Characterization of a plasma jet for biomedical applications: composition, temperature, fluid dynamics and plasma structure

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Abstract: In this work a set of diagnostic methods are used to investigate the behavior of the plasma produced by a nanosecond pulsed Dual Gas Plasma Jet developed by the Authors. The adopted diagnostic techniques include optical emission spectroscopy (OES), gas temperature measurement with optical fiber sensor, iCCD imaging with 3 ns resolution and Schlieren imaging associated with an high speed camera.

Keywords: non-thermal atmospheric plasma, jet, OES, Schlieren, iCCD, temperature

1. Introduction

In recent years, atmospheric pressure non-equilibrium plasmas have been proven to be viable tools for decontamination and sterilization of surfaces and living tissues [1]; currently, exploration of the feasibility of plasma aided medical therapies, such as blood coagulation [2], wound remediation [3] and cancer treatment [4], are at the forefront of research in plasma applications.

This exciting field poses the challenge for deeper understanding of plasma interaction with biological matter and puts a premium on diagnostics as a mean to investigate process feasibility and to develop plasma sources tailored for specific applications.

Consequently, the plasma community has dedicated large efforts to characterize plasma sources for biomedical applications and to identify the most suitable diagnostic techniques.

2. Experimental setup

Dual gas nanosecond pulsed plasma jet

The plasma source (Fig.1) developed by the Authors and already presented in details in a previous article [5] is a single electrode (a sharpened metallic needle with a diameter of 0.3 mm) plasma jet suitable for the treatment of different substrates such as metals, polymers, glasses and biological materials. Two separate gas inlets are employed to control the composition of the plasma and the production of reactive oxygen species (ROS) and reactive nitrogen species (RNS); the primary gas is usually Ar or He, while the secondary gas is generally O2, N2 or air. In this work, we present results for the characterization of a plasma jet powered by a nano-second pulse generator having a peak voltage (PV) between 7 and 23 kV, a pulse repetition frequency (PRF) between 83 and 1050 Hz, a pulse width (50%) of 12 ns and a rise time of 3 ns.

Fig.1 Dual gas nanosecond pulsed plasma jet with He (left and right) and Ar (center) as primary gas

Optical emission spectroscopy

In order to analyze the composition of the plasma plume a spatially resolved optical emission spectra in the ultraviolet (UV) and visible (VIS) regions has been collected perpendicular to the plasma jet and along its axis using a 500 mm spectrometer (Acton SP2500i, Princeton Instruments) synchronized with an iCCD camera (PIMAX3, Princeton Instruments), while voltage signal has been recorded by means of an high voltage probe (Tektronix P6015A) and an oscilloscope (Tektronix DP4040). Measurements have been performed using a lens with 30 mm focal length, slit width set at 20 μm and exposure time at 20 μs.

High Speed Schlieren Imaging

The behaviour of the plasma jet outflow has been investigated through a Schlieren imaging [6] setup in a Z configuration composed of a 450 W Ozone Free Xenon Lamp (Newport-Oriel 66355 Simplicity Arc Source), a slit and an iris diaphragm to limit the light intensity, two parabolic mirrors with a focal length of 1 m, a knife edge positioned vertically and a high-speed camera. The plasma jet has been positioned between the two parabolic mirrors, with a vertically downward direction. A first high speed camera (Memrecam K3R-NAC Image Technology), with a setup of 4 000 fps and 1/50 000 s shutter time, has been used to visualize the free turbulent flow jet, whereas a second high speed camera (Memrecam GX-3-NAC Image Technology), operating at 4 000 fps and 1/200 000 s shutter time, has been used to study the behaviour of an impinging plasma jet on different substrates.

iCCD imaging

In order to characterize the plasma source in different geometrical and operating conditions an iCCD camera (Princeton Instruments PIMAX3) with exposure time down to 3 ns, has been adopted. A synchronous pulses generator (BNC 575 digital pulse/delay generator) is used to time the nano-second rise time pulse generator and the oscilloscope that in turn triggered the iCCD camera. An high voltage probe is adopted to verify the relative time position of the iCCD acquisition gate with respect to the voltage pulse waveform.

