ABSTRACT

Considerations of multiphase and multi-scale transport find their pertinence in a wide gamut of applications in microfluidic processes and systems. A comprehensive theoretical understanding of the underlying issues, therefore, appears to be of immense practical consequence. In the present dissertation, four problems have been studied. The first and the second problems fall under the purview of multiphase transport in microfluidic systems. The third problem addresses multiphase transport in a multi-scale system and the last problem discusses upscaling of transport features in a multi-scale system.

The first problem investigated here attempts to study the shape evolution of sandwiched liquid droplets in microconfined shear flow, under the critical influence of substrate wettability variations. The diffuse interface phase-field formalism has been used for the numerical experimentation. The linear shear flow within the domain is imposed by translating both the planes in anti-parallel direction to each other with equal speeds so that a constant shear rate is maintained throughout. The analysis reveals that the combined influence of substrate wettability and fluidic confinement eventually culminates towards influencing the droplet transients, distortion of the local shear flow field, as well as drop stabilization against breakup or detachment, allowing one to develop different regimes of shape evolution that are fascinatingly distinct from the ones reported in earlier studies on drop breakup in micro-confined shear flows. It further demonstrates that the combined consequences of wall effects and interfacial wettability characteristics can be exploited to pattern microfluidic substrates with pre-designed patches, bearing far-ranging scientific and technological consequences in several scientific and technological applications of contemporary relevance.

The second problem considers the thermocapillary-driven contact line dynamics of two immiscible fluids in a narrow fluidic confinement comprising substrates with patterned wettability variations. The flow is driven by a temperature gradient applied along the length of the channel. The analysis reveals that the velocity of the contact line is a strong function of the combined consequences of the applied thermal gradient and the substrate wetting characteristics. Different energy transfer rates have been evaluated and it has been shown that the dissipation due to fluid slip over the solid surface plays a dominating role in transferring energy into the contact line motion. The present analysis, in effect, provides an elegant way of controlling the capillary filling rate in a narrow fluidic confinement by tailoring the applied temperature gradient and the substrate wettability in tandem.

The third problem considers the imbibition dynamics of two immiscible fluids in a spatially periodic porous structure. The flow is driven by an externally applied pressure gradient. The analysis reveals that the combined consequences of the solid fraction distribution and the substrate wettability significantly alter the resulting dynamics of the contact line. It has been observed that the sequence of spatio-temporal events leading to formation of liquid bridges by trapping a small amount of displaced phase fluid between two consecutive porous blocks is dictated by the combined consequence of substrate wettability and solid fraction. The study demonstrates the existence of a regime of complete interfacial recovery, depending on the parametric space of the governing parameters under concern. The results of the present study essentially demonstrate the intricate mechanisms by virtue of which the wettabilities of the substrates alter the dynamical evolutions of interfaces and the subsequent shapes and sizes of the adsorbed dispersed phases, bearing far ranging consequences in several practical applications ranging from oil recovery to ground water flow.

Finally, the pressure-driven electrokinetic transport of electrolytes in porous media is quantified using matched asymptotic expansion method, in order to obtain a homogenized description of the macroscale transport. An expression of the modified permeability tensor has been obtained, which is analogous to the Darcy permeability tensor with due accounting for the induced streaming potential. The porous medium has been modelled as spatially periodic and the results obtained are validated against the analytical solution for a simplified case. The modified permeability tensor has been obtained for different geometrical inclusions by considering a zero net global current, thereby bypassing the coupling matrix approach of non-equilibrium thermodynamics literature. The present study reinforces the non-equilibrium thermodynamic concepts offered by the Onsager reciprocal theorem, in a sense that the cross coupling coefficients for the particular force-flux relation is obeyed.

Keyword: Microfluidics, Multi-scale transport, Multiphase transport, Interfacial dynamics, Contact line motion, Phase-field model, Homogenization, Electrokinetics