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Numerical simulation and design optimization of an electrohydrodynamic pump for dielectric liquids

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ABSTRACT

With an ever increasing demand for more effective heat sinks, liquid based electronic cooling has become a new prospect in the field. The present study introduces an electrohydrodynamic (EHD) pump with a simple design for dielectric liquids which have potential applications for electronic cooling. The pump consists of an eccentrically sandwiched wire electrode placed at the horizontal centerline between two parallel flat-plate electrodes. The EHD flow of dielectric liquid induced by the space charge generated due to the Onsager effect was obtained by the numerical solution of the Poisson–Nernst–Planck equations for ion transport and the Navier–Stokes equations for fluid flow. Good agreement obtained in the comparison of the numerical and the experimental results of velocity for the centrally sandwiched wire electrode case confirmed the validity of the numerical results. For a fixed voltage, the pump flow rate depends on the eccentricity of the wire electrode with respect to the plate electrodes and also with the electrode dimensions. By using the Taguchi method an optimum design for the EHD pump is obtained considering the wire electrode diameter, the flat plate electrode length and the eccentricity (the horizontal distance between the centers of wire and flat-plate electrodes) as the design parameters for fixed channel dimensions.

1. Introduction

Cooling of engineering components such as power transformers and electronic chips is essential for their safe operation and longevity. Demand for more effective cooling techniques is increasing day by day in the field of electronics and electric power transmission. Liquid cooling is more effective compared with the traditional air cooling of electronics, since liquids have greater heat carrying capacities compared to gases. Recently, the use of dielectric liquids for the cooling of power transformers (Chandrasekar and Montanari, 2014, Fernandez et al., 2013, McShane, 2001) and electronic devices (Bar-Cohen et al., 2006, Chien and Chang, 2011, Kazemi et al., 2009, Kim et al., 2010) has been considered by many researchers. Nanofluids characterized by highly desired thermal properties as heat transfer fluids are found to be very attractive for electronic cooling (Tsai and Chein, 2007, Sakanova et al., 2014, Selvakumar and Suresh, 2012, Yousefi et al., 2013) and the use of dielectric liquids as base-fluids for nanofluids is also a possibility for the near future.

However, one of the main difficulties of liquid based electronic cooling is the pumping of liquids through narrow channels. Though the idea of passive pumping (EHD flow) of aqueous liquids is well researched (Bazant and Squires, 2010, Squires and Bazant, 2004), it suffers from the problem of electrode degradation through electrolysis. In contrast, the EHD flow of dielectric liquids is free of such problems. Another advantage is that dielectric liquids are less corrosive to the channel surfaces compared to aqueous liquids.

Dielectric liquids generally lack free ions and are characterized by low electric permittivity, typically in the range of 2–5 in terms of relative permittivity. Charge is generally created as a result of ion injection from electrode surfaces at a high electric field and through the dissociation of impurity ion pairs (introduced due to the exposure of dielectric liquid to the environment) at a relatively low electric field. At thermodynamic equilibrium, ion generation due to the dissociation process is balanced by ion neutralization due to the recombination process. Application of an external electric field however is known to enhance the dissociation effect and as a result the conductivity of dielectric liquid (equivalently free-ion concentration) increases with the electric field. This is called the Onsager effect. An important consequence of this effect is the emergence of local variation in ion concentration leading to non-zero net space charge density in the bulk. The Coulomb force acting on this space charge subsequently causes the fluid to flow. This phenomenon can be utilized for pumping of dielectric liquid with a careful arrangement of electrodes in small channels. A detailed description of the Onsager phenomenon and its modeling for the corresponding EHD flow can be found in Fernandes et al. (2014), Suh (2012), Suh and Baek (2013), and Suh et al. (2013).

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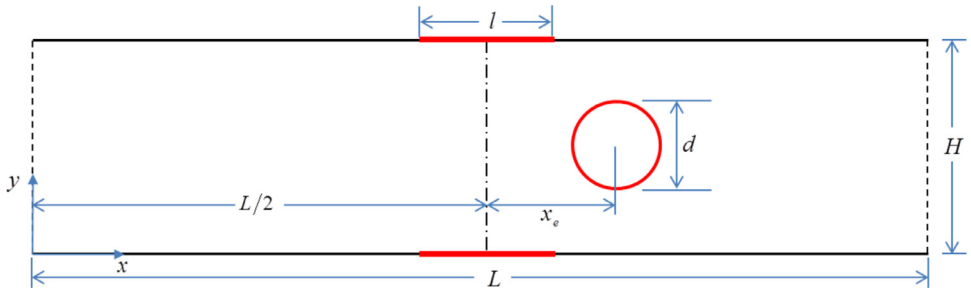

Fig. 1. Schematic diagram of the computational domain.

EHD pumping of dielectric liquids has been studied by a number of researchers starting early 1960s. Including the first study by Stuetzer (1959), many of the earlier works (Crowley et al., 1990, Darabi and Wang, 2005, Kano et al., 2009) in the field of EHD pumping of dielectric liquids were based on the charge injection from the electrode surfaces, which is known as ion-drag pumping. But the ion-drag pumps suffer degradation of both electrodes and dielectric liquid, which makes them not suitable for long term usage. On the other hand, EHD pumps working based on Onsager phenomenon do not suffer from such problems and have long life. Jeong and Seyed-Yagoobi (2002) performed experimental studies on EHD pumps made up of ring and needle electrodes. Feng and Seyed-Yagoobi (2004, 2007) developed a theoretical model for the EHD flow of dielectric liquid based on the dissociation of neutral electrolytic species and recombination of the generated ions. They called the pumping phenomenon "conduction pumping." Later, Pearson and Seyed-Yagoobi (2009) extended their study to different electrode configurations. Then, Kim et al. (2011) showed a good comparison between experimental and numerical results of fluid flow in an EHD pump with three cylindrical electrodes in a channel of mm size. Recently, Kano and Nishina (2013) studied the effects of electrode arrangement on EHD conduction pumping by using three different patterns of planar-comb-finger electrodes.

