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Characterization of electromagnetohydrodynamic transport of power law fluids in microchannel

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ABSTRACT

We characterize, electrokinetically modulated axial pressure driven transport of a power-law fluid through microchannel in the presence of superimposed magnetic field. We obtain solutions for streaming potential, velocity, and temperature fields owing to a combined interplay of the flow rheology, kinematics, influences of finite ion sizes (steric effect), and the electromagnetohydrodynamics. Our results demonstrate that giant augmentations in the energy conversion efficiency and streaming potential field may be achieved for shear thickening fluids in the presence of superimposed magnetic field. Our analysis reveals that heat transfer rate can be amplified by enhancing magnetic field magnitude and the power law behavioural indices. We, further, carried out an exergy analysis for an optimal process design via reducing irreversibilities in terms of “entropy generation analysis”. We found that the total irreversibilities of the system decreases with increasing the values of power law index. We believe that the inferences obtained from the present research may be useful in the design of advanced energy efficient devices, smart sensors, etc., with optimal combinations of power law rheology and magnetohydrodynamic influences.

1. Introduction

Advanced microfluidic devices are designed to perform multifaceted functionalities at various fields of technological and scientific relevance; examples include biochemical and biomedical processes, particle separation, pumping, heat exchanger and reaction [1–3]. A large number of biomedical diagnostic techniques and pharmaceutical applications involve fluids which are characterized by non-Newtonian rheology requiring complex constitutive equations to describe their rheology and ensuing flows. A fundamental understanding of transport characteristics of such fluids in a narrow fluidic confinement is thus important for optimum design and precise control of modern devices.

In general, liquid motion in large-sized channels is produced by applying a pressure-gradient, leading to pressure-driven flow. However, as the channel size reduces, it becomes increasingly difficult to utilize external pressure as the driving force for fluid flow [3]. Alternatively, electrokinetic flow-actuation methodologies have emerged as preferred source for driving fluid flow in extreme narrow passages and confinements, as encountered in micro/nano-channels [3–5]. Transport phenomena at the microscale exhibit distinctly different characteristics, as compared to the macroscale transport behaviour, primarily due to the interfacial effects such as electric double layer (EDL) [5]. Several researchers have demonstrated the use of electroosmosis and streaming potential in thermofluidic management of microelectronic devices [6–8]. To this end, one area of particular interest has been the study of electrokinetic flow of non-Newtonian fluids and the associated thermal energy transport leading to optimization of thermodynamic performance of the system. Das and Chakraborty [9] presented analytical solutions describing the transport characteristics of a non-Newtonian bio-fluid in a microchannel. Berli and Olivares [10] carried out a theoretical study of electrokinetic flow through slits and cylindrical microchannel. Zhao and Yang [11] investigated the electroosmotic mobility of Power law fluids in channel flows. In the recent past, thermal transport characteristics of non-Newtonian fluids under electrokinetic actuation have been investigated taking the effects of Joule heating and viscous dissipation into consideration. Sadeghi et al. [12] analysed the electroosmotic flow of viscoelastic fluids through a slit microchannel with a step change in wall temperature. Goswami et al. [13] investigated the entropy generation characteristics of a non-Newtonian fluid in a narrow fluidic channel under electrokinetic forcing and considered the effect of conjugate heat transfer into their analysis. There are few studies, where conjugate heat transfer problems in microchannels have been analysed [14,15].

Of late, researchers have explored the suitability of using combined

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electrokinetic and magnetic-field driven actuation mechanism in wide spectrum of applications ranging from lab-on-a-chip devices to magnetohydrodynamic (MHD) micropumps [16–19]. Electromagnetic flow control mechanism has been successfully used for actuation, manipulation and detection in microfluidics. Typically such application utilize external magnets which are not in direct contact with the working fluid, and are not affected by physicochemical parameters such as surface charges, pH and ion concentration. In addition, magnetic field does not induce heating and can offer a useful flow actuation protocol for thermally sensitive biological samples. Weston et al. [20] discussed the use of different types of magnetic forces and their applications. Nguyen [21] presented a review on micro-magnetofluidics with focus on physical and engineering aspects of the problem. Although the application of magnetism in microfluidics to gain new functionalities is well established, studies on MHD transport of non-Newtonian fluids in a narrow fluidic confinement and the associated thermal characteristics are relatively scarce. This aspect, therefore, demands for the systematic investigation of the effect of superimposed magnetic field on electrokinetic and thermal energy transport of non-Newtonian fluids in narrow fluidic confinements [22–26].

