

ABSTRACT

of the Thesis

Harnessing Viscoelastic Rheology in Microfluidics: Insights on Electrokinetic Transport

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The electrical mode of flow actuation and manipulation has gained considerable research interest in recent years because of its wide gamut of applications ranging from the engineering to the medical domain. This has led to the emergence of several micro-scale and nano-scale fluidic devices, harnessing the interplay of electro-mechanics and fluid flow over interfacial scales. Several of these microfluidic and nanofluidic devices deal with biological fluids possessing complex rheological behavior, with an aim to replicate physiological phenomena on engineered biochips for disease modeling as well as developing medical diagnostic devices for rapid detection of diseases at the point of care. Transport of complex fluids in miniature conduits is also getting progressively more relevant in several process industries including but not limited to food engineering, chemical processing and oil recovery. These applications clearly exemplify that the consideration of fluid rheology is critical towards understanding the underlying functionalities, and accordingly, the electrokinetic flow of complex fluids has emerged as a thriving research topic in recent times. Despite significant recent advances in the field, however, several critical aspects of electrokinetic flow of viscoelastic fluids remain unexplored, which are the central considerations of this dissertation.

Towards addressing the above, first, a theoretical model is formulated to address the electroosmotic transport of viscoelastic fluids in microfluidic channels in the presence of interfacial slip, by taking into account the presence of finite-sized ionic species (steric effects). Different variants of Phan-Thien-Tanner (PTT) constitutive models for viscoelastic

fluid are considered, including the linear, quadratic, and exponential kernels. For all these PTT models, enhancement in the volumetric flow rate with respect to the Newtonian fluid is observed. Further, the volumetric flow rate is observed to follow an inverse relationship with steric factor (depicting relative dimension of the individual ions). The presented analytical results are also compared with reported experimental findings. Reasonably good agreements in this regard are obtained.

Subsequently, a closed-form velocity distribution is derived for electroosmotic flow of two immiscible viscoelastic fluids in microfluidic channels by incorporating interfacial depletion layer effect. The obtained analytical solutions are compared with in-house experimental results which are carried out using different concentrations of aqueous Polyacrylamide solution (PAM). Results reveal that by a judicious choice of the concentration of the solution, its pH and ionic strength, precise control on the volumetric transport.

Augmenting the dispersion of a solute species and fluidic mixing remains a challenging proposition in electrically actuated microfluidic devices, primarily due to the inherent plug-like nature of the velocity profile under uniform surface charge conditions. While a judicious patterning of surface charges may obviate some of the concerning challenges, the consequent improvement in solute dispersion may turn out to be marginal in practice. Since the uniform velocity profile of classical electroosmotic flow is challenged for applications like mixing and dispersion, guidelines are put forward for harnessing an intricate interplay between the fluid rheology and the coupled modulation of electrical and Joule-heating-induced thermal fields in this regard. It is established that, in this process, one may achieve massive augmentation in the hydrodynamic dispersion without compromising the volumetric flow rate that one would have otherwise obtained under uniform velocity profile conditions. Particular emphasis is laid towards capturing the effect of electro-thermal perturbations on the hydrodynamic dispersion having modulated interfacial charges, under the surface and volumetric heat transfer.

Following the foundations of possible augmentation in solute dispersion in electroosmotic flows due to the transport of rheologically complex fluids such as viscoelastic fluids, the effect of an externally imposed thermal gradient is brought out subsequently towards realizing giant augmentation in dispersion for the electrokinetic flow of viscoelastic fluids. This is effectively mediated by breaking the equilibrium of the charge distribution within the electrical double layer upon imposed thermal gradient, subsequent modulation in thermo-physical properties, and eventual alterations in the fluid motion. The charge redistribution upon the applied thermal gradient, subsequent perturbation on the fluid motion, and its implications on the hydrodynamic dispersion are studied in details for Newtonian as well as viscoelastic fluids. The interplay between thermal and electrical effects, coupled with fluid rheology, is shown to result in an order of magnitude enhancement in the dispersion coefficient in a pressure-driven flow of an electrolyte. Combined with the rheological premises of a viscoelastic fluid that are typically reminiscent of common complex fluids handled in lab-on-a-chip-based micro-devices, these results demonstrate that the consequent

electro-hydrodynamic forcing may open up favourable windows for augmented hydrodynamic dispersion.

Subsequently, electroosmotic flow of viscoelastic fluids in deformable microchannels under axial modulations in the surface potential and interfacial slip is investigated. Considering the substrate ionization process typical to practical microfluidic scenarios, a theoretical framework is presented towards analysing the same where the influence of the coupling between electro-mechanics, hydrodynamics, elasto-mechanics, and solution chemistry becomes imperative towards influencing the load bearing capacity of the deformable conduit. Results reveal that by tuning parameters like modulus of elasticity of the channel walls, electrolyte concentration, pH , asymmetry in slip, the load bearing capacity may be augmented considerably irrespective of the rheology of the fluid. With the effect of slip length being trivially implicating but offering limited scopes in terms of its practical variabilities, the substrate elasticity, solution concentration, and asymmetry factors are shown to offer alternative means for enhancing the load bearing capacity even for lower slip lengths. For viscoelastic fluids, the proposition of a further enhancement in the load bearing capacity opens up by operating in favourable parametric regimes of the polymer concentration, molecular weight, and the specific Newtonian solvent, using common polymeric solutions as representative flow media. These results may turn out to be significant towards designing lubricated electro-chemical systems for in-vitro analytics of physiological flows, where the deformable nature of the fluidic conduit acts as a natural consideration to probe the underlying mechanisms including disease modelling and studying the efficacy of drug delivery.

Findings of the different problems investigated in this work are likely to offer new insights in the understanding of electrokinetic flows of viscoelastic fluids, bearing significant implications in process industries and biomedical technologies. Further scopes of advancement include probing the role of viscoelastic rheology towards augmented energy conversion in charge modulated surfaces, realizing augmented electrokinetic energy conversion in a super-imposed fluidic configuration by employing an external temperature gradient and offering patient-specific insights as well as advancing disease models based on microvascular physiology considering exclusive rheological implications of blood as a complex constitutive fluid in the presence of a charged endothelial glycocalyx layer interface in the blood vessels.

Keywords: Electrokinetics, Electroosmosis, Viscoelastic Fluid, Dispersion Coefficient.