Characterization of different atmospheric pressure plasma jets in He / Ar: electrical, optical and mass spectrometry diagnosis.

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Atmospheric pressure plasma jets are studied nowadays as promising tools for several applications, usually involving direct contact with surfaces. Plasma generated in the electrode gap propagates outside discharge tube, in open air or towards a surface. Several atmospheric pressure plasma jets, running in helium and argon, are investigated by means of electrical, optical and mass spectrometry diagnosis. Experimental results revealed a strong influence of the discharge geometry and working gas upon plasma dynamics and active species production.

1. Introduction

At the end of the last century started the challenge of novel experiments using atmospheric pressure plasmas for worldwide material processing, and even treatment of soft material, such as living cells / tissues / organs. An increasing interest was devoted towards the atmospheric pressure plasma jets (APPJ) use for medical applications. Furthermore a continuously increasing number of reports on plasma based decontamination devices, wound healing, blood coagulation, treatment of dental cavities, and induction of apoptosis for cancer cells, trials in cancer therapy, had appeared in the scientific community [1-7].

In this study, we report the results obtained from the diagnosis of different atmospheric pressure plasma jets in He and Ar. Using microsecond duration high voltage pulses, the plasma is generated using the principle of a dielectric barrier discharge. Moreover global emitted light from the plasma sources was monitored by time averaged techniques, such as emission spectroscopy and ultra-fast photography. Furthermore, mass spectrometry technique was applied in order to investigate the active species produced by plasma jet. Combining the results retrieved from these diagnosis techniques, new insights on the plasma behaviour and potential application can be revealed.

2. Experimental setup

Atmospheric **p**ressure **p**lasma **j**ets (APPJ) are generated in helium and argon, using the principles of dielectric barrier discharge (DBD). The first plasma source used in these experiments consist of two copper tape electrodes fixed on the external surface of a quartz tube (Φ_{out} 6 mm, Φ_{in} 4 mm), and will be referred further on as **Jet-1** (as in figure 1). For the second plasma source a stainless steel hollow electrode (Φ_{out} 3 mm, Φ_{in} 2 mm) centred inside a quartz tube (Φ_{out} 6 mm, Φ_{in} 4 mm) and a copper tape electrode fixed on the external surface of a quartz tube are used, and will be referred further on as **Jet-2** (as in figure 1).

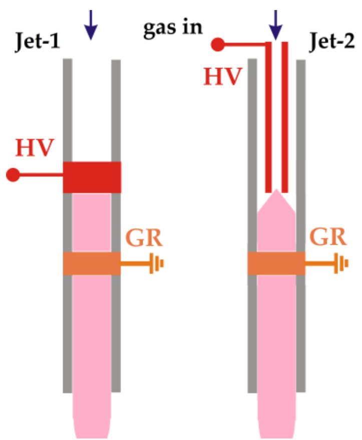

Figure 1. Experimental setup of the plasma sources.

The working gas (He/Ar) flows through the tube with a constant flow rate of 3 L/min, ensuring a laminar flow regime.

High voltage pulses, 6 kV amplitude, are applied on the power electrode, with 2 kHz repetition frequency, using a function generator (Tabor WW5064) and an amplifier (Trek PD07016). Connecting to a digital oscilloscope (Tektronix TDS 5034B) a voltage probe (Tektronix 6015A) and a current probe (Pearson 6585), voltage and current traces are monitored and stored for further statistical analyses.

Using a Triax 550 spectrometer the optical emission spectra between 200-950 nm was acquired, via an optical fiber.

For a better understanding of the plasma jet behaviour we used the fast photography technique. An ICCD system (Hamamatsu C8484-05G camera coupled with an image intensifier) was used to capture up to 30 ns exposure time images of the plasma jet. Behaviour of the helium plasma Jet-1 in open air is reported elsewhere [7-8].

A HPR-60 MBMS mass spectrometer system (Hiden Analytical Ltd) was used for this study, with 2500 amu upper mass range [9]. Mass-to-charge ratio (m/z) spectra were collected, stressing the effect of source geometry (Jet-1 / Jet-2) on plasma active species. For these experimental studies plasma sources were directed to the mass spectrometer extraction orifice.

3. Results and discussions

Electrical diagnosis

The electrical signals for the plasma sources **Jet-1** and **Jet-2** are shown in figure 2.