The present study is purposed to demonstrate the existence of an optimal design for a simple EHD pump for dielectric liquid. Optimization is a well-established branch of mathematics, widely used in every field of engineering and science. There are various optimization methods, such as the Kriging meta-modeling technique (Lee and Kim, 2011), the Lagrange multiplier technique (Kundu and Das, 2009), genetic algorithm (Bryden et al., 2003, Leblond and Gosselin, 2008, Yang et al., 2013), multi-objective optimization (Roper 2011), response surface method (Kim et al., 2008), and the Taguchi method (Comakli et al., 2009, Sivasakthivel et al., 2014), each having its own advantages and limitations. In this study we have selected the Taguchi method (Phadke, 2009, Ross, 1988, Taguchi et al., 2000) as it is easy to implement and it also minimizes variability around the target value.

The overall study has two parts. The first part describes the mathematical modeling, the numerical-solution method and the experimental validation of the EHD flow. The second part of the study describes the optimization of electrode size and positions for maximum flow rate. The paper is organized as follows. Section 2 briefly describes the mathematical modeling of EHD flow of dielectric liquid. Description on the numerical method and the validation of numerical results are given in Sections 3 and 4 respectively. Section 5 describes the optimization of the EHD pump using the Taguchi method with electrode size and position as the prime parameters. The conclusions are listed in Section 6.

2. Mathematical model

The computational domain used in this study is shown in Fig. 1. The channel dimensions are fixed at $H = 3$ mm and $L = 40$ mm. The length of the channel is taken as very large in order to reduce the end effect. The cylindrical wire electrode is grounded, and the two parallel flat-plate electrodes serve as anodes. The working fluid is a dielectric liquid of density ρ, viscosity η and relative electrical permittivity ε_r. When a DC electric field is applied between the electrodes by the voltage difference V_0, space charge is generated in the liquid owing to the non-uniform electric field (Onsager effect), and the Coulomb force acting on this space charge subsequently drags the fluid to flow.

The Navier–Stokes equations governing the steady state, isothermal flow of liquid due to the Coulombic body force are given as follows:

$$\nabla \cdot \mathbf{u} = 0 \tag{1a}$$

$$\rho(\mathbf{u} \cdot \nabla)\mathbf{u} = -\nabla p + \eta \nabla^2 \mathbf{u} + q\mathbf{E} \tag{1b}$$

where $\mathbf{u}$ is the fluid velocity, p the pressure, $q = e\sum z_i c_i$ the space charge density, e the elementary charge and z_i and c_i the valence and the number concentration of the i^{th} ionic species respectively; the summation is taken over all the species. Further, $\mathbf{E} = -\nabla\phi$ is the electric field and ϕ the electric potential. The distribution of ϕ in the domain is governed by the Poisson equation

$$\nabla \cdot (\varepsilon \nabla\phi) = -q \tag{2}$$

where $\varepsilon = \varepsilon_r \varepsilon_0$ is the electrical permittivity of the liquid and ε_0 the vacuum permittivity. The Nernst–Planck equations governing the steady-state ion transport can be written as follows:

$$\mathbf{u} \cdot \nabla c_i + \nabla \cdot (-D_i \nabla c_i + z_i \mu_i \mathbf{E} c_i) = R_i \tag{3}$$

where $D_i = k_B T/(6\pi\eta a_i)$ is the diffusivity and $\mu_i = e/(6\pi\eta a_i)$ the mobility of i^{th} ionic species. Further, k_B is the Boltzmann constant, T the absolute temperature and a_i the ionic radius. For simplification of the analysis, we assume that the neutral ion pair dissociates into a pair of monovalent ions: i.e., we set $z_1 = -z_2 = 1$. In addition, we assume that both ions have equal size ($a_1 = a_2$), and thus the diffusivity and the mobility are taken to be the same for both ions.

Following the Onsager theory (see e.g., Fernandes et al., 2014), we can write the reaction terms on the right-hand-side of Eq. (3) as follows:

$$R_i = \alpha\left[c_0^2 F(b) - c_1 c_2\right] \tag{4}$$

where $\alpha = 2\mu e/\varepsilon$ (Langevin's formula) is a constant for the recombination rate, c_0 the zero-field concentration, which is calculated from the experimentally determined zero field conductivity σ_0 via $\sigma_0 = 2e\mu c_0$ (refer to Fernandes et al. (2014) for the details), and $F(b) = I_1(2b)/b$ the Onsager function. Here, I_1 is the modified Bessel function of the first kind and order 1, and $b = l_B/l_O$ is the ratio of two molecular lengths; the Bjerrum distance $l_B = e^2/4\pi\varepsilon k_B T$ and the Onsager distance $l_O = \sqrt{e/4\pi\varepsilon E}$. Substituting the above distances results in a simplified expression for $b = 2\sqrt{\gamma E}$, where $\gamma = e^3/(16\pi\varepsilon k_B^2 T^2)$ is the Onsager constant and $E = |\mathbf{E}|$ the electric field intensity. In an ascending series for small b, we can write

$$F(b) = \sum_{k=0}^{\infty} \frac{b^{2k}}{k!\,(k+1)!} = \sum_{k=0}^{\infty} \frac{(4\gamma E)^k}{k!\,(k+1)!} \tag{5}$$