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Numerical Investigation of Electrothermal flow Instability in Microchannel

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Abstract: In the last decade, microfluidics has flourished for their required in several sectors. The applications areas involved are huge, from the world of transport to the nuclear engineering, aerospace, engineering wind, and from biomechanics to the micro-electronics (e.g. cooling integrated circuits). In this paper, we present a numerical investigation of electrothermal fluid flow through a microchannel. The main purpose of this study is to investigate the flow instability induced by the electrothermal forces. The mathematical model includes the Navier-Stokes equation coupled with Maxwell and the balance energy equations. The equation system obtained is solved using the finite element method (FEM). The model provides insight and understanding of many physical and dynamic properties of flow. The numerical results show that the flow becomes highly unstable when the potential difference is great inducing the appearance of large swirls localized at the electrodes. Specifically, numerical calculations of voltage influence on the temperature and velocity of fluid flow fields are presented. Numerical suggest that 40 V applied to electrodes can increase maximum velocity by a factor of 600 compared to the inlet velocity. A slight increase in temperature (300 to 318 for Vrms = 40 V) was achieved.

Key words: Modeling, microchannel, fluid flow, heat transfer, ac electric field.

1. Introduction

The rapid evolution of technologies creates significant contributions in various fields of expertise such as in chemistry, biochemistry, biology, environment, materials, mechanics, medicine, physics and other. A very great interesting in the last decades, was taken by the microfluidics as a young field of research [1-7]. The micro/nano-systems are devoted for sample injection, mixing, chemical reaction, separation, and detection on a small chip. These systems are essentially based on liquid displacement. It is useful even indispensable therefore to accelerate global research study and understanding of the dynamics of fluids with low dimension and velocity. The development of highly advanced instruments has become a major challenge to meet the needs and requirements that are increasingly difficult and offer many advantages: better control of the time, extremely fast response, miniature components, and a real-time execution of several operations per second [3, 4]. However, the mixing of fluids is very difficult at the microscale due to the fact that, at low Reynolds number and the flow is always laminar and lacking turbulence [8-10]. In microscopic applications, where the displacement is difficult to achieve efficient mixing, alternative methods such as active “stirring” need to be used. One can use external electric field gradients to move particles in a liquid medium and thus drag or even mix small volumes of reactants. The two electrodes produce an ac electric field that heats the fluid and creates the electrothermal force. This force can be generated to induce a pair of vortices to stir the flow field. In this paper, we will carry out a numerical study on the electrothermal flow in a microchannel. The main purpose of this study is to investigate the flow instability induced by the electrothermal forces.

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The effect of the applied voltage on the fluid flow will be discussed.

2. Mathematical formulation

2.1 Fluid flow

The flow is assumed to be isothermal, incompressible and the fluid is Newtonian.

a-Continuity equation

The mass conservation equation of the flow in x-y Cartesian coordinates is:

$$\frac{\partial \mathrm{u}}{\partial \mathrm{x}}+\frac{\partial \mathrm{v}}{\partial \mathrm{y}}=0 \qquad (1)$$

where u and v are the x- and the y- velocity components, respectively.

b-Momentum conservation equation

The Navier Stocks equation reads as follows:

$$\rho(\frac{\partial \vec{U}}{\partial t}+(\vec{U}\,\overrightarrow{grad})\vec{U})=-\overrightarrow{grad}\,p+\eta\nabla^2\vec{U}+\vec{F} \qquad (2)$$

where ρ is the fluid density, η is the dynamic viscosity of fluid, U is the field velocity of the fluid, and p is the static pressure. F is the electrothermal force given by [11].

$$\vec{F}=-\frac{1}{2}\left[(\frac{\overrightarrow{grad}\sigma}{\sigma}-\frac{\overrightarrow{grad}\varepsilon}{\varepsilon})\vec{E}\,\frac{\varepsilon\vec{E}}{1+(\tau\omega)^2}+\frac{1}{2}\left|\vec{E}\right|^2\overrightarrow{grad}\varepsilon\right] \qquad (3)$$

where ω is angular frequency of the electric field, and τ is the charge relaxation time.

2.2 Heat transfer

To evaluate the temperature rise for a given electrode system, the following energy balance equation must be solved:

$$\rho c_p\frac{\partial T}{\partial t}+\rho c_p\vec{U}\vec{\nabla}T=\lambda\nabla^2T+Q \qquad (4)$$

where c_p is the specific heat, t is the time λ is the thermal conductivity of fluid, and Q is the power density given by:

$$Q=\sigma\left|\vec{E}\right|^2 \qquad (5)$$

where σ is the electrical conductivity. The source term can be derived from the Poisson equation (Eq.6).

