ABSTRACT

of the Thesis

Electrohydrodynamics of droplets in confined fluidic environment

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by

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Confined droplets have been finding ever-increasing applications in many chemical and biological systems where each droplet takes up individual roles of single, independent mini-reactors. Such advancements have opened up several emerging areas such as nanoparticle synthesis, single-cell encapsulation, analysis of proteins and nucleic acids, among several others. However, while in practice the role of confinement has been inevitable in controlling the underlying functionalities, the implications of the same have been grossly overlooked in design and analysis. As a consequence, in electrical field mediated interactions, the complex interplay of droplet electrohydrodynamics and wall-induced hydrodynamic interactions remains to be addressed, which could otherwise bear significant implications towards the advancement of micro-total-analysis systems and lab-on-a-chip technology.

With the above motivation, studying electrohydrodynamics (EHD) of viscous droplets in a confined fluidic domain under the action of an external electric field is considered to be the main focus of the present dissertation. Three different aspects are primarily investigated: (i) EHD of a confined single droplet in the sole presence of uniform electric field; (ii) EHD of the confined single droplet in the combined presence of uniform electric field and imposed background flow; (iii) EHD of the confined compound droplet in the presence of the uniform electric field. Considering both the phases to be either perfect dielectric or leaky dielectrics, numerical simulations are performed to obtain the shape deformation and cross-stream motion of the droplets, placed between two parallel plate electrodes. For corroborating the numerical observations in different physical limits, an asymptotic solution is derived as well as rigorous experiments are also carried out.

For both the perfect and leaky dielectric systems, results reveal that domain confinement has profound effects on the steady and transient deformation characteristics of the droplet and points out that the classical EHD theory may cease to be applicable in the

confined domain. The results also reveal that the interplay of confinement-induced hydrodynamic interactions and transverse electrical forcing may lead to unique transients and motion of droplets over small scales. To investigate further the effect of imposed shear on resulting morpho-dynamics, further numerical simulations are performed. It is observed that a non-intuitive non-monotonic variation in droplet deformation and orientation angle may occur in a confined shear flow, under the influence of an external electric field. Confinement effects are further shown to alter the droplet breakup mode from midpoint pinching to edge pinching at high electric field strength. To decipher the role of different actuating hydrodynamic mechanisms, the combined action of axial electric field and confined oscillatory microflow is subsequently investigated. It is observed that under the sole influence of an oscillatory axial pressure-gradient, the time taken by a droplet to achieve a steady-state transverse position is significantly longer and the direction of the droplet's motion cannot be altered at will. However, confinement-modulated electrohydrodynamic interactions enable this constraint to be overcome, even under the action of an external electric field that is orthogonal to the intended direction of droplet migration; a proposition that is not feasible in an unbounded domain. Furthermore, the oscillatory characteristics in the droplet migration can be completely dampened out by tuning the degree of confinement under electrical forcing.

Towards investigating the electric field modulated interactive motion and coalescence behavior of a droplet pair as opposed to single droplets, subsequent numerical simulations are carried out in the combined presence of uniform electric field and confined shear flow. In this study, two important patterns of motion are identified, namely *(i)* the reversing motion and *(ii)* the passing-over motion. The study suggests that conversion of the passing-over motion to the reversing motion or vice versa can be possible by tuning the strength of the imposed electric field as well as the degree of confinement. However, to establish the unique morpho-dynamics of a double emulsion encapsulated in the form of a compound droplet as against two isolated droplets, numerical simulations are carried out to study the electric field modulated dynamics of a compound domain in a confined microfluidic environment. For low deformation of the droplet in the weakly confined domain, an asymptotic solution is first derived for the droplet's shape. Numerical results are subsequently obtained to bring out the exclusive role of confinement. These results reveal novel propositions towards controlling the droplet transients, distortion of the local field, as well as droplet stabilization or destabilization, allowing one to arrive at different regimes of shape evolution that are completely different from the ones reported in previous studies on single droplet dynamics. Depending on the relative electrical properties of the system, an eccentrically located inner droplet is shown to exhibit a to-and-fro or a simple translational motion. Below a threshold confinement dimension, there appears to be the onset of a definitive translational motion of the inner droplet instead of a more intuitive to-and-fro motion, thereby rendering its migration characteristics to be independent of any electrical properties.

Results from the present dissertation open up the possibility of tuning the motion and deformation of a confined droplet by judiciously modulating the interplay of electrical forcing and confinement-induced hydrodynamics. The findings and conclusion from the present thesis, thus, may create great fundamental interest among the scientific communities

in the exploration of different electrohydrodynamic phenomena over small scale encountered in several emerging applications encompassing chemistry, engineering, and biology.

Keywords: Electrohydrodynamics, Leaky Dielectrics, Perfect Dielectrics, Single Droplet, Compound droplet, Domain Confinement, Shape Deformation, Cross-Stream Motion.