Temperature measurements

Rotational and vibrational temperatures (T_{rot} and T_{vib}) for N_2 molecules in the discharge have been determined by fitting the experimental spectra of N_2(C-B) bands in the range 369-382 nm with the spectra predicted by the SPECAIR software. Moreover the axial temperature profiles of the plasma jet has been measured by mean of fiber optic temperature sensor (OPSENS OTP – M) with a calibration range of 20 °C – 60 °C, a 0.001 °C resolution, a 0.15 °C accuracy and a response time of less than 1 s; a second fiber optic sensor has been employed to monitor room temperature during the measurements.

3. Results

Optical emission spectroscopy

0-dimensional spectrum for the plasma jet generated at 330 Hz, 20 kV and with He as primary gas (5 slpm) are shown in Fig.2. Lines of nitrogen emission have been measured in the near UV (NUV) region, while OH radicals in the UVB region around 307 nm have been registered. A faint emission in the UVC region due to NO radicals has been also observed. The emission spectra in the UV-VIS range at different axial position of the plasma jet for different operative conditions are presented in Fig.3.

High Speed Schlieren Imaging

The behavior of the jet has been investigated through Schlieren imaging in various configuration both with (Fig.4) and without a substrate (Fig.5-6). Results show as plasma ignition induces a turbulent flow propagations along the plasma jet outflow and how this reduce the laminar region along the outflow. The transition to a turbulent flow is anticipated at the increasing of gas mass flow and repetition frequency.

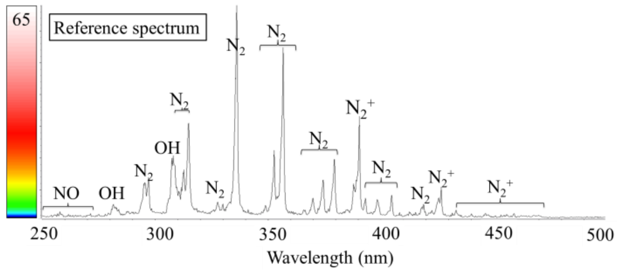

Fig.2 0-dimensional spectrum of the plasma jet at a distance 5 mm from the source outlet

