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Flow field dynamics in an atmospheric pressure plasma jet: A tale of turbulence and transition

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In the past few decades, atmospheric pressure cold micro-plasma jets have emerged as powerful tools across diverse applications such as material processing, surface modifications, functionalization, and biomedical treatments. The effectiveness of the plasma jet is intricately linked to the flow dynamics, which governs its stability. Under varying flow rates, the jet undergoes a laminar to turbulent transition through a transitional state, impacting both its visual morphology and functional efficacy due to heat and particle transport. While the characteristics of plasma jets have been widely studied, the accompanying flow dynamics remain relatively underexplored which is investigated in the present study.

In this work, a helium plasma jet is produced using a ring-to-ring electrode configuration over a capillary tube having its outlet's inner diameter (ID) of 0.8 mm [1,2]. A sinusoidal waveform of maximum amplitude 11 kV (pp) and frequency 10 kHz is used to ignite the He gas. After ignition, the plasma comes out from the capillary as a fine plasma jet. The jet flow (both plasma OFF and plasma ON conditions) has been visualized using a Schlieren imaging setup, as shown in fig. 1, along with the description of the plasma jet system. The Schlieren setup consists of a single LED light source, a pair of spherical mirrors, a slit, a knife-edge, and a high-speed camera (Photron Nova-R3, 4k). The plasma jet is positioned in the test region between the two spherical mirrors and a series of images are captured at a frame rate of 10k in order to visualize the turbulent characteristics. To gain deeper insights into the flow characteristics, Particle Image Velocimetry (PIV) technique is employed. The PIV setup consists of a High-Speed Pulsed Dual Laser system (Diode-pumped Solid-state Lasers (DPSS), Beamtech Vlite-Hi-527), High Speed Camera (MICROVEC), micro-pulse synchronizer (MICROVEC), Microvec Software, particle generator (TSI), and seeding particles (olive oil, 0.8 μm). The camera and laser are synchronized to capture the illuminated jet stream image pairs at a calculated straddle time difference. A window size of 32×32 pixels was assumed, and the particle movement between the image pair was fixed to 25% of the window size to obtain a better cross-correlation. A series of image pairs is captured at a frame rate of 4k, and the laser pair operating frequency was set to 2 kHz. The spatial and temporal velocity fields obtained from PIV formulation using PIV Labs on MATLAB platform will be utilized for turbulence characterization across different flow conditions (0.5–5 lpm, R_e: 119-1185), and also to investigate how plasma influences turbulence and the overall flow structures. Fig. 2 presents the instantaneous Schlieren images illustrating (a) the helium gas jet at 1 lpm (plasma OFF), (b) the plasma jet at 1 lpm (plasma ON), and (c) the plasma jet at 5 lpm (plasma ON). Additionally, fig.2 (d) the instantaneous velocity contour plot and fig. 2 (e) the instantaneous vorticity contour plot corresponds to the case shown in fig.2 (a). The Schlieren images clearly demonstrate that plasma ignition promotes an early onset to turbulence at the same flow rate conditions. Further, the plasma jet becomes more unstable and turbulent at a higher flow rate (5 lpm). While the velocity and vorticity plots shown here correspond to the plasma OFF condition, future experiments will extend to plasma ON conditions to better understand how plasma-induced body forces alter flow structures and turbulence.

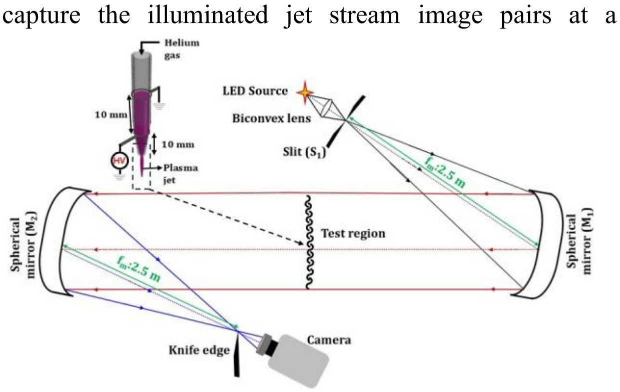

Fig. 1: Schematic diagram of the Schlieren setup along with the plasma jet setup

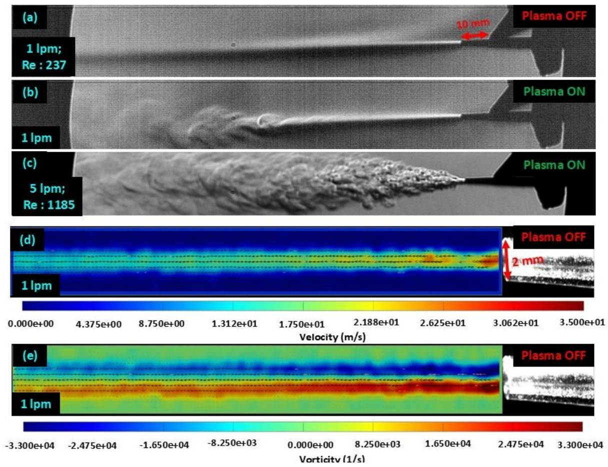

Fig. 2: Schlieren images of (a) He gas jet (plasma OFF) at 1 lpm (R_e = 237), and He plasma jet (plasma ON) at (b) 1 lpm and (c) 5 lpm (R_e = 1185). (d) velocity and (e) vorticity contour plots correspond to the case shown in (a)

References

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