Chemical Engineering Science 171 (2017) 391–403

Contents lists available at ScienceDirect

Chemical Engineering Science

journal homepage: www.elsevier.com/locate/ces

Electrokinetically induced thermofluidic transport of power-law fluids under the influence of superimposed magnetic field

Sandip Sarkar [a,b], Suvankar Ganguly [b], Pradip Dutta [a,*]

[a] Department of Mechanical Engineering, Indian Institute of Science, Bangalore 560012, India
[b] TATA Global R&D Division, India

HIGHLIGHTS

- Thermal transport of non-Newtonian fluid in narrow fluidic confinements.
- Combined effects of interfacial electrokinetics, rheology, and superimposed magnetic field.
- Thermofluidic transport phenomena and entropy generation.
- Effects of the magnetic field on streaming potential and heat transfer.

ARTICLE INFO

Article history:
Received 23 November 2016
Received in revised form 16 April 2017
Accepted 29 May 2017
Available online 31 May 2017

Keywords:
Electrokinetic
Transport
Microfluidics
Power law
Magnetic field

ABSTRACT

This paper presents a theoretical analysis of non-Newtonian (power-law obeying) fluid in a narrow confinement subjected to the combined consequences of interfacial electrokinetics, rheology, and superimposed magnetic field. We devote special attention on the exploitation of magnetic field and power-law exponent, in the development of induced streaming potential and thermofluidic energy transfer characteristics over small scales. In an effort to do so, going beyond the Debye-Hückel limit, we first derive an expression for streaming potential by invoking the consequences of strong EDL (electrical double layer) interactions in the narrow fluidic passage and finite conductance of the Stern layer. In particular, we solve thermal energy transport equation with an illustrative case of classical uniform wall heat flux boundary and considering the volumetric heat generation effects due to viscous dissipation as well as Joule heating. Our results demonstrate that the applied magnetic field imparts a retarding influence on the induced streaming potential development, whereas, it results in enhancement of heat transfer rate. Moreover, additional influences of power law index show reduction in heat transfer as well as the streaming potential magnitude. We unveil the optimal combinations of power law index and the magnetic field which lead to the minimization of the global total entropy generation in the system. We believe that theoretical results presented in this research will be useful in the development of novel narrow fluidic energy efficient devices under electrokinetic modulation.

1. Introduction

In narrow fluidic confinements, interfacial phenomena over small scales play critical role with far-ranging consequences both from technological as well as scientific perspectives. On a small scale, such interactions are crucial to the understanding of different functionalities in micro-electro-mechanical-systems (MEMS) applications at various fields of advanced energy efficient devices/sensors. This constitute many kinds of functional elements such as, pumps, actuators, valves, switches, dispensers, chemical separation devices, lab-on-a-chip system for drug delivery, biochemical analysis and biomedical diagnostics, smart–sensors, mixers, filters, separators, heaters, etc. (Probstein, 1994; Madou et al., 2006; Pamme, 2006). Those small-scale fluidic pathways transport electrolytic solutions, which eventually give rise to the formation of electrical double layer (EDL) as a consequence of the intricate electrochemical interactions between the fluidic substrate and the solution. The final outcome is the populace of mobile counterions in the solution. A potential difference across the fluidic confinement may be established when the pressure-driven fluidic transport cause preferential net advective migration of counterions toward the downstream direction, which is characteristically known as the streaming potential (Hunter, 2001; Goswami and

---

[*] Corresponding author.
E-mail address: pradip@mecheng.iisc.ernet.in (P. Dutta).

http://dx.doi.org/10.1016/j.ces.2017.05.053
0009-2509/© 2017 Elsevier Ltd. All rights reserved.

Nomenclature

a	half height of the narrow confinement
B	magnetic field vector
Br	Brinkman number $(= \eta_0 U_{ref}^2 / a\, q_w)$
e	elementary charge
E	electric field vector
E_X	induced electric field
F	Faraday constant
F_B	net body force
Ha	Hartmann number $(= \sqrt{(\sigma_e B_Y^2 a^2)/\eta_0})$
I_{net}	net ionic current
k_B	Boltzmann constant
m	power–law exponent
n_0	bulk ionic concentration
S_T	total local entropy generation rate
T	temperature of the fluid
u, v	non-dimensional velocity components in x and y directions
x, y	non-dimensional coordinates

Greek Symbols

θ	dimensionless temperature $(= T - T_W/T_M - T_W)$
σ	surface charge density
σ_e	electrical conductivity
ρ_e	net EDL charge density
ζ	zeta potential
ε	permittivity of the medium
Γ	fraction of dissociated chargeable sites
ψ	EDL electrostatic potential
$\overline{\overline{\tau}}$	the stress tensor

Subscripts

av	average
W	wall
M	mean
ref	reference

Chakraborty, 2010; Bruus, 2008). The formation of streaming potential across narrow fluidic confinements has far ranging applications in hydroelectrical energy conversion. For instance, when the spatial scales of fluidic devices is in the order of nanometres, the Debye length may turn out to be of comparable to the dimension of the confinement, and therefore permitting strong EDL interactions. This, in turn, enhances the energy transfer efficiency. On the other hand, strong EDL interactions are accompanied by high surface charge density situations, where ionic species may no longer be considered as point charges with their finite size effect (steric) having considerable far-reaching consequences (Hunter, 2001; Das and Chakraborty, 2011).

