International Journal of Heat and Mass Transfer 127 (2018) 600–615

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Entropy generation of magnetohydrodynamic electroosmotic flow in two-layer systems with a layer of non-conducting viscoelastic fluid

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ARTICLE INFO

Article history:
Received 16 March 2018
Received in revised form 8 July 2018
Accepted 11 July 2018

Keywords:
Electroosmotic flow (EOF)
Magnetohydrodynamic (MHD)
Two-fluid dragging system
Entropy generation
Viscoelastic fluid

ABSTRACT

The entropy generation analysis is investigated in two-fluid dragging systems. The bottom layer fluid is considered as electrolyte solution affected by the applied magnetic field and the upper layer fluid is viewed as non-conducting viscoelastic Phan-Thien-Tanner (PTT) fluid. Under the combined influences of electric and magnetic fields, the upper layer non-conducting PTT fluid can be dragged by the bottom layer fluid due to the interfacial shear stress. Firstly, we obtain the analytical velocity expressions for both bottom layer and upper layer fluids under the unidirectional flow assumption. The bottom layer fluid velocity distribution shows a classical M-type velocity profile. The upper layer fluid flow can be viewed as the plate Couette flow or Couette-Poiseuille flow. Subsequently, the thermal transport characteristic and entropy generation analysis are discussed in the present two-fluid dragging system. The results show that magnetic field can enhance the local entropy generation rate, but viscoelastic physical parameter can restrain the local entropy generation rate. The present theoretical research can be used in the design of thermofluidic device. By manipulating the electric and magnetic fields strength and the ratio of fluid rheological properties, the fluid motion and heat transfer characteristics can be manoeuvred efficiently.

1. Introduction

Microfluidic devices are widely used in biomedical analysis and can be viewed as an effective tool to study fundamental physical and biochemical processes. Fluid transport process and thermal characteristic analysis have received considerable attention through microfluidic devices [1–3]. Three common actuation mechanisms of driving the liquid flow through microscale devices include pressure gradient [4,5], electroosmosis force [6–8] and electromagnetic force [9,10]. Comparing with the purely pressure-driven flow, the electroosmotic and electromagnetic actuation mechanisms are extensively applied in the microfluidic system. In the purely electroosmosis driven flow system, the excess Joule heating generates due to the existence of imposed electric fields and it is always detrimental and unavoidable especially for the processing of thermally labile biological samples and the activity loss of test samples [11,12]. Recently, the researchers found the imposed magnetic field could minimize efficiently the impact of Joule heating. Hence, the liquid flow actuated by a combination of electroosmotic and electromagnetic forces is also studied in a microchannel [13,14].

All the aforementioned studies are focused on the single-layer fluid flow. However, two or multi-layer fluid systems are one of the most important research areas in handing biomedical and biochemical analyses [15]. Generally, a laminar fluid interface is generated when two or more immiscible liquids contact each other. The manipulation of fluid interface can facilitate efficiently the biological sample separation [16,17] and guide the fluid flow direction [18]. Due to the successful application of the classical electroosmotic pump in the single-layer flow system, the electroosmosis actuation mechanism is directly replicated in the two or multi-layer flow systems. However, some low electrical conductivity fluids cannot be driven directly by the electroosmotic force. In order to overcome this limitation, an alternative construction of driving the poorly conductive fluid was proposed by Brask et al. [19], using the high electrical conductivity fluid to drag the low electrical conductivity fluid. According to the difference of the fluid physical property, the following sets of two-layer fluid system are studied theoretically and experimentally, including two-layer Newtonian fluid system [20–23]; two-layer non-Newtonian fluid system [24]; one layer Newtonian and one layer non-Newtonian fluid system [25,26]. Similar to the two-layer electroosmotic system, two-layer electromagnetohydrodynamic (EMHD) flow were also studied. Shail [27] studied theoretically the motion characteristics of EMHD flow in the two-fluid dragging

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https://doi.org/10.1016/j.ijheatmasstransfer.2018.07.065
0017-9310/

