Title of thesis: Physics of liquid jets in electrohydrodynamic jet printing
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Abstract

Electrohydrodynamic (EHD) jet printing involves controlled deposition of a jet issuing from a stretched liquid meniscus attached to a metallic needle under the influence of a strong electric field between the needle and a grounded collector plate. The application of an electric field enables the production of the fine jet, whose diameter can be easily adjusted by varying the operating parameters and physical properties of the liquid. Using fine EHD jets, customized two-dimensional (2D)/three-dimensional(3D) patterns are made by layer-by-layer deposition of the jet onto a non-contact substrate attached to a motion-controlled translation stage. This single-step, mask-less, non-contact method offers high-resolution rapid prototyping of miniaturized 2D/3D patterns, which are generally fabricated through conventional lithographic techniques. Consequently, this method paves the way forward for additive printing in a broad spectrum of applications, including flexible electronics, biotechnology, and microfluidic networks. However, to achieve consistent and reliable printing results, a comprehensive understanding of the physics of liquid jets in the EHD jet printing configuration is essential. In the present study, we aim to discuss the physics of liquid jets in the EHD jet printing configuration by analyzing the characteristics of the jet through experimental observations as well as mathematical modelling.

First, we experimentally investigate the effect of geometrical parameters on the stability domain, 2D space of the applied electric potential difference and the imposed flow, wherein a fine jet emanating from the tip of a stable conical meniscus, also known as Taylor cone-jet, is observed. In this study, we systematically vary the needle diameter, needle-to-collector distance, and physical properties of the liquids and observe the dynamic behavior of the cone-jet. We characterize the various jetting modes through experimental visualization of EHD jets at the needle outlet based on the geometrical shape of the deformed meniscus at varying flow rate and applied electric potential difference between the needle and the collector plate. We show that the various observed modes are similar to those observed in conventional electrospraying. Moreover, the stability domain significantly depends on the geometrical parameters and the physical properties of the liquid. In particular, our observations highlight that the stability domain substantially depends on the needle diameter for relatively viscous liquids; whereas, the stability domain does not exhibit any dependence on the needle diameter for relatively less viscous fluids. In contrast to the needle diameter, the needle-to-collector distance does not affect the jetting characteristics except the magnitude of the electric field at the needle tip.

Next, through experimental visualization of EHD jets and current measurements, we show that steady EHD jetting can occur broadly in three distinct regimes, namely, the cone-jet, moderately-stretched jet, and thick-jet regimes, depending on the flow rate, applied potential difference, and the needle-to-collector gap. To elucidate the underlying physics of these experimentally observed regimes, we perform order-of-magnitude analysis in the current transfer region, a region connecting the conical meniscus with the fine jet where conduction and surface convection currents are of comparable magnitude. Based on the relative size of the current transfer region and the jet diameter, we derive the criteria for observing the three steady EHD jetting regimes. For each of these regimes, we also describe the dependence of the jet diameter and the current carried by the jet on flow rate, potential difference, and aspect ratio in the form of scaling relations. The theoretical criteria for observing the distinct steady jetting regimes and the corresponding scaling relations for the jet diameter and current show good agreement with the experimental observations.

Lastly, through experiments and numerical simulations, we describe the physics of the moderately-stretched EHD jet applicable to the EHD jet printing process. Through comparison with experimental measurements, we show that our simulations correctly predict the jet shape for varying flow rates and applied potential difference. We present the physical mechanism of inertia-dominated slender EHD jets based on the dominant driving and resisting forces and relevant dimensionless numbers. We show that the slender EHD jet stretches and accelerates primarily due to the balance of driving tangential electric shear and resisting inertia forces in the developed jet region, whereas in the vicinity of the needle, driving charge repulsion and resisting surface tension forces govern the cone shape. The findings of the work presented in this thesis can help in operational understanding and better control of the EHD jet printing process.