In the present work, a theoretical model of combined electromagnetohydrodynamic thermally developing flows of power-law fluids through a microchannel is developed and the delicate interplay of the electrokinetics, MHD, rheology, and thermal energy transport is analysed. Physically, the flow is driven by the combination of imposed pressure gradient (applied in the axial (X) direction), electrokinetic effects (streaming potential), and the external magnetic field applied along the transverse (Y) direction (see Fig. 1). We consider different flow behavioural index (m) and the magnitudes of magnetic field to obtain solutions for the induced streaming potential, velocity, and thermal energy fields. We also carried out an entropy generation analysis due to heat transfer and fluid friction irreversibilities, with an objective to optimize the thermodynamic performance of such systems. This is particularly important in several biomedical and micromechanical systems where the magnetic separation of organic compounds, proteins, nucleic acids and other biomolecules are used for purification and extraction processes [21,27]. In all such applications, constitutive relations of the operating media follow the power-law obeying fluid model with electrokinetic effects. From the micromechanical industrial perspective, there have been several applications in the development of smart sensors, reactors, actuators, automotive valves, where the magnetic field distribution has been used widely [21]. Towards the above, present analysis can be utilized to provide necessary information for optimum design of pertinent microfluidic devices of interest.

2. Formulation of the problem

2.1. Physical problem

For our analysis we consider axial pressure-driven fully developed flow of a non-Newtonian fluid through two dimensional slit-type parallel plate microchannel as shown in Fig. 1. The directions parallel and perpendicular to the confinement walls are represented by X- and Y-coordinate, respectively. The centreline is maintained at $Y = a$, whereas the origin is set at the bottom wall of the confinement. We assume that the fluid consists of binary electrolyte solution and the flow is subjected to a superimposed magnetic field of strength B_Y along the transverse (Y-) direction. EDL (electrical double layer) forms when an electrically neutral liquid comes in contact with narrow fluidic substrates by developing a net surface charge. This is counterbalanced by the charges (oppositely to the solid surface) in a layer of wall-adhering fluid. Under the actuation of the external pressure gradient, the counterions in the diffuse layer of EDL drift towards the downstream end of the confinement. Owing to the migration of surplus ionic species within the mobile part of the EDL a voltage difference across the two ends of the confinement sets up through a competing advection-electromigration mechanism, customarily recognized as the streaming potential (E_X). This induced electrical field (E_X) generates a current flowing back against the axial pressure gradient direction, so as to oppose the very mechanism to which it is due. Considering the steric (finite size) effect of the ions, we characterize interesting confluences between the axially induced electric field (E_X) and the applied magnetic field (B_Y) during electromagnetohydrodynamic transport. Under this situation, thermal energy transport analysis has been carried out for thermally developing flow at a situation when the confinement walls are prevailed with a uniform temperature, T_W.

2.2. Ionic charge density and EDL potential distribution

In a slit-type microchannel, the governing equation describing steady state advection of each ionic species may be described as: $\nabla\cdot\vec{G_i} = 0$, where, the ionic flux density is given by $\vec{G_i} = \vec{U}n_i - D_i n_i \nabla\left\{\ln s_i + \frac{z_i F\chi}{RT_0}\right\}$ [28]. Here, z_i denotes the valency of the ith ionic species, n_i represents the number density of the ith ionic species, $\vec{U}$ is the advective velocity, D_i is the diffusivity of the ith ionic species, F is the Faraday constant, T_0 is the absolute temperature, and χ being the resultant electric potential. Furthermore, s_i is the activity of the ith ionic species and may be expressed in terms of the ionic concentrations n_i as $s_i = (n_i/n_0)/\{1 - \gamma\sum_k (n_k/n_0)\}$; $\gamma = 2n_0 s_r^3$ representing the steric factor [29]. Here, n_0 is the bulk ionic concentration at the reservoir and s_r is the representative ionic length scale. One may

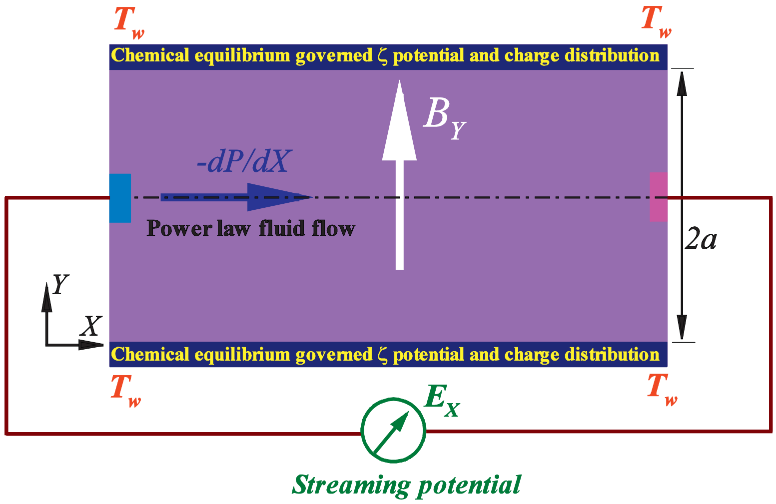

Fig. 1. Schematic depiction of the physical domain under consideration.