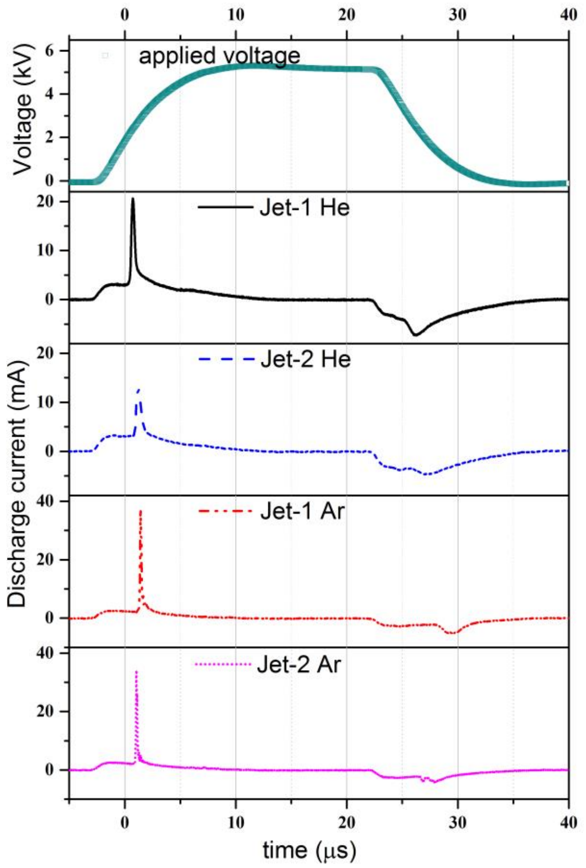

Figure 2. Typical waveforms of the applied voltage and discharge current for **Jet-1** and **Jet-2** in He and Ar.

For both plasma sources (**Jet-1** and **Jet-2**), a double discharge behaviour is observed, in helium and argon, characteristic for monopolar pulsed DBD discharges.

Discharge current varies from 13 mA (Jet-2 He) to 21 mA (Jet-1 He), and increases to 34 mA (Jet-2 Ar) respectively to 38 mA (Jet-1 Ar). Total charge (sum of integrated current peaks) varies from 46 nC (Jet-2 Ar) to 78 nC (Jet-1 He). The mean pulse energy determined to be of ~ 6 W/s for plasma jet operating in He and ~ 3 W/s for plasma jet operating in Ar. These values are in conformity with those reported in risk assessments articles concerning the use of plasma in medicine [4-5].

Optical Emission Spectroscopy

Emission spectra of investigated plasma sources contain molecular bands assigned to hydroxyl radicals, neutral nitrogen molecules and nitrogen molecular ion. Atomic lines are assigned to helium and argon atoms, the working gas, and O_2 or H_2O products of dissociation (figure 3.). Estimated gas temperature, using the rotational temperature of OH radicals, in these experiments was about 290K, in He, and up to 310K, in Ar.

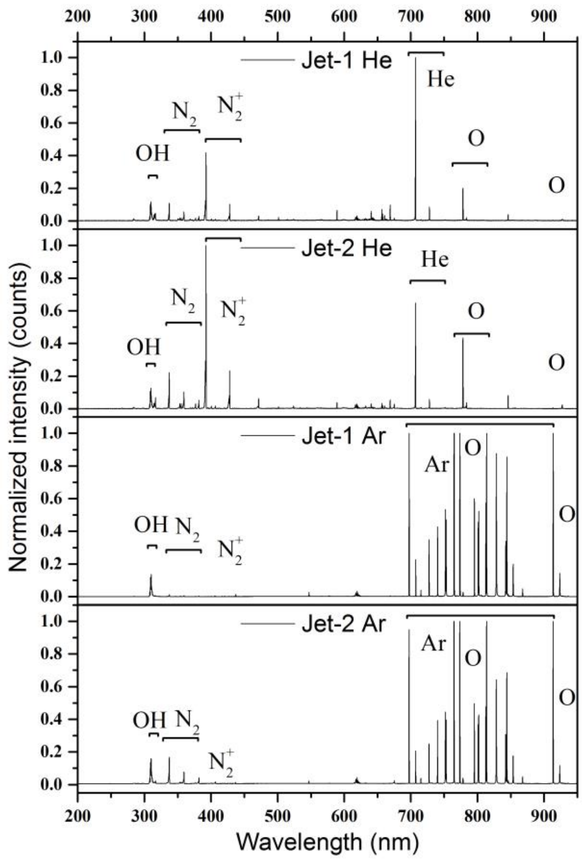

Figure 3. Emission spectrum for **Jet-1** and **Jet-2** plasma sources in He and Ar.

