LAMINAR VERSUS TURBULENT FLOW OF AN ARGON RF APPJ INVESTIGATED BY OH PLIF AND ITS INFLUENCE ON THE DISCHARGE PROPAGATION

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ABSTRACT

An argon radio frequency –RF– atmospheric pressure plasma jet for biomedical applications is investigated regarding its laminar and turbulent flow regimes. Additionally, the influence of the gas curtain around the plasma jet effluent on the global flow is studied. By using planar laser-induced fluorescence –PLIF– technique on tracers, observations of flow pattern with and without plasma are possible for different flow rates. The transition between laminar and turbulent is determined experimentally since the classical Reynolds number approach may be not suitable to our plasma features. Simultaneous acquisitions of PLIF signal and argon emissions from the streamer are in excellent agreement and it is shown that streamer and turbulent gas flow have an identical path.

1. INTRODUCTION

For more than a decade now, cold atmospheric pressure plasma jets have been in the focus of research mainly due to their application in biomedicine [1]. Many promising results on plasma interactions with living material have been published and lead to auspicious researches worldwide [1] and references therein. However, understanding applications of plasma sources in biology requires investigations of a great variety of parameters such as reactive nitrogen and oxygen species – especially radicals – (V)UV radiation, electric field, charged particles. Great efforts are required to control the discharge for a tailored reactive component output aimed at the biological interests such as the implementation of a gas shielding in order to control the plasma jet atmosphere surrounding [2]. Following this approach, it becomes clear that laminar or turbulent flow regimes have significant influence on the plasma interaction with the species surrounding the active plasma zone and the effluent.
The present work reports experimental results on gas flow regimes from an atmospheric pressure plasma jet. Flow pattern comparison with and without plasma investigated by PLIF as well as discharge propagation are presented. Significant correlation between streamer pathway and flow pattern will be reported and interpretations will be discussed.

2. MOTIVATION

Fluid flow situations can be roughly described by the Reynolds number, Re[1]:

$$Re = \frac{\rho v D}{\mu} \tag{1}$$

It mainly allows to determine the transition between laminar and turbulent flow. For instance, for a flow in a pipe, the flow is laminar for $Re < 2300$ and becomes fully turbulent for $Re > 3800$. Between, the flow regime is in transition mode and depends on various characteristics of the fluid. However, as useful as this dimensionless quantity is, many assumptions are taking place and appropriate care must be addressed when one applies it to specific geometries. In the experimental conditions of this work, significant discrepencies have been observed between calculated Re and real flow

[1] with ρ $(\mathrm{kg/cm^3})$ the density of the fluid, v $(\mathrm{m/s})$ the fluid mean velocity, D (m) characteristic length and μ $(\mathrm{Pa \cdot s})$ the dynamic viscosity of the fluid.

patterns of the plasma jet's effluent. This fact is mainly attributed to the geometrical features of the nozzle as well as the influence of the plasma on the flow field. Thus, a pure experimental approach to characterize the flow pattern according to gas flow variation is strongly motivated. Additionally, simultaneous space-resolved optical emission spectroscopy –OES– brings information regarding the discharge propagation and interactions between streamer and gas flow.

3. RF PLASMA JET

The cold atmospheric-pressure discharge investigated within this work is a commercial device or so-called kINPen (neoplas GmbH, Germany) [1]. It is driven by a 1 MHz radio frequency (RF) electric input and globally described as a DBD-like plasma jet [3]. Figure 1 shows the basic geometrical and electrical configuration which consists of a high-voltage (HV) needle electrode centered within a 1.6 mm dielectric capillary. The electrode potential is brought from 2 to 6 kV and delivers an output power from 0.9 to 2.2 W. Through the ceramic capillary flows from 0.5 to 3.0 standard liter per minute (slm) dry argon and yields outside an effluent of 10 mm length.

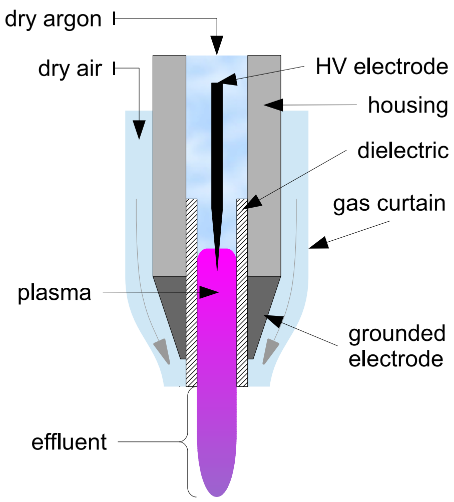

Fig. 1: Schematic of the plasma jet apparatus fed with argon [4].

