International Journal of Heat and Mass Transfer 127 (2018) 901–913

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Entropy generation of electromagnetohydrodynamic (EMHD) flow in a curved rectangular microchannel

Yongbo Liu [a], Yongjun Jian [a,*], Wenchang Tan [b]

[a] School of Mathematical Science, Inner Mongolia University, Hohhot, Inner Mongolia 010021, PR China
[b] State Key Lab for Turbulence and Complex Systems and Department of Mechanics and Engineering Science, College of Engineering, Peking University, Beijing 100871, China

ARTICLE INFO

Article history:
Received 18 January 2018
Received in revised form 5 June 2018
Accepted 28 June 2018

Keywords:
Electromagnetohydrodynamic (EMHD) flow
Curved rectangular microchannel
Entropy generation rate

ABSTRACT

The entropy generation analysis of electromagnetohydrodynamic (EMHD) flow of Newtonian fluids through a curved rectangular microchannel is performed in this study. Under the assumption of thermally fully developed and the condition of constant wall heat flux, the distributions of velocity and temperature are derived analytically and numerically, which are utilized to compute the entropy generation rate. Analytical solutions of the velocity are contrasted with the numerical and experimental solutions and the agreements are excellent. The results show that the flow and the temperature depend on the strength of the electric field (S), magnetic field (Ha), aspect ratio of the rectangular cross section (α), curvature ratio (δ), peclet number (Pe) and viscous dissipation (Br). Then the entropy generation rates are investigated under the appropriate nondimensional parameters. The results show that the local entropy generation has a decreasing trend from the wall towards the centerline of the microchannel. Moreover, the entropy generation rate increases with the increase of S and Br but decreases with Pe and α. Finally, the entropy generation rate increases with the increase of Ha when Ha is small, and reaches a constant as further increase of Ha. The present endeavor can be utilized to design the efficient thermal micro-equipment.

1. Introduction

Over the last decades, many researchers have devoted to investigating the micro/nano-scale transport phenomena, leading to a radical technological change towards miniaturization. The transport in micro/nano channels has been used as promising platforms for diverse applications in mechanical, chemical and biochemical engineering and micro-electro-mechanical systems (MEMS) [1–4]. According to different driving forces, microfluidic devices can be divided into electro-osmosis micropumps [5–12], pressure actuated micropumps [13,14] and EMHD pumps [15–17]. Among these driven mechanisms, magnetohydrodynamic (MHD) and EMHD micropumps, driven by Lorenz force, have attracted significant attentions due to certain advantages such as simple fabrication process, bidirectional control and the possibility to achieve relatively high flow rates [18–21]. The Lorentz force is generated through an interaction of an externally imposed electrical current across a channel and a transverse magnetic field orthogonal to the current.

Numerous studies have been carried out to explore the behavior of EMHD as well as heat transfer in micro-scale devices. Jang and Lee [22] first proposed the conception of EMHD micro-pump and demonstrated by experiment that low-magnitude magnetic fields can be utilized to substantially augment the average flow rates in micropumps. Chakraborty and Paul [23] theoretically showed the possibilities of exploiting a combination of two electrical fields in horizontal directions and an externally imposed transverse magnetic field. Under the joint action of a lateral uniform electrical field and a spatially non-uniform vertical magnetic field, the EMHD velocity of viscous fluid through a slit microchannel was discussed by Jian and Chang [24]. A "coffee stain" phenomenon generated by EMHD transport was incorporated by Das et al. [25]. Jian et al. [26] explored the transient rotating EMHD micropumps in a slit microchannel and demonstrated that the magnitude of EMHD velocity increases with Hartmann number Ha for a given low parameter range of Ha. By using perturbation method, Buren et al. [27] examined the EMHD flow in a microchannel with corrugated walls. The corrugations of the two walls are periodic sinusoidal waves of small amplitude either in phase or half-period out of phase. Escandónet et al. [28] investigated the hydrodynamics of a mixed EMHD-pressure driven flow for non-Newtonian fluids in a rectangular microchannel. They found that the volumetric

* Corresponding author.
E-mail address: jianyj@imu.edu.cn (Y. Jian).

https://doi.org/10.1016/j.ijheatmasstransfer.2018.06.147
0017-9310/

flow rate of EMHD flow increased about 40% comparing with the case of a purely electroosmotic flow. Paul and Chakraborty [29] discussed the wall effects in macromolecular separation under the EMHD influences and demonstrated that macromolecular pairs with less disparity in sizes give rise to higher value of resolution. By employing the perturbation method, Si and Jian [30] studied the EMHD micropump of Jeffrey fluids through two parallel microchannels with corrugated walls. The results of direct numerical simulations of low Reynolds number turbulent channel flow using electromagnetic forces were presented by O'Sullivan and Biringen [31]. Additionally, under a spatially varying magnetic field, electroosmotic flow and particle trajectories were analytically examined by Das et al. [32] in narrow fluidic confinements. The above-mentioned studies were mainly focused on the two-plate geometry, which is a better approximation of rectangular shape in microfluidic applications when length to height ratio is large [33]. However, EMHD-based microfluidic applications are often used for mixing [34,35]. If lateral confinements are not considered (e.g., a channel of two parallel plates), the performance of mixing may not be properly evaluated because no secondary flow is induced to alter flow dynamics. Therefore, the two-dimensional rectangular cross-section model is more general and practical.