The OH radical band is present between 306 – 310 nm. Bands of the nitrogen second positive system are visible between 315 nm and 380 nm, as well as at 399 nm and 405 nm.

The nitrogen molecular ions (N_2^+) have bands starting at 391 nm till 470 nm. The second order of diffraction is also observed for these bands.

Helium atomic lines were observed starting at 501 nm till 706 nm and 728 nm.

Argon transitions, much more lines than in helium spectra, were observed starting from 697 nm to 923 nm.

Atomic oxygen has lines at 777.4 nm and 844.6 nm.

Ultra-fast photography

Even though the plasma column that expand into air (for about 2 cm) seems continuously for both helium and argon, a different behaviour at ns scale is revealed when using ultra-fast photography technique. ICCD images for the plasma sources operating in He revealed a 'bullet-like' behaviour for both discharges (as in figure 4). When using Ar, plasma expands from the electrode region, through discharge tube and in open air, in a more continuum way (as in figure 5).

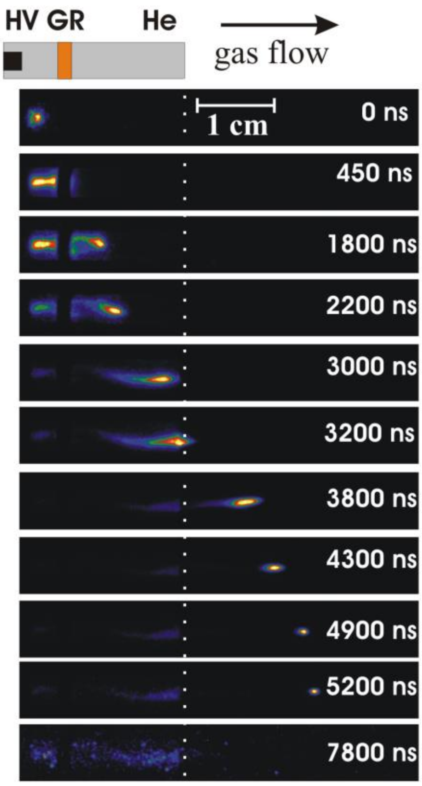

Figure 4. Typical ultra-fast images of **Jet-2** in He. '0ns' correspond to current peak rising.

Using ICCD images, 'plasma-bullet' velocity for **Jet-1** plasma source, in He was found to range between 0.2 to $30 \cdot 10^4$ m/s, as reported previously in [6-8]. For the second plasma source, **Jet-2** in He (figure 4), the velocity value was found to range between 0.6 to $2 \cdot 10^4$ m/s.

In the case of using Ar as working gas, no 'bullet-like' structure was observed. Instead a 'snake-like' rotating plasma structure, moving along the inner surface of the discharge dielectric tube (as in figure 5).

Figure 5. Typical ultra-fast images of **Jet-2** in Ar. '0ns' correspond to current peak rising.

Even though, when using Ar, plasma dose not 'form' distinct and compact structures (bullets), it remains for a longer time inside discharge tube. Almost 6 μs more than in the He case.

Mass spectrometry

Mass spectrometry technique was applied in order to have an insight on plasma source chemistry. Plasma effluent is composed of neutrals, ions, photons and it is sampled through MS extraction orifice. Due to experimental conditions (atmospheric pressure sampling) along plasma related species (He, N_2, N_2^+, O, Ar) also water clusters appeared in mass-to-charge ration spectra. More information about the charges species produced in plasma volume was monitored. Similar results were also reported by Oh et. all. [9] and Benedikt et. all. [10].

4. Conclusions

Two electrode configuration plasma sources were investigated by means of electrical, optical and mass spectrometry techniques, using He and Ar as working gas. A strong influence of both electrode geometry and working gas type upon plasma dynamics was found. Although from electrical diagnosis both Jet-1 and Jet-2 plasma sources seems equivalent, optical diagnosis revealed different plasma behaviour. 'Bullet-like' plasma structures were observed only when the discharge was operating in He. That was not the case when working in Ar. Plasma mechanisms are of great importance every time we have to apply a plasma based device in technology. Therefor in order to create or to use reliable and controllable plasma based devices more diagnosis techniques must be used in direct connection with the desired application.

5. Acknowledgments:

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