Additionally, an external gas flux is implemented via a gas shielding device in order to control the interaction of the effluent with the surrounding atmosphere. This gas shroud can be fed with different gases and operates at various fluxes to vary the impact on the effluent. More information can be found in the literature [4].

4. DIAGNOSTIC METHODS

The flow pattern diagnostic is based on PLIF. The gas flow structure is imaged via the fluorescence signal of either hydroxyl radical –OH– in case of plasma on produced by the plasma itself, or the LIF signal of an organic compound for the plasma off case. The principle and details about the application of PLIF to flow diagnostics can be found e.g. [5] and references therein. Briefly, a doubled frequency dye laser pumped by a primary stage Nd:YAG laser at 10 Hz repetition rate generates radiations around 283 nm. Both tracer, OH and acetone are known to absorb efficiently the energy at this wavelength and in the case of OH, the transition is well separated from other neighboring lines. The energy of the laser beam is adjusted by a couple of polarizing optics in order to keep the laser properties constant. The linear responses of the signal according to the energy of the laser beam is checked in order to avoid any saturation effects of the transition. A telescope made of a cylindrical lens expands the laser beam into the vertical direction whereas it focuses on the horizontal direction. This laser sheet of approximately 200 μm trick and 15 mm height goes vertically through the effluent of the plasma. The inhomogeneity fluence of the laser sheet is determined by Rayleigh scattering and then corrected in post-processing. Moreover, in order to reduce pertubation due to Rayleigh scattering while recording the fluorescence signal, the polarization of the laser is switch from –s to –p.
The detection of the fluorescence is done by an ICCD camera located at 90°from the laser beam. A macroscopic lens 100 mm f\2.8 50 mm diameter is mounted on the camera and ensures the collection of the isotropic fluorescence signal. An additional stereoscopic optical system is implemented in front of the camera in order to observe simultaneously the fluorescence and the emission from the streamer. This apparatus enables to split vertically the sensor area in two areas where the plasma effluent is imaged. By means of an optical bandpass filter – 313.0 nm $\pm$ 5 nm – OH fluorescence is transmitted through one of the optical input. On the second optical input, used to collect the spontaneous emission of the streamer, a neutral density filter for the visible radiations is installed. The laser pulse, the camera gate as well as the discharge are all synchronized via a delay generator, a computer and a self-made elec-

tronic. Consequently, electrical and optical signals are simultaneously phase-locked and recorded in a single-shot acquisition mode respectively for the gas flow and the discharge propagation diagnostic.

5. PROPERTIES OF THE GAS FLOW

The gas flow pattern is imaged for different flow rates by admixing an organic compound to the feed gas. The fluorescence signal is recorded over a single laser pulse, which allows to visualize vortexes and details of the flow structure.

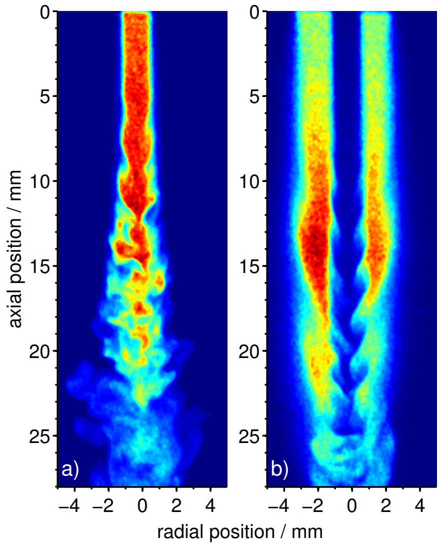

*Fig. 2: Argon flow imaged by PLIF on acetone. The plasma is **off**. Feed gas and curtain gas are set at 1.5 slm (Re = 1395) and 2.5 slm respectfully. a) the tracer is admixture in the feeding gas –here dry argon–. b) the tracer is admixted in the shielding gas –here dry air–. The 2 mm outer diameter nozzle is aligned on the absolute zero position.*

Figure 2 depicts the resulting flow pattern with 1.5 slm flow rate and 2.5 slm gas shielding when admixing the tracer either in the feeding gas or in the shielding. Under these conditions, the flow is laminar up to 8–10 mm and then becomes turbulent. It is clear that with such a flux, the surrounding molecules –mainly air– are mixed with the plasma jet effluent and affect the output chemistry such as generation of nitric-oxide, NO or oxygen metastable, $O_2\ ^1a\Delta_g$.

While figure 2a) confirms a strong interaction between feeding gas and gas curtain, figure 2b) shows the effective action of the gas curtain – until the global flow stays laminar– to isolate the plasma effluent from the uncontrolled air compound chemistry such as humidity. The wave-like structure at the feeding/curtain gas interface results from the shear force occurring when two fluids have significant different velocity gradient and dynamic viscosity. Interestingly, the gas curtain can also be used as an additional chemical compound to tailor the plasma effluent chemistry necessary for specific applications.

