Journal of Electrostatics 93 (2018) 137–145

Contents lists available at ScienceDirect

Journal of Electrostatics

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

Synergy between injection and dissociation mechanisms in electrohydrodynamic pumps modeled numerically

Masahito Nishikawara*, Hideki Yanada, Kota Shomura[1]

Department of Mechanical Engineering, Toyohashi University of Technology, 1-1, Hibarigaoka, Tempaku, Toyohashi, Aichi, 441-8580, Japan

ARTICLE INFO

Keywords:
Charge injection
Conductivity
Dielectric liquids
Electrohydrodynamics
Field enhanced dissociation
Pumps

ABSTRACT

This paper reports a numerical investigation into the effects of interactions between two mechanisms of charge injection and dissociation on overall Electrohydrodynamic (EHD) pump characteristics. The following three types of electrode configurations are modeled: a plate and a bar, two plates on a channel wall, and embedded two-plate electrodes. The simulation results show that when the both mechanisms act in concert, the total developed pressure is augmented to be larger than the sum of the pressures developed by each mechanism separately. The degree to which the pressure is synergistically augmented depends on the configuration of electrodes.

1. Introduction

Electrohydrodynamic (EHD) flow is induced by the Coulomb force acting on excess charges in a dielectric fluid under a strong electric field. This phenomenon can be applied in (especially microscale) pumps and actuators and for heat-transfer enhancement [1–4]. Excess charges in the fluid are generated through the following two known mechanisms: electrodes inject charges into the fluid (injection) and dissociative molecules dissociate (dissociation). The density of the dissociated charges can increase with increasing electric field strength (field-enhanced dissociation). Charges injected from one electrode move to another electrode, and dissociated positive and negative charges gather around the negative and positive electrodes (formation of heterocharge layers), respectively. Neutral molecules are dragged by the charges moving toward the electrodes with the polarity opposite to the charges and a flow is generated.

EHD pumps designed to exploit the injection mechanism are ion drag pumps, whereas those designed to exploit dissociation are called conduction pumps. Both types of EHD pump have been investigated experimentally and numerically [5–10], but each design has generally been investigated under the assumption that either of the two charge-generation mechanisms accounts for all the relevant physics within the pump.

Atten et al. [11] investigated EHD phenomena in wire-cylinder and knife-plate electrodes theoretically, numerically, and experimentally, and concluded that not only field-enhanced dissociation but also injection affect current–voltage characteristics in the quasi-ohmic regime. The effects of the injection and field-enhanced dissociation mechanisms on EHD phenomena have been studied by Chirkov et al. [12,13]. They simulated current–time characteristics and the distribution of ion concentrations in EHD systems consisting of plane-plane and pin-plate electrodes with only injection, only dissociation, both injection and dissociation, and only field-enhanced dissociation acting on system [12]. EHD non-dimensional simulations were conducted in which Chirkov et al. varied the injection current density and the field-enhanced dissociation rate [13]. These results led them to insist that both the injection and conduction mechanisms contribute to the phenomenon of EHD flow. Yazdani and Seyed-Yagoobi [14] numerically investigated the effect of unipolar and bipolar injection from the whole electrode surface due to surface roughness in conduction-driven pumps, and showed that in the unipolar injection, the injected charges augment or reduce the original conduction-driven flow according to the polarity of the injected charges. In Refs. [12–14], the models assumed that positive and negative charges are free in the dielectric fluid and that the charge carriers generated by injection are the identical with the positive or negative charge carriers generated by dissociation. Daaboul et al. [15] observed an EHD flow with HFE-7100 fluid driven by blade–plane electrodes using a particle image velocimetry (PIV) technique under electric fields lower than 0.5 MV/m. The fluid flowed towards the blade tip in weak electric fields but was reversed in strong electric fields, thus showing that a transition between conduction-driven flow and injection-driven flow occurred. These observations demonstrate that the transition between dominant mechanisms does not occur suddenly, but it occurs within a certain range of electric field strength. Neither the

* Corresponding author
E-mail address: nishikawara@me.tut.ac.jp (M. Nishikawara).
[1] Currently at MITSUBISHI ELECTRIC ENGINEERING COMPANY LIMITED 1, Hishimachi, Inazawa, Aichi, 492–8161 Japan.

https://doi.org/10.1016/j.elstat.2018.04.009
Received 22 December 2017; Received in revised form 23 March 2018; Accepted 18 April 2018
Available online 30 April 2018

conduction and nor the injection mechanisms is fully dominant within this range.

Though some researchers have researched the synergistic reactions between the two mechanisms driving EHD pumps, the literature is still limited. Especially, the effect of the interaction of the injected and dissociated charges on pumping characteristics has not been sufficiently examined. In ion drag pumps, excess charges can be generated in the fluid not only by injection but also by field-enhanced dissociation. The same goes for conduction pumps. Therefore, this paper reports a numerical investigation of the effects on EHD pump characteristics of interactions between the two charge-generation phenomena using three types of electrode configurations. Numerical models are developed that account for both the ion drag and conduction actions. An EHD pump driven by only the ion drag action, only the conduction action, and both actions is simulated, and the pump characteristics observed in the three simulated cases are compared.