Apart from the usual electrokinetic interactions involving Newtonian fluids in narrow confinements, the possible non-trivial interplay between the fluid kinematics and flow rheology has become significant for the case of non-Newtonian fluids. For instance, the transport of complex biofluids, cell suspensions, protein chains in solvents, gels, colloids, may, in general, fall in the category of a generalized non-Newtonian fluid whose constitutive behaviour is pertinently construed by the power-law. There has been a large number of experiments as well as theoretical analyses for such flows reported in literature. Das and Chakraborty (2006) have derived analytical solutions for the electro-osmotic transport of non-Newtonian fluids in rectangular microchannels. They analyzed a representative transport of blood, where the size of the red blood cell (RBC) relative to the channel dimension plays a key role toward altering the transport characteristics. Berli and Olivares (2008) studied the effect on the formation of depletion layers in the flows of non-Newtonian fluids involving macromolecules. Utilizing Phan-Thien Tanner (PTT) model, Afonso et al. (2009) presented analytical solutions for combined electro-osmotic and pressure driven flows of viscoelastic fluids in microchannels. Hadigol et al. (2011) carried out numerical simulations to obtain the pressure rise for the electro-osmotic flow of power-law fluids in slit channels. In another study, Vasu and De (2010) analyzed the electroviscous effects for the flow of power-law fluids in slit microchannels. Incorporating the issues of streaming current and streaming potential, over the past few years, many researchers have been investigating on the various aspects of electrokinetic transport of non-Newtonian fluids (Chakraborty, 2007; Zhao et al., 2008; Olivares et al., 2009; Zimmerman et al., 2006; Park and Lee, 2008; Akgul and Pakdemirli, 2008; Dhinakaran et al., 2010; Bandopadhyay and Chakraborty, 2012a, 2012b, 2012c, 2015; Bandopadhyay et al., 2013, 2014). Bandopadhyay and Chakraborty (2011) reported semi-analytical results on the possibilities of augmenting the energy transfer efficiencies in narrow fluidic confinements with an alternation in the interfacial electrokinetics and the fluid rheology. In an another study, they (Bandopadhyay and Chakraborty, 2012a, 2012b, 2012b) have discussed analytical solutions of velocity distribution and streaming potential with a consideration of dynamical interplay between interfacial electrokinetics and a combined dissipative and elastic behaviour of flow through narrow confinements. A few studies have been dedicated to understand the thermal transport phenomena in electroosmotically driven flow in narrow confinements (Burgreen and Nakache, 1964; Levine et al., 1975; Patankar and Hu, 1998; Yang et al., 1998; Dutta et al., 2002; Maynes and Webb, 2003; Horiuchi and Dutta, 2004; Chakraborty, 2006; Rawool and Mitra, 2006; Zade et al., 2007; Chen et al., 2013; Duwairi and Abdullah, 2007) with and without considering the effects of axial pressure gradients. Such studies are important in many practical engineering applications dealing with the internal heat generation arising out of the temperature rise of the narrow fluidic passage.

While the hydrodynamic consequences of non-Newtonian fluids, described as above, appear to be somewhat intuitive, the concerned implications may turn out to be significantly more non-trivial when the electromagnetic effects are additionally taken into account. These additional interactions may be triggered by its great importance in a wide spectrum of narrow-fluidic applications ranging from lab-on-a-chip devices to MHD micropumps (Jones, 1995; Jang and Lee, 2000; Zimmerman and Parada, 2006; Chakraborty and Paul, 2006; Das et al., 2012; Nguyen, 2012; Turkyilmazoglu, 2012; Munshi and Chakraborty, 2009). Most of the research endeavours on electromagnetic influences have been directed towards Newtonian fluids as the transporting media. However, studies on magnetohydrodynamic transport of non-Newtonian fluids in a narrow fluidic confinement are relatively scarce. Although some studies with similar objectives have been reported recently (Escandon et al., 2014; Kiyasatfar and Pourmahmoud, 2016; Jian et al., 2015), but all of them have considered electroosmotically driven flow actuation mechanism. Focusing primarily on the electromagnetic influences for electroosmotic micropumps with non-Newtonian fluids, a common consensus that can be realized