2.3 Electric field

The Maxwell-Gauss equation of the flow in steady-state is expressed as:

$$div(\varepsilon(-\overrightarrow{grad}\varphi))=\rho_e \qquad (6)$$

where ε is the electrical permittivity, φ is the electrical potential and ρ_e is the charge density of the electrolyte. Here, the electrolyte is assumed to be neutral (ρ_e=0).

2.4 Boundary conditions

The fluid flows from left to right. The incoming flow profile is characteristic for fully developed laminar flow, that is, parabolic with zero velocity at the channel walls. An applied electrothermal force creates swirling patterns in the flow at the center of the channel. The two electrodes produce an ac electric field that heats the fluid and creates the electrothermal force. This model assumes that the electrodes are perfect heat conductors and remain at a constant ambient temperature. At the inlet and the outlet, the temperature gradually approaches the ambient. All of the other boundaries of the channel are thermally and electrically insulated.

3. Numerical results and discussions

Numerical calculations were performed by the finite element analysis software Comsol Multiphysics [12]. The model used in our simulation is shown in Fig. 1. It consist of a section of a rectangular channel 40 µm high and 250 µm width, the two electrodes, each 60 µm wide, are located on the lower boundary at distance of 50 µm and 130 µm from the inlet. First, the two -dimensional quasi-static potential field is calculated, according to Laplace equation. The resulting electric field gives grow to a non-uniform temperature filed through Joule heating. The gradient of temperature T in the liquid causes inhomogeneities of the permittivity ε and the conductivity σ, which in turn gives rise to the forces causing fluid motion. Based on the previous results of electric field, the temperature field and the flow velocity field are calculated by solving energy balance and incompressible Navier-Stokes equations.

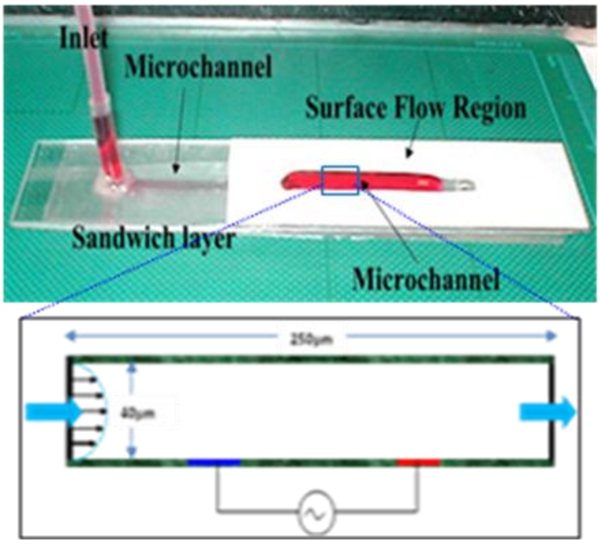

Fig. 1 2D model simulation: a section of microchannel with two electrodes in lower boundary.

3.1 Velocity field of fluid flow

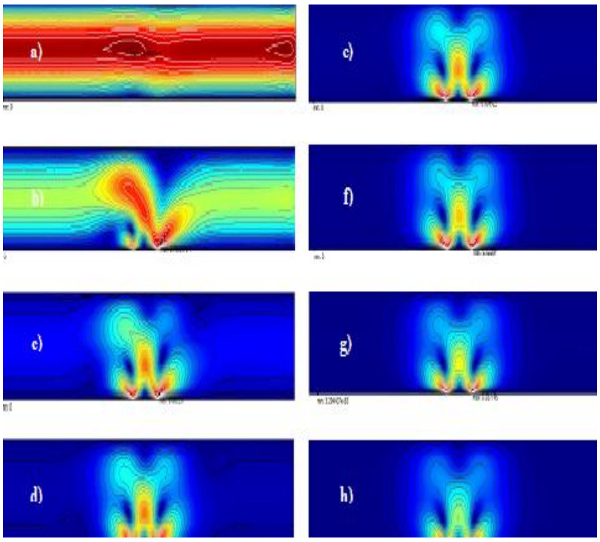

Fig. 2 The distribution of the flow velocity field with 15 kHz for different applied voltage: a) 5V, b) 10V, c) 15V, d) 20V, e) 25V, f) 30V, g) 35V, and h) 40V, respectively.

