## Fundamental Studies in Electro-Coflow: Whipping Analysis

In this project, we developed a novel microfluidic device based on electrospray in glass-based coflow geometries, to generate drops with sizes that can be tuned from well above to well below the smallest geometric feature of the device. The method relies on coupling electric and hydrodynamic forces and uses a liquid collector rather than a metallic component as counter-electrode to allow the steady-state operation of the device.

The device also allows fundamental studies on the electric current behavior of electrospray processes and on droplet generation mechanism in microfluidics. Our previous work on electric current behavior [1] revealed a strong voltage dependence and weak flow rate dependence, in stark contrast to classical electrospray. This study opens a way to induce electric control over the current, and as a result, over the size of the drops that are formed in the process. We also used optical microscopy and high-speed imaging techniques to demonstrate that the device can be operated in various regimes: dripping, electro-dripping, and an electrically controlled regime [2]. These various regimes allow generation of drops in various sizes compared to the tip diameter. We found that the balance between electrical relaxation and residence times plays an important role in determining the shape of the meniscus in the electrically dominated regime, which is ultimately responsible for the resultant drop size.

We made further investigations into the electrically dominated regime, interested by the unique features exhibited by the liquid meniscus in this regime. The liquid meniscus assumes a conical shape, with the apex of the cone opening into a microjet that either directly breaks into drops due to axi-symmetric hydrodynamic instabilities or non-axi-symmetric hydrodynamic instabilities (similar to a whipping jet in classical electrospinning). These non-axi-symmetric instabilities have been focus of our recent attention. By operating the device in the whipping regime (Figure 1), we are currently making fundamental studies on the whipping mechanism, which is typically hard to study in classical electrospinning with air as outer medium. In our experiments, the inertial and viscous forces due to the outer liquid result in less chaotic whipping motion and hence allow detailed study.

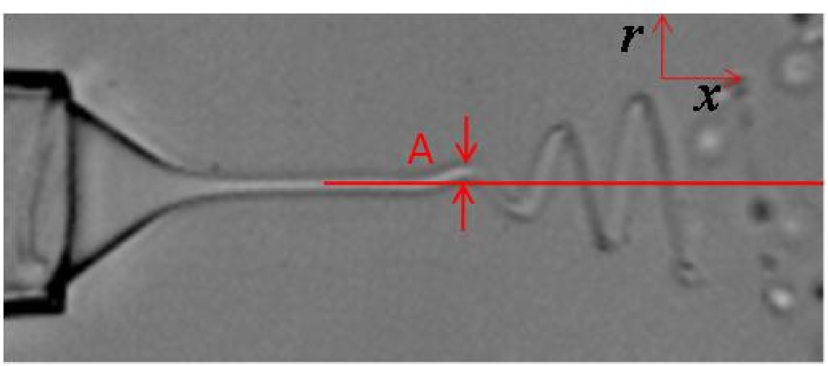


**Figure 1: Image showing the whipping jet.**

By analyzing the videos taken using a high speed camera, we track the motion of the fluid element in the whipping region. The height of the 1st peak (amplitude) from the center of the jet (Figure 1) is tracked as a function of time. The sequential images in time indicate a straight line motion of the fluid element. Figure 2 shows a typical plot of the amplitude vs. time at constant voltage. The different data points are for different inner flow rates. We can see that the amplitude increases linearly with time for all the flow rates. It implies that the radial whipping speed, which is the slope of the curves, is constant. One interesting feature we observe from this data is that, for continuous increase in inner flow rate, there is a sudden increase in the slopes (Compare the slopes for inner flow rate of 45 microL/hr and 50 microL/hr). This indicates that there is a jump in radial whipping speed with inner flow rate. One can appreciate the jump in whipping speeds from the two videos corresponding to the two flow rates. By tracking the 1st peak motion in the axial direction, we observed that the axial whipping speed also shows a jump with the inner flow rate. We are currently investigating the physics behind this observed jump.

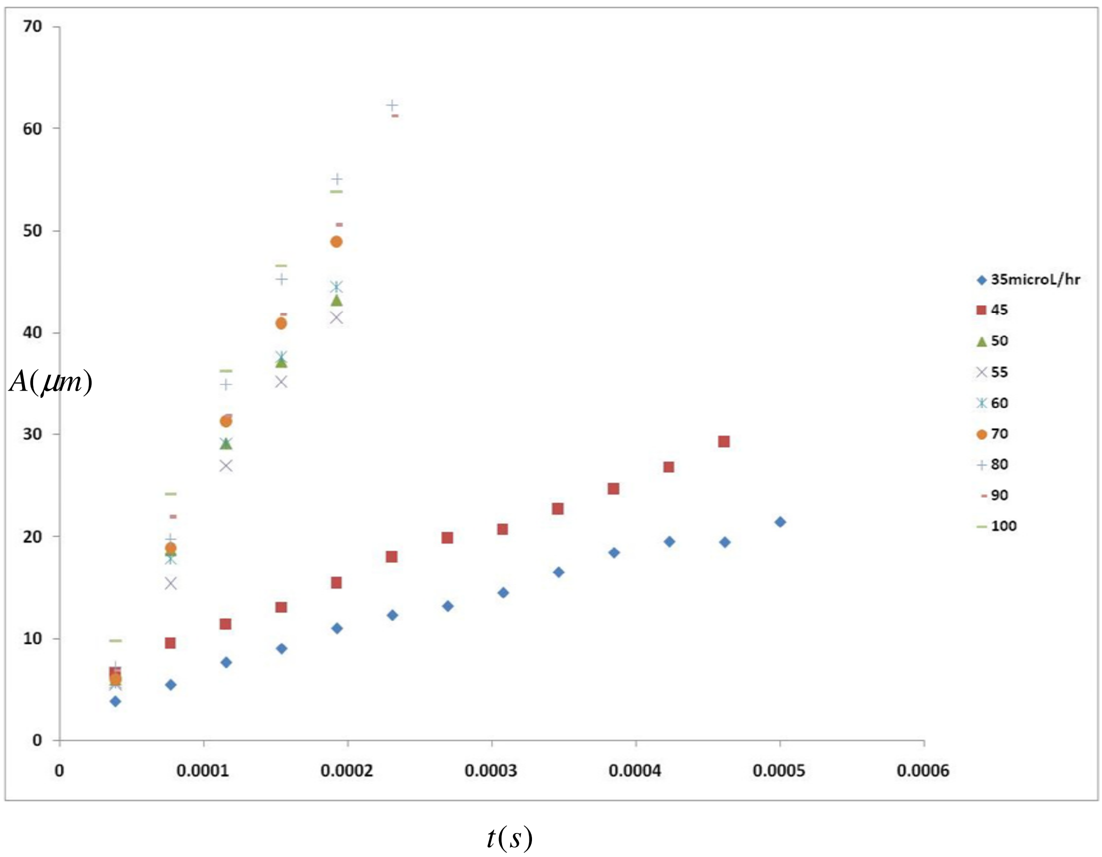


**Figure 2: Plot of the Amplitude vs. time at 1950V for different inner flow rates.**

[1] V.R. Gundabala, N. Vilanova, and A. Fernandez-Nieves, "Current-Voltage Characteristic of Electrospray Processes in Microfluidics", *Phys. Rev. Lett.* **105**, 154503 (2010).

[2] N. Vilanova, V.R. Gundabala, and A. Fernandez-Nieves, "Drop Size Control in Electro-coflow", *Appl. Phys. Lett.* **99**, 021910 (2011).