ABSTRACT

Fundamental insight into contact line dynamics over interfacial scales is important for optimizing the functionalities of lab-on-a-chip based microfluidic devices pertinent to several practical applications of emerging relevance, including biomedical diagnostics and biochemical analysis. With the advancement of miniaturization, electrically driven two phase flows have received growing attention in the microfluidics research community. In the present study, some of the pertinent issues are investigated. These include contact line motion under steady electric field over wettability-gradient surfaces, effect of pulsating electric field on the contact line dynamics over surfaces having constant wettability, the contact line dynamics of immiscible binary fluids with contrasting properties under simultaneous effects of electrokinetic actuation and surface wettability and finally, the rheology driven contact line dynamics in presence of electric field and wettability gradients, encompassing the broad theme of electrically modulated contact line dynamics of an immiscible binary system. A brief summary of the problems considered in the present thesis are given below.

The first problem investigated here aims to capture the dynamics of electrically actuated contact line motion of an immiscible binary fluid system over chemically patterned surfaces, invoking a diffuse interface based phase-field formalism. The surface patches are selectively attracting towards either of the fluids. The surface potential is assumed to be spatially uniform, and an electrical double layer is assumed to form at the walls. The analysis reveals that the contact line undergoes stick-slip motion over the chemical patches and its velocity is a strong function of the interfacial electrokinetics. It has also been shown that, depending on the ratio of the permittivities of the two fluids, the tendency of the contact line to get pinned over the selected patches can decrease or increase with its progression along the channel. Finally, the functional dependency of the time taken by the contact line to move across the patches (capillary filling time) on the combined consequences of interfacial electrochemistry and wettability patterning has been established.

The second problem considers the case of an alternating electrical field in investigating the contact line motion of property matched immiscible fluids over the surfaces having constant wettability. Pulsating nature of the externally applied electric field, in conjunction with the wetting characteristics of the surface, may lead to some fascinating behavior of the contact line motion because of the presence of a complicated local dynamics owing to the dynamical change of the driving force as the interface progresses along the channel. It is revealed that the contact line motion in a time periodic electric field affects the capillary filling dynamics in an intriguing manner.

The combined phase-field-electro-hydrodynamics model is further enhanced to investigate the non-trivial effect of fluid properties on the contact line of dynamics of electrically actuated transport of two immiscible fluids through narrow fluidic pathways where surfaces are chemically patched. Results reveal that the interfacial dynamics gets affected by both the viscosity and density contrasts of binary fluids, which, in turn, affect the capillary filling dynamics significantly, owing to additional gradients in the Maxwell stress. The study further reveals that the interplay of the chemical patches and the contrast in the fluid properties culminate in the forms of two distinct regimes, namely, interface breakup regime and a stable interface regime.

Finally, the effects of fluid rheology on the interfacial dynamics of an immiscible binary system are investigated under electrokinetic influences. To describe the non-Newtonian fluid rheology, the study employs power-law fluid model that encompasses both the shear-thickening ($n > 1$) and shear-thinning fluids ($n < 1$). It is revealed that rheology driven alteration in the interfacial stress and its interaction with the Maxwell stress due to electrokinetic effects significantly alter the interface shape following the dynamics of contact line motion. This, in turn, strongly affects the filing dynamics into the capillary.

Keyword: Microfluidics, Lab-on-a-chip, Interfacial dynamics, Contact line motion, Electrokinetics, Phase-field model