gas or with mixture of noble gases and small concentration of reactive gases, such as oxygen or nitrogen.

A lot of work has been done and published in characterization of these plasma jets [29–35], but only a handful [36] (argon jet) on the influence of the treated sample material on the discharge parameters, such as voltage, current, power, electromagnetic (EM) field, and plasma parameters (shape of the jet, jet length, concentrations of plasma species, overall color, etc.). These results are presented in this paper for the case of a single electrode (SE) atmospheric pressure helium plasma jet.

2. Experimental

The probes for both discharge and plasma parameters were installed around atmospheric plasma needle jet. Four different probes: a high voltage probe (Tektronix P6015A), Pearson current monitor (model 8590C), Rohde&Schwarz Hz-11 Rod 6 mm for electric E-field measurements, a standardized Rohde&Schwarz Hz-11 Loop 6 cm for magnetic H-field measurements and spectrometers Ocean Optics LIBS2000+ with resolution of 0.1 nm in the range from 200 to 970 nm and Avantes AvaSpec 3648 with a nominal spectral resolution of 0.8 nm in the range from 200 to 1100 were used during all measurements. The spectral response was determined by means of a combined deuterium tungsten reference light source. It was important to perform spectral response

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calibration for each integration time of the charge-coupled device (CCD) spectrometers. In order to determine plasma jet length, all the measurements were photographed with Canon HF200 Legria.

In Fig. 1 two experimental setups are presented. Fig. 1a shows setup for an EM characterization of a free standing jet (jet without a sample or a sample holder nearby). The setup consists of a spectrometer, current, voltage and movable E and H probes. An investigation on reciprocal influence of sample surface and atmospheric pressure plasma jet was performed in a setup presented in Fig. 1b. Optical emission spectroscopy (OES) and EM parameters were measured during the treatment of samples that were mounted on a movable holder made from an insulating material (glass plate).

For the atmospheric plasma reactor an end-field jet design was used [37,38]. Copper wire with a diameter of 0.1 mm inserted inside of a 50 mm long and, 1.2 mm inner diameter borosilicate glass tube was connected to a commercial 25 kHz high voltage alternating current power supply from Conrad Electronic. Helium was leaked through glass tube at 2 slm, except if stated otherwise.

