International Journal of Thermal Sciences 55 (2012) 114–121

Contents lists available at SciVerse ScienceDirect

International Journal of Thermal Sciences

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

Effects of the channel geometry and of the fluid composition on the performances of DC electro-osmotic pumps

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A R T I C L E   I N F O

Article history:
Received 14 July 2011
Received in revised form
16 December 2011
Accepted 30 December 2011
Available online 31 January 2012

Keywords:
Electro-osmotic flow
Microfluidics
Electro-osmotic pump
Micro/nanochannel

A B S T R A C T

The operational behavior of silicon open channel DC electro-osmotic (EO) pumps is numerically investigated to highlight the role of the micro channel cross-sectional geometry and the influence of the electrical properties that characterize the fluid/wall interaction on the fluid-dynamic performances. The mathematical formulation is based on the classical theory for isothermal electro-osmotic flows but all the modeling assumptions have been deeply discussed, since they represent the limit to the application of the model itself. The equations that determine the electric potential and the local velocity field have been numerically solved using a specific in-house code. The model has been applied to micro and nano channels, manufactured by chemical etching on silicon wafers, that feature rectangular or trapezoidal cross-sections and a broad range of operating conditions has been examined. The interactions between the channel geometry and the fluid/wall electrical properties have been deeply analyzed and their role on the pumps performance is discussed in terms of macroscopic parameters, namely the volumetric flow rate and the pressure head. With the aim of giving a useful tool to designers, numerical results have been processed to develop two simple correlations that enable the computation of the characteristic curve of the EO pump. Their formulation directly stems from the comparison between results obtained using the model and analytical results for parallel plates and it puts in evidence the effect of the flow confinement due to a finite cross-section. Such correlations can be used for both rectangular and trapezoidal channels in the whole range of the operating conditions considered within this work.

1. Introduction

Electro-osmotic pumps (EOPs) are used to move fluids inside microfluidics-based devices by means of an electric field. An ionized liquid can flow over a stationary charged surface whenever an electric field is applied because of the Coulombian forces that act upon charged molecules; this phenomenon is known as electro-osmosis [1]. When in contact with an aqueous solution most surfaces spontaneously acquire a finite charge density, which induces an uneven distribution of charges in the fluid. The overall result is the formation of the so called Electrical Double Layer (EDL), whose extension varies significantly with the electrolyte concentration [2].

In the last few decades, the advance and the diffusion of microfluidics in several fields have enabled the development of high performance reliable EOPs [3–5]. More recently, their use has been further spurred by the progression of nanofluidics and biomedicine, whose applications present some technical difficulties for mechanical pumps because of high pressure drops, manufacturing of micro or even nano scale moving components and risk of fluid contamination [6].

EOPs present a number of different architectures and design configurations. Open channel pumps are made of one or more straight channels, the last being arranged both in series or in parallel [7]. Porous material pumps are manufactured with a porous material monolith or a porous membrane, or else, with a packed column of silica nano spheres [8–11]. Besides the structure, a difference exists due to the type of electric field applied on the whole length of the channels or of the porous medium. It is therefore use to characterize EOPs either as DC or AC. Focusing on open channel pumps, it is worth noting that their channels may feature very different cross-sectional geometries. Nevertheless, most of those fabricated on silicon substrates are generally

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doi:10.1016/j.ijthermalsci.2011.12.016

obtained by chemical etching [12], thus the cross-section may be a trapezoid with an apex angle $\theta = 54.74°$, if the etched wafer is of <100> silicon, or a rectangle with an apex angle $\theta = 90°$, if the etched wafer is of <110> silicon (Fig. 1).

In spite of the broad diffusion of silicon EOPs with rectangular or trapezoidal micro channels, most of the theoretical studies published up to now consider different geometries, i.e. tubes or parallel plates [13–17]. This is mainly due to the fact that both the circular and the planar cross-sections can be addressed by a one-dimensional formulation in the space variable, thus it is almost always possible to find analytical solutions for the governing equations that model the behavior of the EOP. The solution for parallel plates is even often used to predict the behavior of EOPs with micro channels featuring a finite, but narrow cross-section [4]. However, such approximation has never been fully investigated to understand what conditions enable its use in the prediction of the electrical and fluid-dynamic characteristics of the pumps. In the literature numerical solutions are available for more complex geometries [18], but since they usually investigate very specific operating conditions, their results cannot be generalized to a wide range of pumps architectures. Additionally, the number of studies that consider a realistic geometry of the channel cross-section is relatively small and, to the best of the Authors' knowledge, a systematic analysis of the influence of the cross-sectional geometry has never been undertaken so far.

