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Slip driven micro-pumping of binary system with a layer of non-conducting fluid under electrical double layer phenomenon

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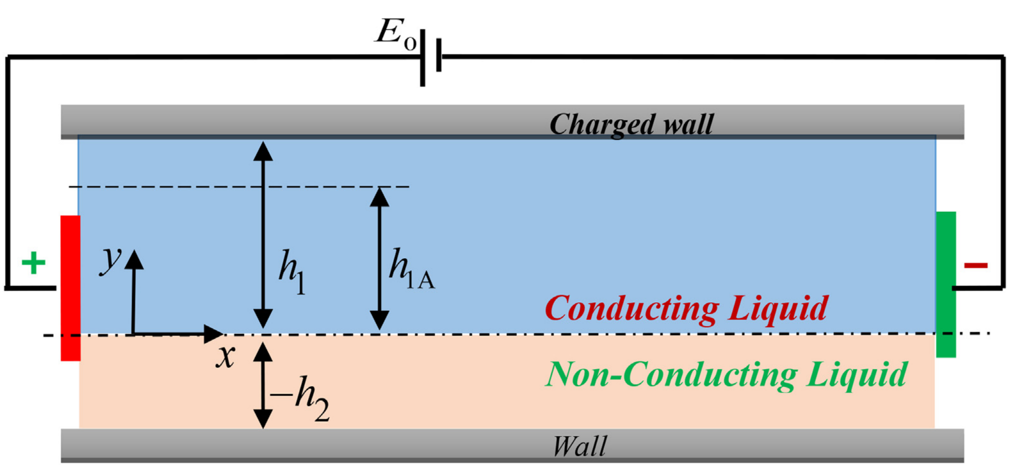
GRAPHICAL ABSTRACT



HIGHLIGHTS

- Slip modulated micropumping of non-Newtonian/Newtonian binary fluid system.
- Combined influences of pressure gradient and electrical forcing on flow dynamics.
- Complex effect of interfacial slip on the underlying binary fluid transport.
- Nonlinear interactions between fluid rheology and the interfacial slip.
- Augmentation in the flow rate over characteristic regimes of interest.

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ABSTRACT

In this study, we report the consequences of the fluid/wall slippage on the micro-pumping of an immiscible binary system constituted by conducting (non-Newtonian) and non-conducting (Newtonian) fluid pair through a microchannel. We consider power-law model to represent the constitutive behaviour of the non-Newtonian fluid. We explore the effect of the combined influences of the applied pressure gradient and electrical forcing on micro-pumping by analytical calculations considering a flat interface between the fluids. We highlight the alteration in underlying dynamics, mainly attributable to the rheology driven modification in viscous resistance in the field as modulated by the interfacial slip and electrical double layer effect. Also, we establish a phenomenal amplification in micro-pumping effect, as realised through an enhanced volumetric flow rate though the channel

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under combined forcings environment. We believe that the inferences obtained from this analysis may improve the design of various bio-microfluidic devises/systems, which are often used for the transportation of binary layers including one non-Newtonain fluid in the system.

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1. Introduction

Micro total analysis system (μTAS) finds huge importance in chemical, biochemical and biomedical applications[1–3]. In these systems transportation of the immiscible binary layers, which is very common in the domain of biomedical and biochemical process engineering and also for the cooling in micro-electro-mechanical systems (MEMS) [4–6], is an important issue, owing to the difficulties associated with the implementation of any mechanically moving components in such a miniaturized platform. Aiming towards this area, several means have been proposed in the literature concerned with suitable micro-pumping of immiscible layers in a miniaturized platform by the experimental and theoretical research community [5–16].