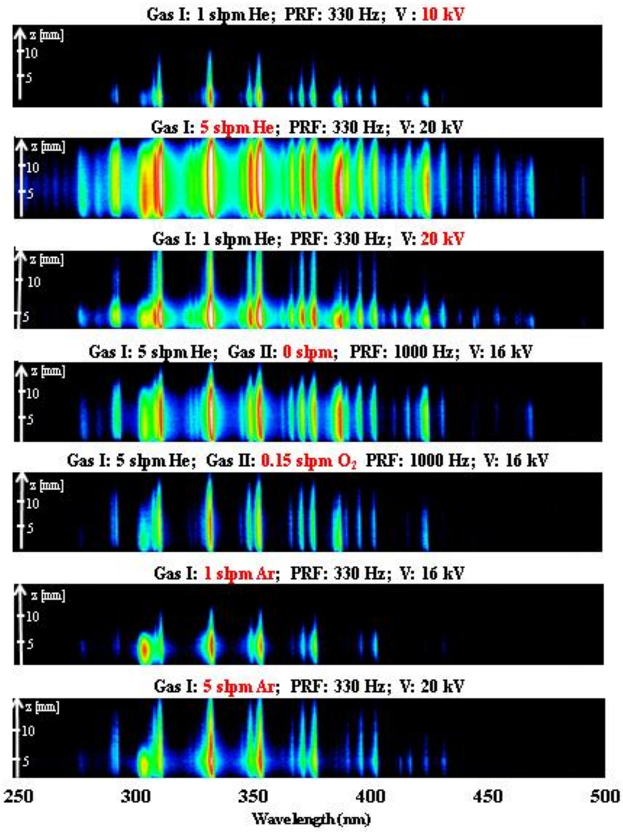

Fig.3 Emission spectra in the UV-VIS range for different operating conditions

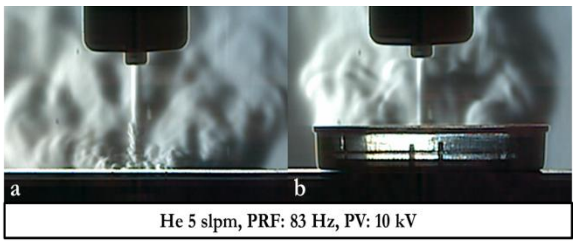

Fig.4 Plasma jet impinging on: (a) metallic plane substrate (b) Petri dish

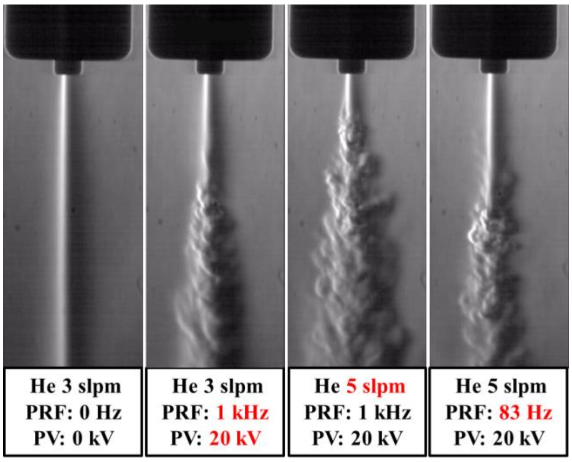

Fig.5 Laminar flow region reduction induced by plasma ignition for different operating conditions

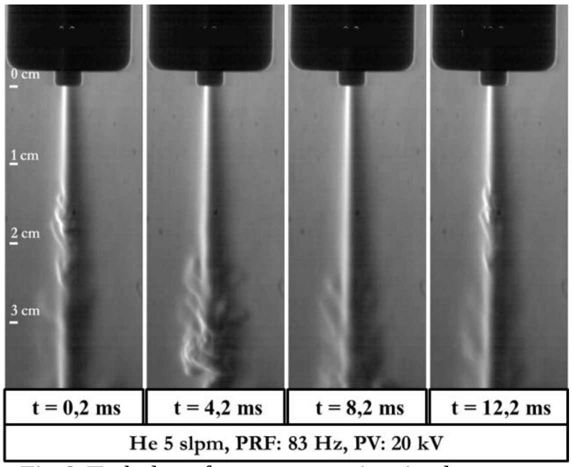

Fig.6 Turbulent front propagation in downstream region between two voltage pulse (0 ms, 12 ms)

iCCD Imaging

The time evolution of the jet discharge is presented in Fig.7. The plasma appears composed of multiple discharge of the duration of few nanoseconds separated by blank periods with no light emission. The length of the plasma region increases from the first to the third discharge probably due to the residual ionization.

Peak voltage and repetition frequency seem to influence the aspect of the second and third discharge while appear to have no effect on the time development of the discharge which is similar for all the presented cases.

Temperature measurements

Measurements of molecular temperature at source outlet for different composition of primary gas, obtained with the software SPECAIR are presented in Fig.8. We considered two configurations with similar operating conditions (mass flow rate of 3 slpm, peak voltage 11 kV, pulse repetition frequency 140 Hz, no secondary gas) but different primary gas species. In the first configuration He has been used as primary gas, whereas in the second configuration the primary gas is Ar.