From all the above considerations it follows that a thorough investigation of the influence of the channel cross-sectional geometry on the pump behavior is important in order to fulfill an in-depth understanding of the operation of such devices. The main goal of this work is twofold. On the one hand, the intent is to provide a numerical analysis of the performances of silicon open channel DC EOPs and to determine how the confinement of a finite cross-section affects the flow characteristics. On the other hand, a more pragmatic purpose is the development of two simple correlations for the design of EOPs, that allow the evaluation of the pump behavior in terms of volumetric flow rate and pressure head, in the whole range of the working conditions analyzed in the paper. The elaboration of such correlations additionally highlights which operating conditions do enable the one-dimensional approximation of the cross-section and which do not, for both rectangular and trapezoidal channels. A dedicated section that accounts for the limitations of the mathematical formulation used to model the EO pumping is also included.

2. EOP model

A DC open channel EOP can be modeled considering an induced electro-osmotic flow inside a channel, acting against a constant back pressure [13,14,17,18]. For an isothermal incompressible fluid with constant properties and a fully developed flow, the momentum equation can be written as:

$$\mu \nabla^2 u(\xi, \eta) = -\rho_e^{eq}(\xi, \eta) E_{\text{ext}} + \frac{\mathrm{d}p}{\mathrm{d}\omega} \tag{1}$$

where $u(\xi, \eta)$ is the fluid axial component of the velocity and μ is the dynamic viscosity of the fluid. On the right hand side of Eq. (1), the first term is the electric force acting on diffusive ions at the solid/liquid interface, where ρ_e^{eq} is the net charge distribution over the channel cross-section, assumed as independent of the local velocity field, while E_{ext} is the applied electric field, supposed to be uniform over the channel cross-section; the last term is the pressure gradient along the channel. Since, by assumption, the electric force is not influenced by the velocity field, neither for what concerns the charge distribution nor for the electric field strength, the equation is linear and can be solved with the superposition principle once the charge distribution is known and the boundary conditions (BCs) are defined. For the configurations and the operating conditions analyzed in the paper, it is possible to assume that the velocity field satisfies no-slip BCs at the wall; the congruity of this assumption will be discussed in the next paragraph.

Assuming that ions are displaced as for the static case, when the liquid is at rest, and that no overlap of the EDLs occurs over the channel cross-section, the charge distribution can be determined by means of the Poisson equation of electrostatics [13]:

$$\varepsilon \nabla^2 \phi(\xi, \eta) = -\rho_e^{eq}(\xi, \eta) \tag{2}$$

where a flat-wall Boltzmann distribution of ions is considered:

$$\rho_e^{eq}(\xi, \eta) = e \sum_{i=1}^{N} z_i n_{i\infty} \exp\left(-\frac{e z_i \phi(\xi, \eta)}{kT}\right) \tag{3}$$

In Eqs. (2) and (3), $\phi(\xi, \eta)$ is the unknown electric potential, ε is the permittivity of the liquid electrolyte, e is the magnitude of the elementary charge, z_i is the valence of the ith-ionic species with the appropriate sign, $n_{i\infty}$ is the ionic number concentration at the neutral state ($\phi = 0$), k is the Boltzmann constant and T is the thermodynamic temperature which, since the flow is considered isothermal, is a known scalar quantity throughout the model. The summation includes the contribution of all the N ionic species. Proper boundary conditions for Eq. (2) consider the electric potential as equal to the so called zeta-potential (ζ) at the wall. Substituting Eq. (3) into Eqs. (2) and (1) yields a set of two uncoupled PDEs that are the governing equations for an open channel EOP. While the momentum equation is linear, the Poisson–Boltzmann equation is strongly non-linear, but a linearization can be performed if the Debye–Hückel approximation holds, i.e. if ions mainly act under the influence of their thermal energy [14], which means:

$$e\phi \ll kT \tag{4}$$

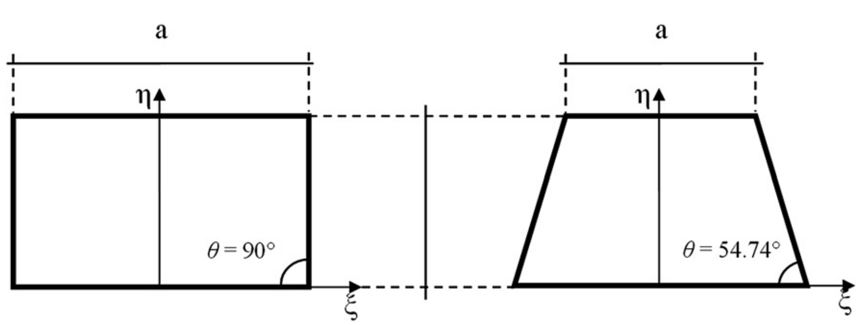

Fig. 1. Typical cross-sections of silicon micro channels made by chemical etching.