It should be mentioned in this context here that in a two fluids transport, formed between a conducting and non-conducting fluids pair, the electroosmotic effect could be effectively used to pump a non-conducting liquid through a microfluidic confinement as well, solely by exploring the momentum exchange phenomenon through viscous shear stress across the fluid–fluid interface [4,7,16]. Electro-hydrodynamic (EHD) micro-pumping have gained huge popularity among the researchers owing to a number of inherent expedient features like the exclusion of mechanically moving components in driving flows, on-chip integrability and flow controllability to name a few [17,18]. We would like to mention here that, no matter what kind of driving force is applied to make the flow occur in the channel, the pressure gradient always develops in the field with flow initiation in the channel [5,19,20]. On the other hand, in the purview of electrically actuated transport, we cannot the trivially rule out the fluid/soild slippage, arising because of the relative motion between the fluid molecules and the bounding solid substrates. We would like to mention here that a high shear rate pertinent to electroosmotic flow, originating from the electrical double layer (EDL) phenomenon[21], shearing the liquid molecules from the solid boundaries essentially by overcoming the interfacial forces of attraction, thus culminating in an apparent slip at the fluid-solid interface. In addition to the strong shearing effect in electroosmotic transport, the formation of nanobubble layer arising due to complex hydrophobic interactions leads to an apparent interfacial slip on the microscale/nanoscale transport as well [22–26].

Also, we should mention here that the underlying dynamical features become even more critical in presence of non-Newtonian fluid in the binary system, largely attributed to the rheology-driven modification in viscous drag in the flow field as modulated by the slipping dynamics and electrical forcing. Accounting above issues, an attempt towards investigating the slip influenced electrochemical hydrodynamics of an immiscible binary system formed by a non-Newtonain and another Newtonian fluids under the influences of an applied pressure gradient could be an interesting proposition, primarily attributed to the nontrivial role of the physico-chemical forces arising because of the interplay among electrochemistry, interfacial slip, rheological effect of the fluid and applied pressure gradient.

Here we attempt to analyze the underlying transport of two immiscible fluid layers, containing one non-Newtonian (assumed to be electrically conducting in this study) and other Newtonian fluid (non-conducting in nature), in a microfluidic channel under interfacial slip as influenced by the combined effects of applied pressure gradient and electrical forcing. Our results unveil a regime of slip driven enhancement in the flow rate under the combined forcing environment, as modulated by the rheological behavior of the fluid. We believe that the results obtained from the present study may enhance the understanding of the underlying dynamics of two fluid layers transport, configured with non-Newtonian and Newtonian fluids, which may be of potential interest towards designing microfluidic devices, very often used for the transportation of rheological fluid like blood.

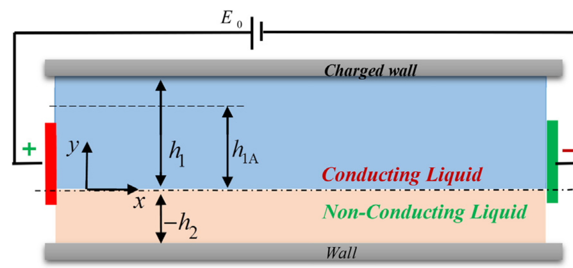

Fig. 1. Schematic diagram showing the physical dimension of the channel as considered in the present study. The top layer fluid (non-Newtonian) is electrically conducting, while the bottom layer is non-polar fluid. The flow is taking place in the x-direction upon the application of the external electric field $\mathbf{E} = (E_0, 0, 0)$ and the applied pressure gradient.

2. Theoretical formulation of the problem

We here consider the transport of immiscible binary layers having one conducting non-Newtonian fluid (top layer) and another non conducting Newtonian fluid (bottom layer) through a microfluidic channel. To initiate flow through the channel, we consider an imposed pressure gradient as well as an electric field (E_x) applied along the axial direction of the channel. In presence of conducting fluid, the surface acquires charge by ion-adsorption or ionization which leads to formation of the Electric Double layer (EDL) near to the walls [18]. Under the effect of EDL phenomenon and applied electric field, the conducting fluid comes into the motion and drags the non-conducting fluid layer by viscous drag. The flow of conducting fluid is recognized as Electroosmotic flow [18]. In this case, the flow is also assisted by imposed pressure gradient. We consider a channel with $W >> 2H$, where W and H are width and height of the channel respectively. We schematically show the channel geometry and its dimensions in Fig. 1. For this study, we consider following assumptions:

1. The flow is assumed to be incompressible, laminar, steady and fully developed, while the rheology of non-Newtonian fluid is described by Ostwald-de Waele power law model [27].
2. The thermophysical properties of the two fluids are constant, while they are assumed to be independent of temperature and applied electric field as well [28]. We neglect the effect of Joule heating [29].
3. The interface between the fluids is flat so that there is no charge density variation across the interface.

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