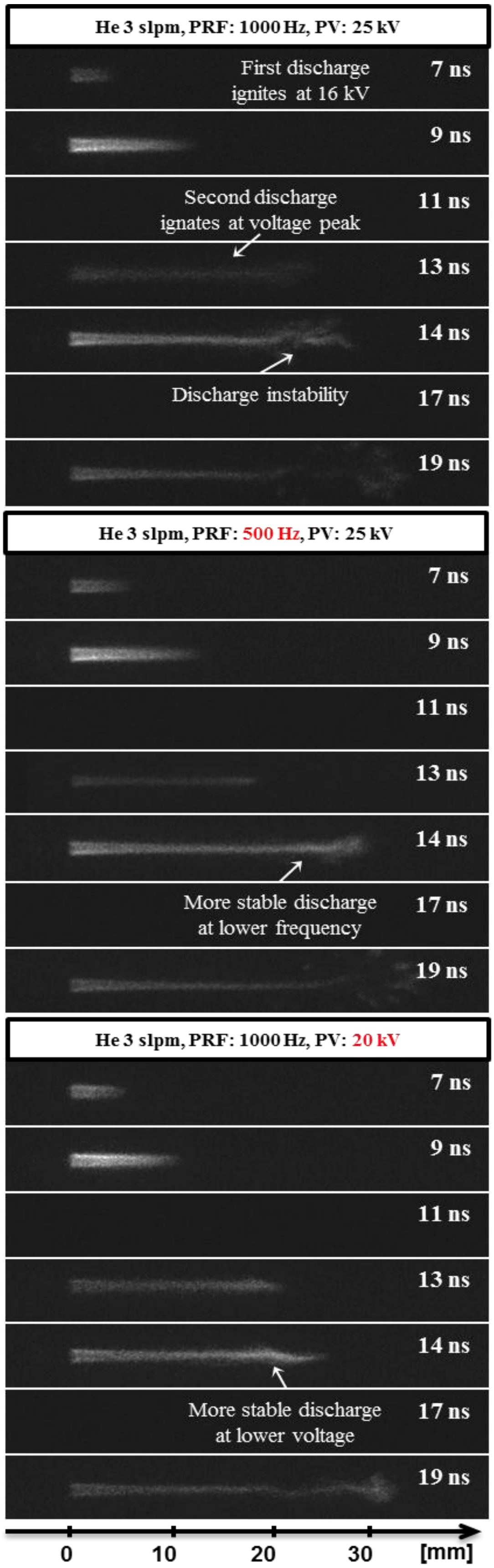

Fig.7 iCCD images of the plasma jet in different operative conditions

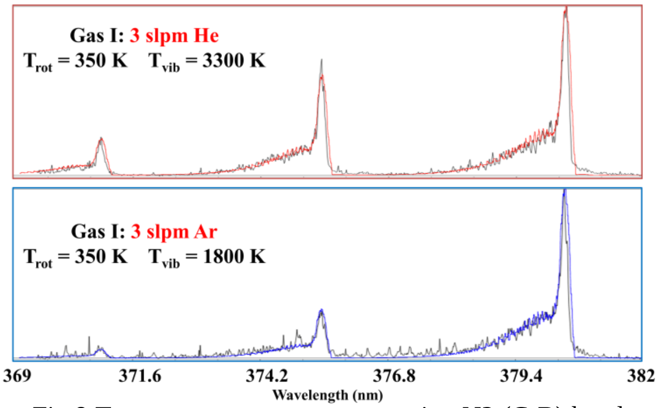

Fig.8 Temperature measurements using N2 (C-B) bands for different compositions of primary gas