Figure 3 shows the transition between laminar and turbulent flow regime. It has been shown by Iseni *et al.* that turbulent has an effect on the discharge propagation and more details can be found in [6].

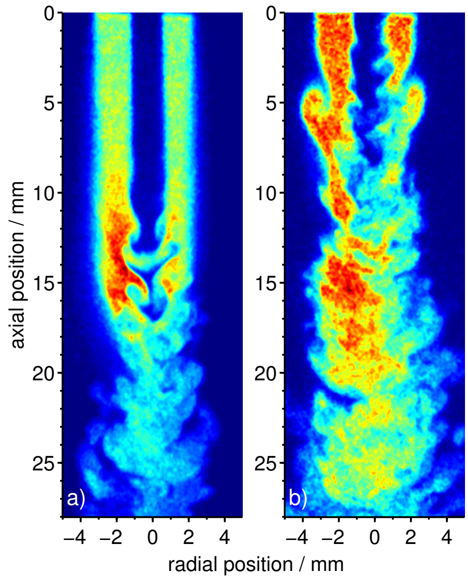

*Fig. 3: Gas flow patterns for different gas flow rate. The plasma is **off**. The ratio between feeding gas and gas curtain is constant. a) 2.0 slm feeding gas flow rate, Re = 1860. b) 2.5 slm feeding gas flow rate, Re = 2325.The nozzle is aligned on the absolute zero position.*

6. STREAMER-BULLET PROPAGATION

With plasma on, it is not possible to admix any organic compound as a tracer, therefore the OH radical is used as tracer. Figure 4 presents on one hand the OH fluorescence resembling the argon / air boundaries on the second hand the streamer propagation. First of all, under the present gas flow rate, the effluent flow is expected to be laminar in 0-10 mm range (cf figure 2) which is not the case with plasma on. Here, Kelvin-Helmholtz instabilities are strongly supposed to be the origin of this difference with plasma off. Recently, Robert *et al.* have reported similar observations for a helium pulsed atmospheric-pressure plasma streams –PAPS–[7].

Comparing figures 4a) and b), both signals appear to have very similar shapes which points to the fact that discharge and gas flow pattern are correlated. Indeed, Iseni *et al.* have explained that the streamer is propagating within a thin argon channel strongly dependant from the diffusing air into the argon flow. Confronting streamer propagation and flow field developement time scales means that the gas flux remains static regarding the discharge time frame. Consequently, it is claimed that metastables and ions have a longer lifetime within this argon channel than surrounded by air. Moreover, at 1 MHz excitation frequency, the memory effect induced by these energetic species constitute excellent conditions for pre-ionization and hence initiating the discharge.

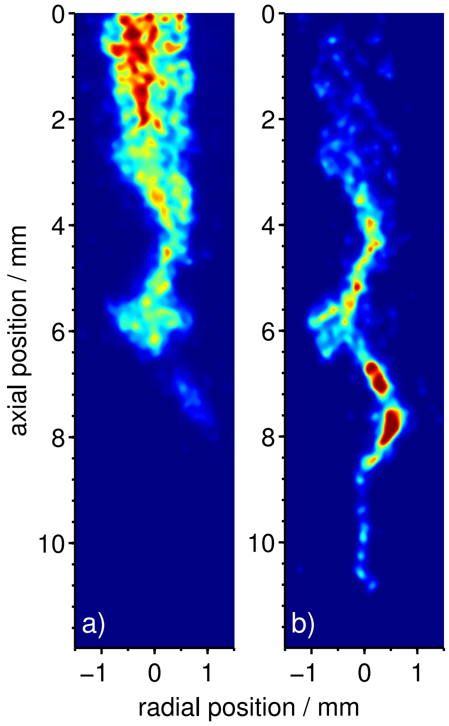

Fig. 4: Stereoscopic simultaneous single-shot image acquisition over one excitation periode of the plasma jet. a) OH fluorescence revealing the argon/air boundaries. b) argon emission from the discharge resulting from the streamer propagation. The feeding gas flow rate is 1.5 slm and the exposure time sets at 200 ns. The nozzle is aligned on the absolute zero position.

7. CONCLUSION

This work reports experimental studies of gas flow patterns at laminar, intermediate and turbulent conditions and relevant for applications. PLIF imaging of the flow points that special care needs to be attributed according to the plasma jet nozzle geometry. Effects of plasma on the effluent pattern are demonstrated and partially explained. Finally, by means of PLIF on OH and stereoscopic OES, strong correlations between gas flow and streamer propagation are found. The role of ambient species diffusion and energetic species such as metastables and ions are claimed to play a predominant role for streamer propagation especially when turbulence occurs.

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