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Schlieren flow visualization of helium atmospheric plasma jet and influence of the gas flow rate and applied voltage frequency

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Abstract. We used schlieren photography to visualize the influence of gas flow rates of 1, 2.5, 5, 10 L/min and of the applied voltage frequency on a helium atmospheric plasma jet induced at the nozzle of a capillary tube. The expansion of the gas in the surrounding medium (air) was analyzed in the two different modes – plasma on/plasma off. Changes in the above parameters affect the gas flow regime and the hydrodynamics of the jet.

1. Introduction
Atmospheric pressure plasma jets are rapidly gaining importance as potential tools for plasma processing in a number of applications, such as film deposition [1], surface modification [2], sterilization [3], and biomedical processes [4]. The plasma jets are technologically simple, environmental friendly and very economical. Therefore, exploring the behavior of the exhaust gas and the effects of varying the operating parameters is very important.

The schlieren method introduced by Foucault [5] and Toepffer [6] has long been an important optical tool for the study of different types of flows, especially compressible flows. Schlieren images are also used to investigate fluid dynamic characteristics of plasma jets. For example, Bradley et al. [7] studied the outflow of a helium plasma jet. Boselli et al. [8] investigated the fluid dynamic characteristics of a nanosecond plasma jet. Zheng et al. [9] also used schlieren photography to study the hydrodynamic of a helium plasma jet. In addition, many other related studies have been published. For example, the group at INP Greifswald applied laser schlieren deflectometry to the temperature analysis of filamentary plasmas [10, 11].

In the present study, schlieren photography was utilized to investigate the gas behavior of the plasma jet under different conditions. The plasma jet was generated in open air in a simple micro-discharge configuration by flowing helium through a coaxial dielectric barrier discharge chamber (DBD) excited by an AC voltage at frequencies of some tens of kHz.

2. Schlieren optical system
A schlieren system visualizes variations of the refraction index of light, thus effectively depicting the density gradient variation in a fluid. Figure 1 shows the setup of the experiment. A small-size source illuminates a concave mirror of long focal length. The distance between the source and the mirror is

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equal to two focal lengths of the mirror. About half of the reflected beam is blocked by the edge of a blade. A long-focal-length camera is focused on the mirror image to capture the shadow image of the plasma jet flow. In our experiment, the imaging system set-up consisted of a jet tube ($\Phi_{\text{int}} = 2\, \text{mm}$), a concave mirror with a diameter of 130 mm (a focal length of 1470 mm), a six-megapixel compact digital camera (Nikon Coolpix L820 with a maximal focal length of 120 mm) and a 6 V continuous LED as a light source.

3. Influence of the flow rate

Figure 2 shows schlieren images of the helium jet without (upper panel) and with (lower panel) plasma ignition, operating at 35 kHz and 5 kV, for different flow rates. The micro-discharge is visible on the bottom of each figure. It is clear that the laminar-turbulent transition occurs at flow rates exceeding 2.5 L/min.

![Figure 1. Schematic diagram of the set-up used in the experiment.](image)

![Figure 2. Transition point without plasma (top) and with plasma (bottom) as a function of the flow rate. The plasma is generated by 5 kV AC voltage with frequency 35 kHz.](image)

Figure 3 shows schlieren imaging of a helium flow into ambient air at two different flow rates before plasma ignition. The buoyancy is vertically upward. The output diameter of the jet is 4 mm. Thus, in the case of a flow rate of 5 L/min, the Reynolds number at the exhaust section was about 225, and in the case of 2.5 L/min, about 112.5. It is clear that at the higher velocity cases, eddy flows (vortices) are created in the upper part of the imaged flow (the turbulence section) due to the buoyancy. For all flow rates below 5 L/ min, the displayed flow is laminar. Similar results were reported in earlier studies [7], [9].
The transition from laminar to turbulence flow depends on the plasma ignition. Figure 4 shows a comparison of these cases. The flow rate in both cases is 5 L/min. One can conclude that in case (a), vortices are created earlier than in case (b), in analogy with [12].

Figure 3. Schlieren imaging of a helium flow into ambient air at different flow rates before plasma ignition: (a) 5 L/min, (b) 2.5 L/min.

Figure 4. Schlieren imaging of laminar to turbulent mode transition: (a) plasma on, (b) plasma off.

4. Influence of the operating voltage frequency
In addition, we examined the effect of the applied voltage frequency. The flow rate was set at 2.5 L/min and four sinusoidal AC voltages of 34.84 kHz, 35.15 kHz, 36.14 kHz and 36.84 kHz were considered. A comparison between these cases is presented in figure 5. It is clear that the laminar length decreases as the frequency of the AC voltage is raised.

Figure 5. Transition point as function of the applied frequency for a flow rate of 2.5 L/min.

5. Conclusions
The gas behavior in a high-voltage driven single-electrode plasma jet (at atmospheric pressure) was studied by Schlieren imaging. First, the fluid dynamic behavior of the exhaust gas was investigated at different flow rates. The result showed that the transition from a laminar to turbulent mode takes place prior to the flow rate reaching 5 L/min. In addition, the plasma ignition increases the turbulent length. The influence of the plasma is more important at higher flow rates. Next, the effect of the operating frequency was studied. As one should expect, as the frequency is increased, the length of the turbulent flow also increases. The results presented could serve as a basis for the design, optimization and analysis of plasma processes in various applications.
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