The inlet flow velocity (=10^{-4} m/s) and the angular frequency (=15 kHz) remain the same through the channel cross section in each case for various voltage applied. As mentioned Fig. 2 shows the spatial distribution of the flow velocity field within the microchannel for 5 V to, 10 V, 15 V, 20 V, 25 V, 30 V, 35 V, and 40 V applied voltage.

The electrothermal force generated by the applied of ac electric field produce swirling patterns in the fluid and thereby can create the instabilities and fluctuations in the flow. The generated vortices are involved in increasing the fluid velocity especially near the polarized portion. The fluidic behavior in the microfluidic device is very interesting and cannot be ignored to improve transport of molecules in liquid.

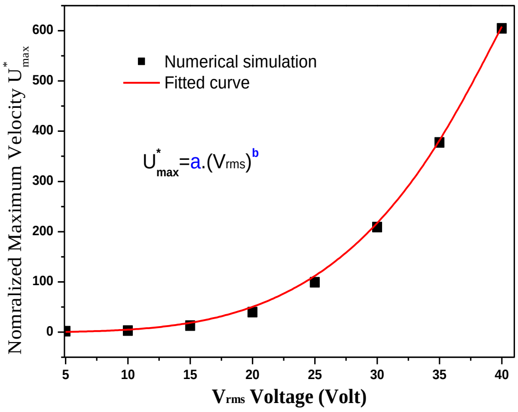

Fig. 3 Numerical simulation result of fluid velocity as a function of the applied voltage at 15 kHz.

With the same parameters used in the previous section, we are presented the influence of the applied voltage on the velocity of the flow. As mentioned in Fig. 3, the velocity of the flow is very much influenced by the voltage. The numerical result is fitted, which is shown in the same figure.

3.2 Temperature distribution in microchannel

As indicated above Fig. 4 illustrates the distribution of temperature within the microchannel for different voltage applied. It is see that a maximum temperature is located near the electrodes and it's greater when the voltage is important.

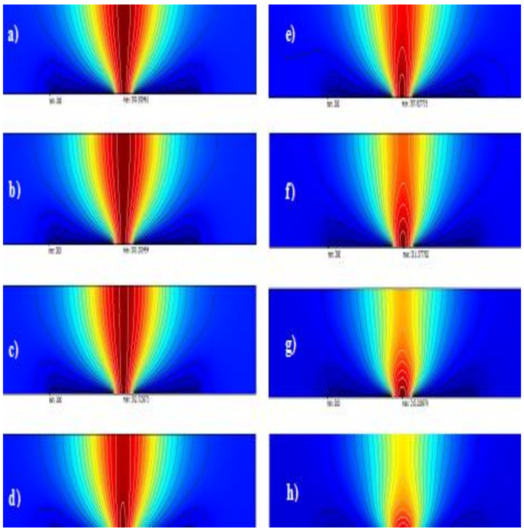

Fig. 4 The distribution of the temperature field with 15 kHz for different applied voltage: a) 5V, b) 10V, c) 15V, d) 20V, e) 25V, f) 30V, g) 35V, and h) 40V, respectively.

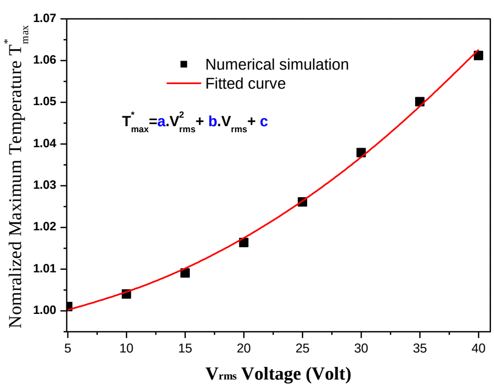

Fig. 5 Normalized maximum temperature at 15 kHz with the curve-fit.

Figure 5 presents the numerically-simulated of maximum temperature field versus voltage applied. The rise of the non-uniform temperature field is given by through Joule heating when the voltage is applied. It is seen that higher temperatures may be achieved with higher voltages. From the curve-fit the normalized maximum temperature of the flow appear to follow a relationship at the angular frequency (=15 kHz).

4. Conclusions

This work presents 2D numerical simulation of a fluid flow in microchannel which two electrodes are placed on bottom of the channel by using the finite elements method. One can considered that the mechanism is great means used in microfluidic system to enhance many phenomenon such as transport, diffusion of particle in small sample.

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