



Numerical study of electroosmotic micropump using Lattice Boltzmann method



Shahram Derakhshan*, Iman Adibi, H. Sarrafha

School of Mechanical Engineering, Iran University of Science & Technology, Narmak, 16846 Tehran, Iran

ARTICLE INFO

Article history:

Received 26 January 2014

Received in revised form 24 November 2014

Accepted 16 March 2015

Available online 23 March 2015

Keywords:

Electroosmotic

Lattice Boltzmann

Thermodynamic efficiency

Joule heating

ABSTRACT

In the present study, the effects of the Joule heating and viscous dissipation on the electroosmotic flow pattern has been investigated using the coupled momentum, Poisson–Boltzmann and energy equations by the Lattice Boltzmann method. The main objective of this research was to study the effects of temperature variations caused by the dissipative terms on the thermodynamic efficiency of electroosmotic pumps. The results showed that the Joule heating affects temperature-dependent properties via changing the temperature distribution of the micro channel. Meanwhile, it was observed that the thermodynamic efficiency predicted by the isothermal model, deviated substantially from that predicted by the non-isothermal model when the Joule heating is significant.

© 2015 Elsevier Ltd. All rights reserved.

1. Introduction

Clearly electroosmotic mechanism is rapidly developing and it has become a powerful method for fluid manipulation in microsystems within the past decades. Nowadays, electroosmotic method is widely used as an elegant mechanism to generate flow in micro-scale laboratories which are called Lan-On-A-Chip. Unlike the conventional pressure driven micropumps, known as displacement micropumps, in which the manufacturing process is daunting due to their complicated structure, the dynamic micropumps like electroosmotic micropumps, have featured simple structure. These micropumps generate continuous pulse free flows with considerable flow rates [1–6].

A majority of solids, produce an electric double layer, known as EDL, when are in contact to either weak or strong electrolyte solutions. Counter ions from the bulk liquid are attached to the surface coating these solid charges. On the other hand, Dissolved co-ions are rejected from the solid. Actually, EDL is a high capacitance charged region of ions at the liquid/solid interface. The layer of immobile counter-ions immediately next to the charged surface is called the Stern layer. The outer, diffuse part of the layer is called the Gouy–Chapman layer forming a net positive region of ions that span a distance on the order of the Debye length of the solution. If an electric field is applied tangentially along the surface, ions move in response to the field dragging surrounding liquid

with them. As a result of this ion drag, the fluid is drawn by the ions and therefore it flows tangent to the wall [7].

The electroosmotic flow was firstly explored about two centuries ago [8]. The new theories related to electroosmotic flow can be traced back to Burgreen and Nakache, who theoretically studied the electrokinetic flow in ultra-capillary slits [9]. Rice and Whitehead [10] analyzed electrokinetic pressure driven flow in a narrow cylindrical capillary, assuming low zeta potentials and Debye–Hückel linearization. Later, Levine et al. extended their model for high zeta potentials [11].

Santiago [12] predicted that the ideal electroosmotic flow would only be observed for low Reynolds numbers steady flows. Subsequently, Dutta and Beskok obtained analytical solutions of unsteady electroosmotic flows, proving Santiago's results [13]. Yang and Li developed a numerical algorithm based on Debye–Hückel Linearization and studied electrokinetic effects in pressure driven liquid flows [14]. There have been numerous studies on numerical electroosmotic flow simulation using classic CFD methods since then.

Within the past decade, a mesoscopic static-based method, known as Lattice Boltzmann Method (LBM), has been developed to simulate EOF in Microsystems [15–22]. Benzi, Succi, and Vergassola reviewed the lattice Boltzmann equation theories and applications in 1992 [23]. In their study, they present a comprehensive discussion on lattice Boltzmann equation development from lattice gas dynamics as well as different applications of lattice Boltzmann model for various flow conditions. Wang et al. presented a Lattice Poisson–Boltzmann Method (LPBM) for solving EOF problems in microchannels, which was a combination of Lattice Poisson

* Corresponding author. Tel.: +98 (21) 77 240206; fax: +98 (21) 77 24 04 88.

E-mail addresses: shderakhshan@iust.ac.ir (S. Derakhshan), i_adibi@mecheng.iust.ac.ir (I. Adibi), sarrafha92@mecheng.iust.ac.ir (H. Sarrafha).

Method (LPM) and Lattice Boltzmann Method (LBM) [24]. The model simultaneously solves non-linear Poisson–Boltzmann equation for electric potential distribution as well as solving simplified BGK–Boltzmann equation in order to solve the fluid flow field. Subsequently, similar as the external force term treatment in lattice BGK method, they presented a thermal evolution equation with generalized heat source term in their latter work [25].