Nomenclature

B_0	magnetic field
Br	Brinkman number
C_p	Constant pressure specific heat
$\mathbf{D}$	deformation tensor rate
De	Deborah number
e_0	electron charge
E_1	principle axis electric field
E_2	lateral electric field
f	a function of the stress tensor
$\mathbf{F}$	body force vector
$\mathbf{J}$	ion current density
k	thermal conductivity
k_b	Boltzmann constant
L	length of the microchannel
H	whole height of the microchannel
Ha	Hartman number
H_1	height of bottom fluid
H_2	height of upper fluid
n_0	ion density of bulk solution
p	pressure
S	non-dimensional parameter
t	time
T_a	absolute temperature
$\mathbf{u}$	flow velocity vector
u_r	velocity ratio
z_v	ion valence
u, v, w	flow velocity components
x, y, z	Cartesian coordinates
Greek symbols	
$\boldsymbol{\tau}$	the stress tensor
λ	the relaxation time
η	viscosity coefficient
ε	elongational behavior
μ_r	viscosity ratio
ρ_e	net charge density
ε_0	permittivity
κ	Debye–Hückel parameter
ψ	electric potential
ψ_I	interface electric potential
ψ_w	wall electric potential
ρ	fluid density
τ_u	integral constant
σ	electrical conductivity
Subscripts	
i	fluid layer
1	bottom layer
2	upper layer

system and obtained the analytical velocity distribution. Subsequently, Lohrasbi and Sahai [28] extended the results obtained by Shail [27] and studied the thermal transport characteristics by using the analytical and numerical methods in the same two-fluid system. Besides, the researches of two-layer electroosmotic flow [29–32] and electromagnetohydrodynamic flow [33–36] were widely studied in non-dragging fluid system, where both of the fluids were electrically conducting and driven by electroosmosis force or electromagnetic force. Very recently, we [37] studied the two-layer magnetohydrodynamic electroosmotic flow through a microparallel channel, considering the combined influences of electroosmosis and magnetic field. In our previous study, the analytical solution of flow velocity is obtained and the influences of related physical parameters are discussed in detail.

Complex fluids are often manipulated in the biomedical and biochemical fields and cannot be simply treated as Newtonian fluid in general. Hence, the use of Newtonian fluid constitutive model is insufficient to describe satisfactorily the behavior of such complex fluids. This necessitates us to find more appropriate rheological models to simulate the flow of these complex fluids. The Phan-Thien-Tanner (PTT) fluid model [38–40] has been widely used and it often exhibit three strong non-Newtonian characteristics, including a non-linear relationship between the viscosity and the shear rate, the elongational properties and the time-dependent effects. Oliveira and Pinho [41] gave firstly the analytical velocity distributions of PTT fluid through a channel and pipe. Subsequently, they [42] studied the thermal transport characteristics of PTT fluid through a cylindrical microtube and gave the analytical temperature distribution and heat transfer coefficient. Based on the exact solutions given in Refs. [41,42], Afonso et al. [43] studied the motion characteristics of PTT fluid through a microparallel channel. They discussed the influences of fluid rheology and electric double layer (EDL) on the flow velocity and fluid stress. Later, they [24] investigated the electroosmotic flow of PTT fluid in a two-layer fluid system and the effects of three different pressure gradients on the velocity of PTT fluid were discussed in detail. Escandón et al. [44] studied the hydrodynamic and thermal transport characteristics of PTT fluid which are driven by a combination of electroosmotic force, pressure gradient and electromagnetic force. They obtained the theoretical expressions of flow velocity and temperature and further discussed the influences of imposed magnetic field and fluid viscoelasticity. Besides, the fluid motion and heat transfer analysis of complex fluids, including PTT fluid [45–47], Jeffrey fluid [48], third grade fluid [49] and nanofluid [50,51] are also studied.

In general, entropy can generate in various flow systems especially in the field of thermal management system since heat transfer irreversibility, Joule heating effect, flow driven force and fluid viscous friction can cause the entropy generation. Due to the reduction of microfluidic devices scale, the analysis of entropy generation becomes more significant comparing to the macroscale flow because the velocity gradient and temperature gradient are higher in microscale flow system [52]. Besides, according to the relationship between lost work and entropy generation (Gouy Stodola theorem) [53], we know the quantity of entropy generation can determine the amount of lost work. Thus, understanding the entropy generation characteristic is rather significant. Moreover, in order to reduce the amount of useless energy which can cause the irreversibility in a fluid system, the scientific community concentrates on the design of the fluid systems to improve energy utilization. In fact, entropy generation can be viewed as a criterion to assess the irreversibility in the fluid system. Therefore, the entropy generation minimization concept, based on the second law of thermodynamics, has attracted much attention in thermal engineering and one can minimize the entropy generation by appropriate selection of design parameters in some efficient fluid systems. Bejan [54] first employed the entropy generation minimization method in many convection problems and such method has been widely utilized to analyze the thermal transfer characteristics. Shamshiri et al. [55] analyzed the heat transfer and entropy generation of power-law fluid through a cylindrical microtube. They obtained the distributions of velocity and temperature by finite difference