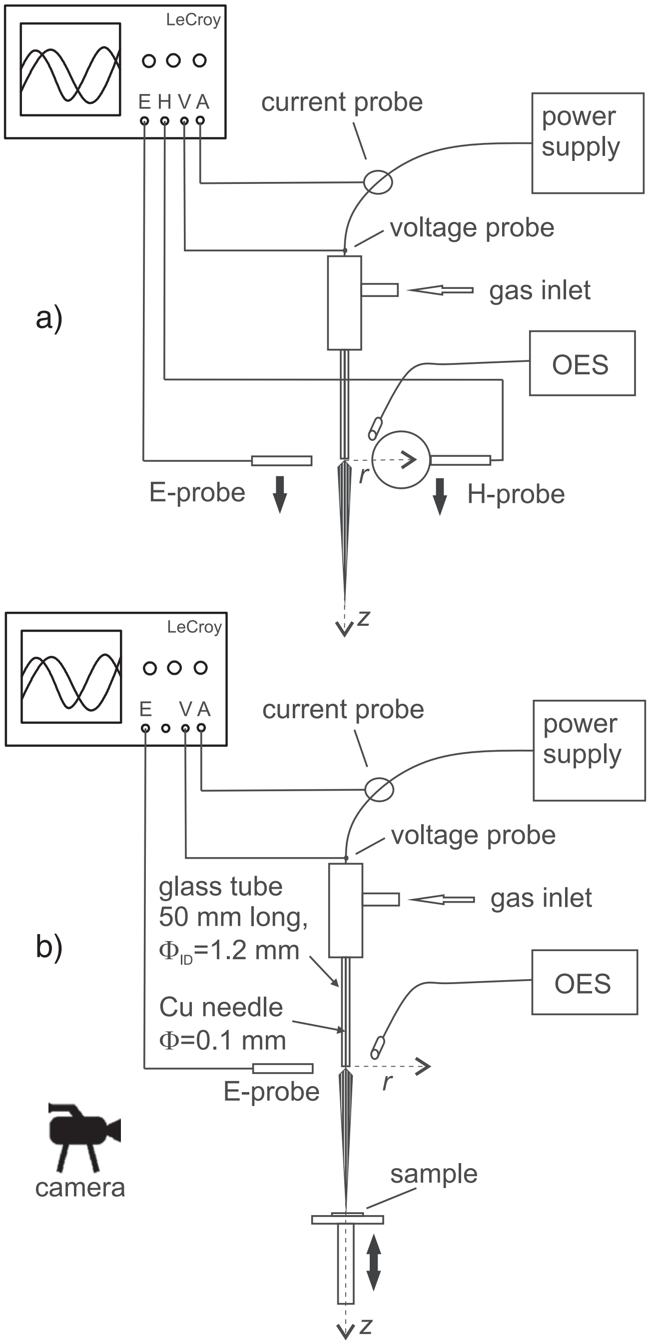

Fig. 1. Experimental setups for free standing plasma jet (a) and for treating samples with jet (b).

For the characterization of atmospheric plasma needle jet in interaction with different materials, six different samples of various sizes and conductivities were used: polystyrene, distilled water, a thin slice of a tooth and samples of silicon, nickel and bronze. The thickness, diameter (length and width in the case of tooth slice), electrical conductivity and relative permittivity of the samples are shown in Table 1. Samples and sample holder were not grounded, they were on a floating potential. The nearest ground potential was more than 10 cm below the sample holder. During the measurements one sample of each material was used throughout the experiment with an exception of water. After each measurement distilled water was replaced, because properties of water are immediately changed when processed with atmospheric plasma.

A simplified equivalent circuit of the plasma needle jet with the treated sample is shown in Fig. 2. Power supply is represented as an alternating voltage source and a 50 Ω resistor as its output resistance. Plasma is created between needle electrode, which is described as a resistor, and the sample (if present). The plasma–electrode gap is approximated with a resistor and a capacitor (C_1) in series. The sample is presented as impedance Z_{sample}, which can be, depending on the sample material, either mainly resistive or capacitive. The sample is capacitively (C_2) coupled to the ground, since it is placed on an insulating holder. When no sample is present, Z_{sample} is a capacitor, because the plasma is capacitively coupled to the surroundings.

3. Results and discussion

3.1. Free standing plasma jet

Voltage and current waveforms of a free standing helium atmospheric plasma jet are presented in Fig. 3. From these measurements root mean square (rms) values of voltage and current, power and first harmonic frequency of plasma jet power supply can be derived.

Plasma jet power supply produces power of a few W with the typical voltage around 2.5 kV, the current flowing through the electrode of approximately 3 mA and the first harmonic frequency around 25 kHz. To determine the power dissipated into the plasma, we subtracted the power measured without any flow, i.e. without plasma, from the measured power when plasma was ignited. For this the source voltage was kept constant. The determined power used for plasma generation was usually below 1 W [38].

Optical emission spectrum of a free standing helium plasma jet is presented in Fig. 4.

In order to collect light from the whole jet, optical fiber was placed at a distance of 1 cm from jet axis, around $z = -1$ cm and was pointed down toward plasma jet as shown in Fig. 1. It can be seen that besides He, which is the working gas of the plasma needle, there are also other emission lines present: neutral O atom lines, Balmer H-alpha, OH ($A^2\Sigma - X^2\Pi$), N_2^+ first negative ($B^2\Sigma_u^+ - X^2\Sigma_g^+$), N_2 second positive band ($C^3\Pi_u - B^3\Pi_g$) and N_2 first positive band ($B^3\Pi_g - A^3\Sigma_u^+$) are observed. The color of the plasma jet is not uniform; the intensities of

Table 1
Sample thickness, diameter, typical electrical conductivity (σ) and relative permittivity (ε_r).

Sample	d (mm)	D (mm)	σ (S/m)	ε_r
Polystyrene	1	40	$<1\times10^{-14}$ [39]	2.7 at 1 MHz [39]
Si–B doped	0.525	11.3	2×10^{4} [40]	–
Ni	0.1	11	1.4×10^{7} [39]	–
Bronze	1.5	20	7.4×10^{6} [39]	–
Tooth slice	0.8	7 × 13	$\sim10^{-7}$ [41]	4 at 100 kHz [41]
Distilled water	6.6	22	$\sim10^{-4}$ [42]	80 at 1.6 GHz [42]