Unlike the hydrodynamic features, the study of thermal effects and heat transfer in an electroosmosis pump is a new topic. Moreover, majority of the available literature is mainly focused specifically on thermal aspects them, i.e., temperature distribution or the rate of heat transfer [1,26–28]. However, it should be considered that physical properties, including zeta potential, viscosity, electric permittivity, thermal conductivity, and electric conductivity also depend on temperature [22,29–31]. As a consequence, velocity distribution and power term are affected by temperature variations in a microchannel. Temperature variations are generated by both internal heat sources like viscous dissipation and Joule heating, a phenomenon that arises from applied electric field and fluid electrical resistivity, as well as external thermal conditions [25,31,32]. Mala et al. investigated the basic structure of a thermal field in a microchannel in their earlier attempt [33]. Subsequently, other researchers studied typical thermal problems, e.g., the effects of Joule heating and viscous dissipation [29,34–36]. Chen and Santiago studied the thermodynamic efficiency of a micropump analytically and obtained the maximum thermodynamic efficiency as a function of concentration [37]. Additionally, they illustrated the importance of each and every power term in energy balance equation including the Joule heating, the viscous dissipation, and the pressure work as functions of concentration. However, the effect of temperature variations on temperature dependent physical properties was neglected in their study.

Tang et al. considered all the physical properties as functions of temperature [29,35]. However, their numerical research focuses on the structure of temperature field and the effects of temperature-dependent properties are examined implicitly. Since the effect of temperature variation on physical properties is not negligible, several researches have been conducted to study the effect of the dissipative terms like Joule heating on the velocity profile [22,24–31]. Sinton et al. explained the non-plug-like electroosmotic flow as a possible result of Joule heating [39]. Guo et al. proposed a finite-difference-based Lattice Boltzmann algorithm for electroosmotic flows where the Joule heating effect was considered [22]. In their attempt the effects of Joule heating on temperature distribution and velocity profile is examined. Kwak et al. studied the possibility of thermal control of EOF in a microchannel [31]. They obtained a non-plug-like EOF by implementing non-uniform wall temperature. However, they neglected the dissipative terms assuming a low electric field.

To the authors' best knowledge, none of the previous studies present a comprehensive study in which the dependency of all the physical properties on temperature variation and dissipative terms are simultaneously considered to evaluate the power terms and thermodynamic efficiency. Hence, the aim of the present attempt is to investigate the effects of temperature variations, caused by the dissipative terms, on thermodynamic efficiency of an electroosmotic pump via Lattice Boltzmann method, in this study, the spirit of the model developed by Wang et al. [24,25] is borrowed. The method of applying thermal boundary conditions and solving energy equation is developed using the method presented by Annunziata D'Orazio and Sauro Succi in their paper, which is about simulating thermal channel flow by means of lattice Boltzmann method with new boundary conditions [40]. The primary objective is to introduce appropriate relations to modify thermodynamic efficiency as well as power terms deviated by the isothermal assumption. In other words, neglecting the energy equation and

the temperature-dependent properties, the electroosmotic flow is simulated isothermally, and then the results can be modified by correlation factors in order to obtain the real power terms and thermodynamic efficiency.

2. Model description

An electroosmotic flow in a straight two-dimensional microchannel between two parallel walls is shown in Fig. 1. The channel dimensions are l and h in x and y directions, respectively. An electric potential difference is applied between inlet and outlet. The walls are kept at a uniform temperature distribution, T_w . A symmetric dilute 1 mM KCl solution fills the channel and the surfaces of the horizontal planes which are in contact with the ionized solution are charged with a zeta potential ζ .

2.1. Governing equations

Generally, the following assumptions are considered in mathematical models for electrokinetic transport: (i) the system is in chemical and dynamic equilibrium; (ii) the transport process is in steady state; (iii) the ions in the Stern layer are rigidly attached to the surfaces and they have no contribution to the bulk ionic current; (iv) the flow is slow enough that the ion convection effect is negligible; (v) the bulk ionic concentration is not too high (<1 mol/l) or not too low (the Debye length is smaller than ten times the channel width), therefore the Poisson–Boltzmann (PB) model is still applicable; (vi) no other chemical reactions occur at surfaces except for chemical adsorption and dissociation [38]. Furthermore, the electrolyte is treated as a continuum Newtonian fluid. Considering a flow over a non-conducting stationary surface and under the condition of moderate ionic concentration, the ion transport is described by the weakly coupled Poisson–Boltzmann model instead of the highly coupled Poisson–Nernst–Planck model [39]. Therefore, in this study, the governing equations including continuity, momentum conservation, Poisson–Boltzmann and energy equations are obtained considering the aforementioned assumptions.

The driving force of an EOF is originated from the interactions between the net charge density within the EDL region and the applied external electric field. By assuming that the electrolyte solution is incompressible and the density fluctuation caused by temperature variations is negligible, the motion of the fluid is governed by the Navier–Stokes equations given as [22]:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0, \quad (1)$$

$$\frac{\partial (\rho \mathbf{u})}{\partial t} + \mathbf{u} \cdot \nabla (\rho \mathbf{u}) = -\nabla p + \nabla \cdot [\mu \nabla (\rho \mathbf{u})] + \rho_e \mathbf{E}, \quad (2)$$

where $\mathbf{u}$ and p represent flow velocity and pressure, respectively. Although the solution density, ρ , is assumed to be constant, the



Fig. 1. Schematic of the model problem of a two-dimensional microchannel between two plates with constant wall temperature.

Download English Version:

<https://daneshyari.com/en/article/7157035>

Download Persian Version:

<https://daneshyari.com/article/7157035>

[Daneshyari.com](https://daneshyari.com)