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# Evidence of the Influence of Plasma Jets on a Helium Flow into Open Air

Marc Foletto, Vincent Puech, Jérôme Fontane, Laurent Joly, and Leanne C. Pitchford

**Microplasma jets propagating in a helium flow surrounded by open air at ambient temperature have attracted the attention of many researchers for their putative ability to deliver high fluxes of reactive oxygen and nitrogen species to a target situated some centimeters away. This is of particular interest in biomedical applications. In this paper, we use Schlieren images to show that ignition of the plasma jet causes a reduction in the length of the laminar zone of the helium flow.**

**Atmospheric-pressure plasmas, hydrodynamics.**

**T**HE experiments reported here were conducted using a microdischarge configuration, in which a helium jet impinging on open air at atmospheric pressure is generated by flowing helium at several liters per minute through a dielectric tube with an inner diameter of 2.35 mm. A plasma is initiated by applying a positive voltage (5.5 kV, 20 kHz,  $\sim 100$  ns rise time, and  $\sim 250$  ns pulse width) to a hollow electrode (1.6-mm inner diameter) centered inside the dielectric. The dielectric extends 6 mm beyond the end of the electrode. The photograph in the far right in Fig. 1 shows a typical plasma jet. The plasma appears continuous when viewed by eye, but rapid imaging techniques reveal that the plasma is reignited at each voltage pulse. Most of the light emitted by the plasma jet is produced by an ionization wave propagating in the helium-rich region past the exit of the tube. The air surrounding the helium flow is much more difficult to ionize, and so the propagation of the ionization wave is confined to the volume of the helium channel. The length of the plasma jet is determined by the length of the helium channel and the applied voltage waveform. The plasma so generated has been referred to variously as a plasma bullet, a plasma jet, and as a guided streamer [1], [2].

Because of the significant difference in mass densities of helium and air (a factor of about 7), Schlieren imaging can be used to easily visualize the helium flow into open air. This is

an optical technique that converts variations of refractive index caused by spatial gradients in concentration profiles into spatial variations in the intensity of a collimated light source traversing the medium.

Schlieren images of the helium channel are shown in Fig. 1 without (upper row) and with (lower row) ignition of plasma jets for different Reynolds number,  $Re$ , in the conditions defined above. Emission from the plasma is not observable. The Reynolds number of the flow at the exit plane of the dielectric tube is defined as  $Re = V\phi_{int}/\nu$ , where  $V$  is the mean helium flow velocity,  $\nu$  is the helium kinematic viscosity, and  $\phi_{int}$  is the inner diameter of the dielectric. From left to right, the Reynolds number increases from 150 (2 L/min flow rate) to 550 (7.3 L/min flow rate). The helium flow is laminar in the tube for these values of  $Re$  and remains laminar for a certain distance past the tube exit. (The presence of the electrode inside the tube could influence the laminarity of the helium flow past the tube exit, but for our geometry, this is not the case.) In the laminar zone, there is little mixing of helium with air, and the radial components of the helium flow velocity are almost zero, as evidenced by the small opening angle of the helium column. The flow becomes turbulent past some transition point that is indicated by the red symbols in the panels in Fig. 1, and thereafter mixing is rapid. The one shot images in the right on each row are photographs taken with an exposure time of 10 ms, and these show the presence of vortices not distinguishable in the images that have been averaged over 100 shots (for a more precise identification of the transition point). As expected, the transition point moves closer to the tube with increasing  $Re$ . For low  $Re$  ( $< 360$ ), the generation of the plasma jet causes a significant decrease in the length of the laminar zone, a phenomenon first reported in [3] and [4]. For higher  $Re$ , where the transition occurs naturally closer to the dielectric, the influence of the plasma is less. Other effects of the plasma ignition on the helium flow have been discussed recently in [5].

One possible reason for the influence of the plasma on the helium column is via the momentum imparted by the ions to the neutrals in the advancing sheath region near the surface inside the dielectric tube, where the power deposition is highest. This effect of the ion wind is well known from studies of surface discharges in air for flow control [6].