Moreover, EMHD heat transfer and the corresponding entropy generation play a crucial role owing to its wide applications in liquid metal flows in the metallurgical industry, micropump, medical and biological sectors, etc. Duwairi and Abdullah [36] first presented the temperature distribution of EMHD flows in rectangular micropumps, where the heat generation was solely due to the inherent Joule heating and did not address the electrokinetic effects associated with such flows. In a later work of Chakraborty et al. [37], considering the electrokinetic effects, the heat transfer characteristics of EMHD combined thermally fully developed flows of Newtonian fluids in slit microchannels were analyzed. However, their study ignored the coupling interaction terms of electrical and magnetic fields, stemming from the inherent electromagnetic effects, in the energy equation. As a slight modification of the problem [38], Jian investigated the transient EMHD heat transfer and entropy generation in a parallel plate microparallel channel. This particular work included the contribution of this coupling interaction terms in the energy equation. Recently, the steady EMHD flow of blood and heat transfer in a capillary was investigated by Sinha and Shit [16] under the conditions of thermal radiation, constant heat flux and slip velocity. Later on, Mirza et al. [39] extend the work of Sinha and Shit [16] by considering two-phase EMHD thermal transport of blood and particles suspension with the Joule heating effects. In addition, the mathematical model of transient laminar two-phase EMHD flow and thermal transport of blood is formulated using a two-phase continuum model and Newton's second law. Most recently, Xie and Jian [40] analyzed the entropy generation of two-layer EMHD flows in microparallel channels, the distributions of velocity and temperature were analytically derived and were utilized to compute the entropy generation rate. Although the above mentioned literatures studying the heat transfer of EMHD flows of Newtonian fluids, the EMHD flows and thermal transport of non-Newtonian fluids have attracted many interests of several researchers [41–43]. Lately, the MHD heat transfer of nanofluids, a new kind of fluid to improve the thermal conductivity and convective heat transfer, has received great attention of many scholars [44–50]. Daniel et al. [51] investigated the unsteady MHD flows of nanofluids through a permeable linear stretching sheet. However, the heat generation effects were not considered in this article. In their next work [52], they provided a more general model by adding the heat generation effects. Though the two works consider the unsteady condition, the steady cases were explored by Daniel et al. also [53–55]. Another significant work about the heat transfer of nanofluids of MHD flow was completed by Sheikholeslami and Bhatti [56]. Their results indicated that the increase of Reynolds number and Coulomb forces enhance the distortion of isotherms. Then, in their following work [57], they considered the shape effects of nanoparticles and demonstrated that the platelet shape has the highest rate of heat transfer. An analytical solution was presented by Bhatti et al. [58] to determine the entropy generation on electro-kinetically modulated peristaltic propulsion on the magnetized nanofluid flow through a microchannel.

During the investigation of the EMHD flows, the geometry of the channels will play an important role. In the past few years, a great deal of efforts had been put to study the internal flow in curved pipes [59–64]. Dean [65,66] was the first to report the hydrodynamic flow of Newtonian fluids in a curved channel. They proposed the Dean number to characterize the flow phenomena of Newtonian fluids in a curved channel. As a fundamental problem, the flow and heat transfer of Newtonian fluids through curved pipes has been widely studied since the initial work of Dean [67–70]. Dean's work forms an important basis for the studies related to the flow of non-Newtonian fluids in curved pipes. In fact, most biofluids are viscoelastic. Blood, for example, is a non-Newtonian fluid and it is a suspension of formed elements in plasma. In addition, viscoelastic fluids are very important and widely used in industry. Therefore, there have been some studies on viscoelastic fluids flow and heat transfer in curved pipes [71–74]. Among the investigations of internal flows, those which involve analysis of the effects of reactive centrifugal force on the flow characteristics of viscous fluids passing through curved pipes are essential due to frequent occurrence of them in heat engines, industries, heat exchangers, biophysical equipment and chemical reactors. This reactive centrifugal force causes the presence of radial pressure gradient and makes the flow to leave its rectilinear distribution, leading to the appearance of a pair of secondary flow. However, in fully developed creeping Dean flows, the effect of reactive centrifugal forces is negligible due to the small velocity values, which makes the velocity field keeps its rectilinear distribution [75]. Therefore, creeping Newtonian flows in curved channels are always stable.

As mentioned above, a lot of research works have been reported to study the velocity and the heat transfer of EMHD flows. However, to the best of the authors' knowledge, the study of the EMHD micropump implemented in a curved rectangular microchannel has not been reported yet. The EMHD flow of Newtonian fluids through a curved rectangular microchannel is an essential and significant problem. The governing equations of Newtonian fluids are simpler in comparison to non-Newtonian fluids. So the present work is focused on the EMHD flow and heat transfer of Newtonian fluids through the above microchannels. The non-Newtonian effect will be studied in further research. The dependence of velocity and temperature profiles on Hartmann number and strength parameter of electrical field will be determined graphically.

As the authors know, the value of the EMHD velocity in a microchannel is small usually, which is about $10^3 \mu m/s$ typically. So we can take it as a creeping Dean flow in our following analysis. The rest of the work is arranged as follows. In Section 2, under a stationary electric field and magnetic field, the EMHD equations of velocity, temperature and energy generation are derived and their analytical solutions are achieved. The influences of electrical field strength parameter S, Hartmann number Ha and aspect ratios α on EMHD velocity and temperature are interpreted in Section 3. We draw the conclusions in Section 4. The results of the present study can be utilized as a valuable guideline in the design of the thermodynamic microdevices.