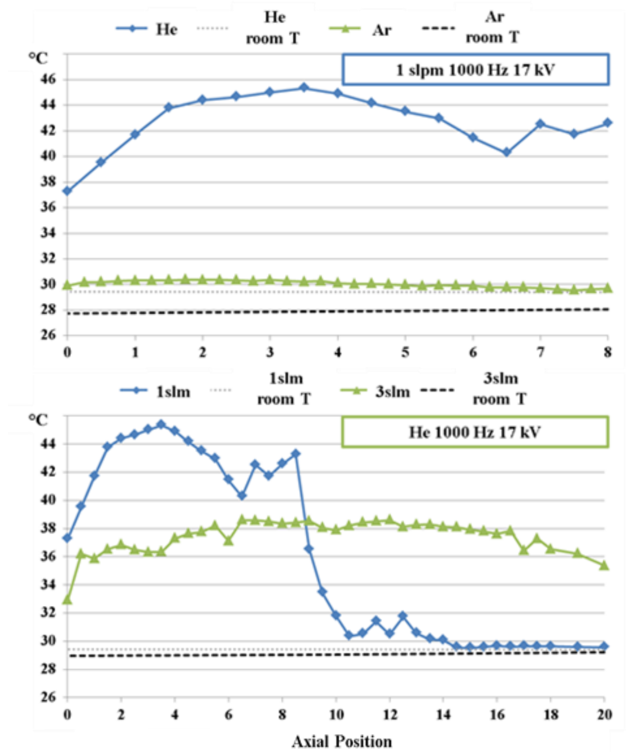

Fig.9 Temperature measurements for different gases (upper) and mass flow rate (lower)

For He an higher T_{vib} is obtained with respect to the case with Ar. T_{rot} doesn't seem to be much influenced by the primary gas type. Moreover, fiber optic sensors have been used to measure the axial temperature profiles of the plasma jet for different primary gas compositions, primary gas mass flow rates, peak voltages and pulse repetition frequencies. The most important results are reported in Fig.9 and 10.

5. Conclusions

The novel dual gas plasma jet device is able to produce a cold atmospheric pressure plasma discharge characterized by a macroscopic temperature lower than 38 °C and a vibrational temperature at about 3300 K and 1800 K for He and Ar, respectively.

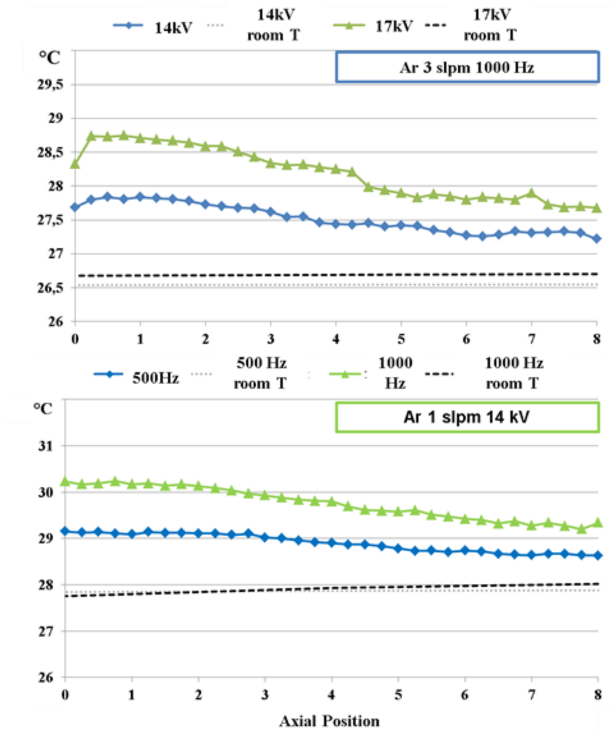

Fig.10 Temperature measurements for different peak voltages (upper) and repetition frequency (lower)

The OES spectrum in the UV-VIS range shows a strong emission from N2, N2+, OH, and NO bands, in particular OH emission is higher when using Ar as primary gas, whereas the injection of small quantities of O2 results in a generally lower emission.

The iCCD imaging reveals a continuous structure of the jet (no evidence of plasma bullets) with instabilities arising in the discharge in correspondence of turbulence onset regions.

The turbulent behaviour of the jet has been visualized with Schlieren high-speed videos.

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