2. Numerical modeling

The governing equations are the continuity equation (equation (1)), the Navier–Stokes' equation (equation (2)) including the Coulomb force as an external force, Gauss' law (equation (3)), and the charge conservation equations for injected charges (equation (4)) and dissociated charges (equation (5)).

$$\nabla\cdot\mathbf{v} = 0, \tag{1}$$

$$(\mathbf{v}\cdot\nabla)\mathbf{v} = -\frac{1}{\rho}\nabla p + \frac{\mu}{\rho}\nabla^2\mathbf{v} + \mathbf{f}, \tag{2}$$

$$\nabla^2\varphi = -\frac{q_{total}}{\varepsilon}, \tag{3}$$

$$\nabla\cdot\mathbf{j}_{in} = 0, \text{ and} \tag{4}$$

$$\begin{pmatrix}\nabla\cdot\mathbf{j}_+\\ \nabla\cdot\mathbf{j}_-\end{pmatrix} = k_r(w_0^2F(E) - qw), \tag{5}$$

where the Coulomb force, **f** (equation (6)), total space charge density, q_{total} (equation (7)), and current density vector, **j** (equations (8)–(10)) take the following expressions,

$$\mathbf{f} = -\frac{q_{total}}{\rho}\nabla\varphi, \tag{6}$$

$$q_{total} = q_{in} + q - w, \tag{7}$$

$$\mathbf{j}_{in} = q_{in}\mu_{in}\mathbf{E} + q_{in}\mathbf{v} - D_i\nabla q_{in}, \tag{8}$$

$$\mathbf{j}_+ = \mu_+ q\mathbf{E} + q\mathbf{v} - D_i\nabla q, \text{ and} \tag{9}$$

$$\mathbf{j}_- = -\mu_- w\mathbf{E} + w\mathbf{v} - D_i\nabla w. \tag{10}$$

In these equations, $\mathbf{v} = (u, v)$ is the velocity vector, ρ is the liquid density, p is the pressure, μ is the viscosity, ϕ is the electric potential, ε is the permittivity, $\mathbf{j}_{in}$, $\mathbf{j}_+$, **j**-are the current density vectors of injected positive charge, positive and negative dissociation charges, k_r is the recombination rate constant, w_0 is the negative dissociation charge density at equilibrium, q_{in} is the density of the positive charges injected from the positive electrode, q and w are the densities of the positive and negative charges generated by dissociation, μ_{in}, μ_+, μ-are ionic mobilities of injected positive charge, positive and negative dissociation charges, respectively, **E** is the electric field vector, and D_i is the diffusion coefficient of ions. This model assumes that only positive charges are injected and that they do not combine with the negative dissociation charges because the injected positive charges are in general not the same as the dissociated positive charges. It is assumed for simplicity that $\mu_{in} = \mu_+ = \mu$-.

$F(E)$ is a function representing the field-enhanced dissociation effect. $F(E)$ can be expressed approximately by the following equations [16]:

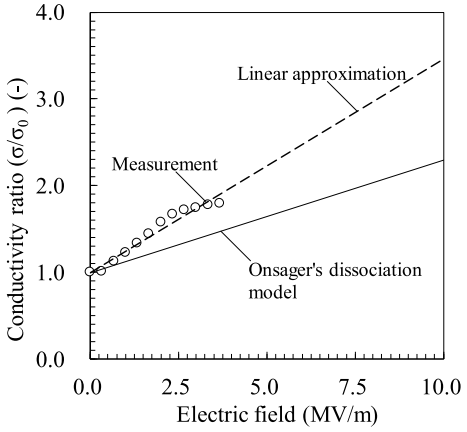

Fig. 1. Electric field dependence of conductivity of DBS.

$$F(E) = \frac{k_d}{k_{d0}} = \left(\frac{\sigma}{\sigma_0}\right)^2 \text{ and} \tag{11}$$

$$\frac{\sigma}{\sigma_0} = \gamma E + 1. \tag{12}$$

In these equations, k_d is the dissociation constant, k_{d0} is the dissociation constant under no electric field, σ is the conductivity, σ_0 is the conductivity under no electric field, and γ is the gradient of electric field dependence of conductivity. To obtain $F(E)$, the electric-field dependence of the electric conductivity of dibutyl sebacate (DBS) was measured in the laboratory using concentric cylinder electrodes [17]. The results are plotted in Fig. 1. These measurements showed that $\gamma = 2.46 \times 10^{-7}$ m/V for DBS. The field-dependence of the electric conductivity was calculated according to Onsager's theory [18] to find that $\gamma = 1.31 \times 10^{-7}$ m/V. Therefore, the measured result was larger than the theoretically predicted value. In this numerical simulation, $F(E)$ was represented by a linear approximation of the measured values.

The recombination rate constant, k_r, and the negative dissociation charge density at equilibrium, w_0, are expressed by the following equations:

$$k_r = \frac{\mu_+ + \mu_-}{\varepsilon} \text{ and} \tag{13}$$

$$w_0 = \frac{\sigma_0}{\mu_+ + \mu_-}. \tag{14}$$

It was assumed that charges are injected from the spot and its vicinity of the maximum electric field strength on the emitter electrode. Numerical simulation results of the EHD pump characteristics and EHD flows obtained using the above assumption were compared with experimental results and both results agreed relatively well [8,19]. Therefore, the present numerical simulation was conducted using the same assumption as that used in Refs. [8,19] and the charge injection region was limited to the upper right corner of the HV electrode as shown in Fig. 2. The charge density, q_e, injected from an electrode can be given by

$$q_e = k(E_{static} - E_{thres}), \tag{15}$$

where k is the proportionality constant, E_{static} is the mean value of the electrostatic field strength at the charge-injection region (see Fig. 2), and E_{thres} is the threshold value of E_{static} below which no charge injection takes place. A preliminary experiment showed that for DBS, positive charges are injected but negative charges are hardly injected. Further details of the model are presented in Refs. [8,10,14].

3. Electrode configuration

Three EHD pumps with the electrode configurations shown in Fig. 2