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Heat and fluid flow in electro-osmotically driven systems

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Abstract

A numerical investigation of heat and fluid flow in electro-osmotically driven systems is presented, by considering plain channels and channels packed with charged solid particles. The results show that the introduction of charged solid particles affects the internal potential distribution, fluid flow and temperature distribution in the channel. Under the analysed conditions, the effect on heat transfer is confined to the centre of the channel. This topic needs to be further investigated since it is of interest in practical applications.

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Keywords: Numerical modelling; CBS; Flow obstructions; Joule heating.

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1. Introduction

Electro-osmotically driven flow systems are used for many applications in the field of biology and engineering, such as pumping, cooling, mixing and separation processes, and recently also for dehumidification and regeneration of desiccant structures [1]. In all these applications, the effect of heat transfer and Joule heating needs to be taken into account [2]. As an example, the analysis of heat transfer due to electro-osmotic flow can be useful in heat-dose sensitivity tests, needed to perform appropriately electromagnetic hyperthermia for the treatment of cancers and tumors [3].

The operation of electro-osmotically driven flow systems depends on the interaction between a solid surface and an electrolytic solution. In fact, a solid surface in contact with an electrolyte becomes spontaneously charged, usually negatively. The positive ions of the solution are then attracted and form a high concentration region close to the charged surface. This high concentration region is called Electric Double Layer (EDL) [4]. Under the application of an external electric field the ions accumulated in the EDL tend to restore the electro-neutrality of the system, moving

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towards the negative electrode. As a result, the nearby ions are also dragged and Electro-Osmotic Flow (EOF) is produced. As the distance from the charged surface increases, the ionic concentration reduces and, as a consequence, EDL effect decreases. For this reason, EOF driven systems are effective at micro- and nano-scale. In plain channels, only the walls play a role as charged surfaces, while when solid particles are introduced inside channels, their charged boundaries can also be taken into account. As a consequence, EOF can potentially be enhanced.

As Joule heating increases, the fluid temperature was found to increase [5, 6]. The Joule heating effect was observed to grow with the capillary size [7, 8], the strength of the applied electrical field [7, 9] and the solution concentration [7, 10]. Several authors studied the Joule heating effect by considering temperature dependence to determine the thermo-physical properties of the system [7, 10, 11, 5], while others neglected this dependence [12, 8]. In fact, it was demonstrated that fluid properties can be assumed to be constant when EDL becomes sufficiently thin [13].

Tang et al. [7] proposed a numerical analysis of Joule heating effect on the electroosmotic flow and mass species transport. Temperature distribution in the liquid presented a parabolic shape, with the highest temperature occurring at the capillary centerline. This was due to the heat generated by Joule effect that moves from the central region to the wall by convection, and then is dissipated through the capillary wall by conduction. The temperature increment due to Joule effect increased the average EO velocity and, as a consequence, mass transfer and dispersion of the species. Tang et al. [10] extended the analysis of Joule heating effects on EOF in polydimethylsiloxane microfluidic channels. The EO velocity profile was found to deviate from the classical plug-like shape, to a concave configuration in the hydrodynamically developing region and to a convex pattern in the fully developed region, due to the Joule heating. Also the sample band shape was distorted, broadening its width and reducing its peak.

Perturbations to the EO velocity profile in a homogeneous capillary due to Joule heating effect was also observed by Xuan et al. [9]. They compared experimental and numerical results founding a good agreement in both the inlet and the outlet regions of the capillary, with a slight underestimation of numerical simulations for the time needed to make stable the flow rate when the electrical field was applied. During the first several seconds after the application of the electric field, a quick increase in the liquid temperature was observed.

Horiuchi and Dutta [12] analysed fluid temperature distribution under different conditions. In case of isothermal channel surfaces, when the channel surface temperature was higher than the inlet temperature of fluid, an increase of dimensional fluid temperature was found as the flow progressed. Conversely, in case of channel surface temperature lower than the inlet temperature of fluid, the local fluid temperature and heat flux decreased along the channel. Under constant surface heat flux conditions, the fluid temperature increased monotonically along the channel in case of heat addition to the channel, whereas it decreased in case of heat rejection. However the temperature distribution was observed to remain constant across the channel after ten characteristic dimensions from the entrance. Finally, it was found that the contribution of Joule heating needs to be taken into account only for channels larger than 20 μm.

Nithiarasu and Eng [11] proposed a modelling procedure for studying Joule heating due to EOF. The fluid temperature distribution was found to be different along the channel: a rapid temperature variation was observed in the inlet region, whereas a constant value was detected in the outlet region, where the heat transferred and heat generated are approximately equal.

Sánchez et al. [5] observed that the temperature gradients along the capillary make the electric and flow fields non-uniform along the axial and longitudinal directions due to the dependence of viscosity and electrical conductivity on temperature.

Vocale et al. [8] compared EOF in elliptical and rectangular geometries in order to optimize thermal performance of the micro heat sinks. They demonstrated that rectangular cross-sections are more effective in case of small values of aspect ratio, whereas the elliptical microchannels are preferable as the aspect ratio increases. Misra and Sinha [14] observed a reduction in fluid temperature as the temperature-jump or the vertical distance between channel walls increase. Shit et al. [3] derived a mathematical model to analyse EOF and heat transfer of power-law fluids in a hydrophobic micro-channel by considering a constant heat source at the boundary of the channel.

Due to the small scale of the phenomenon, the collection of experimental data is quite difficult, especially in complex geometries, such as channels packed with solid particles. Hence numerical modelling is very used to study EOF, but many simplifying assumptions are considered [15] For this reason, the authors analyse EOF in a channel packed with charged solid particles, with prescribed geometric characteristics, using a microscopic approach, that provides minute details of the quantities of interest [16]. To the authors' knowledge, the effect of introducing solid particles on heat transfer due to EO is here investigated for the first time. For this reason, a comparative study between micro-channels