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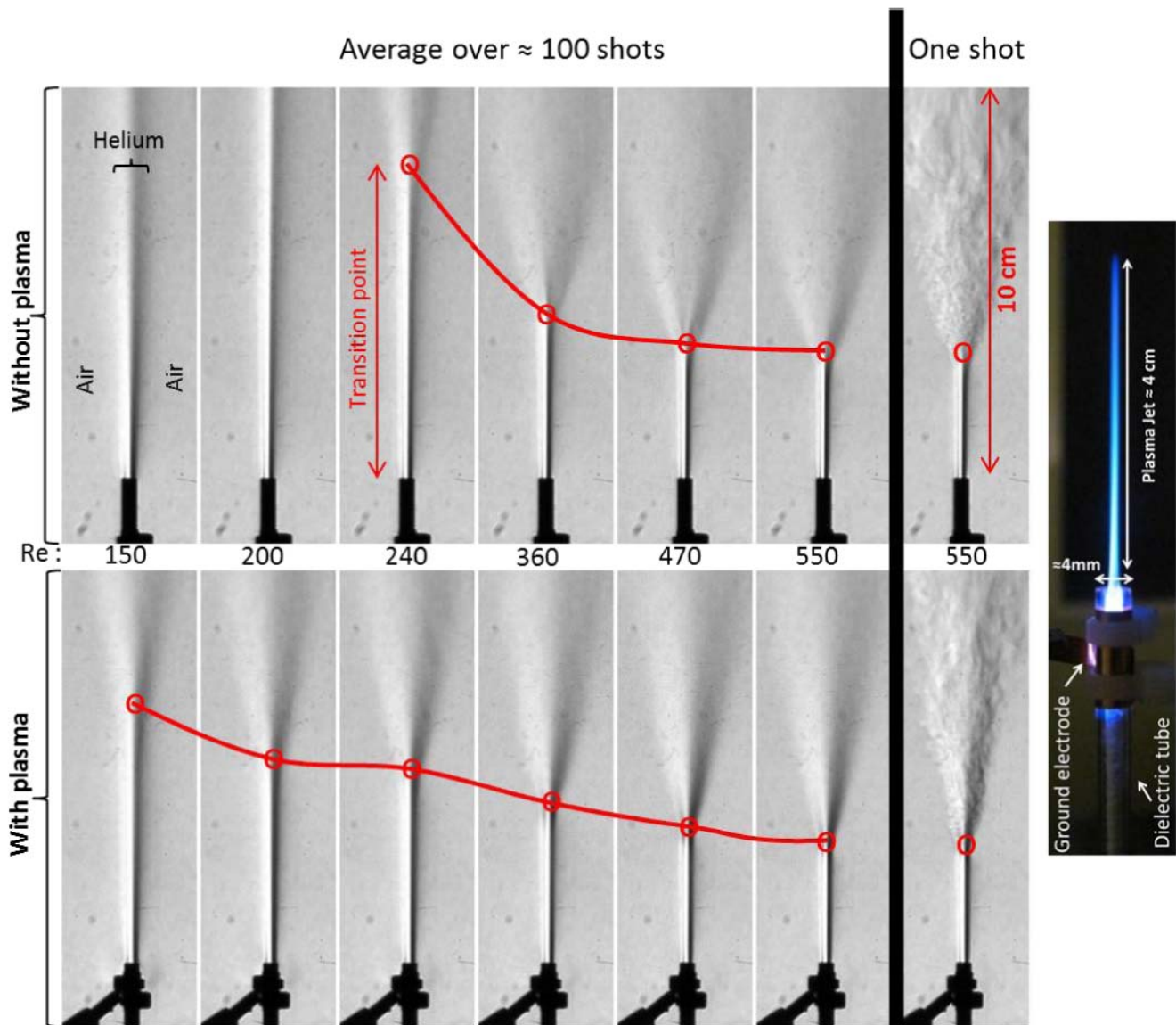


Fig. 1. Schlieren visualization of a helium flow exiting a dielectric tube (2.35-mm inner diameter) and impinging on open air, as a function of helium flow rate, expressed in terms of the Reynolds number,  $Re$ , in the tube. The tube is positioned vertically and can be seen in the shadow in the lower part of each image. The images in the upper row correspond to cases without plasma ignition, whereas the lower panels correspond to cases where a plasma jet is present. The laminar-to-turbulent flow transition point is indicated with red symbols (the transition point is outside the field of view for the two images in the upper left).

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