



Numerical investigation of the characteristics of an ion drag pump

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ARTICLE INFO

Article history:

Received 26 April 2016

Received in revised form

3 August 2016

Accepted 5 August 2016

Keywords:

Charge injection

Electrode configuration

Electrohydrodynamics

Ion drag pump

Numerical simulation

ABSTRACT

Simple, lightweight electrohydrodynamic pumps having no moving parts and producing no mechanical vibration or noise can enhance heat transfer, control fluid flows, and increase drying. This paper reports a numerical investigation of electrohydrodynamic (EHD) pumps having one centrally located emitter and two collector electrodes. Results show that optimum sizes exist in the length of and spacing between the collectors. Collector electrodes with triangular cross-sections can yield better performance than those having rectangular cross-sections. The magnitude and distribution of the charge density significantly influence pump performance.

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1. Introduction

The flow generated in a dielectric fluid by applying a high electric field is called an electrohydrodynamics (EHD) flow. EHD flows can be applied in various fields [1] such as pumping [2–4], heat transfer enhancement [5–9], flow structure control [10,11], and drying [12,13]. EHD pumps have many advantages: they produce no mechanical vibration or noise and have a simple, lightweight configuration. They are classified into three types: ion drag pumps, conduction pumps, and induction pumps, all of which utilize Coulomb's force acting on excess charges in the dielectric liquid. The difference between the three types of EHD pump lies in the mechanism by which excess charges are generated. Ion drag pumps utilize charges generated by a charge injection phenomenon [6,7,10–17]. Conduction pumps utilize charges generated by a non-equilibrium state of dissociation–recombination of dissociative molecules [8]. Induction pumps utilize the charges generated by a gradient of electric conductivity in the liquid, e.g., as caused by a temperature gradient [5,9].

As mentioned above, excess charges can be generated by charge injection and dissociation of dissociative molecules under high

electric field strengths. For some types of liquids, one of the two phenomena dominates over another, and for some other types of liquids, both phenomena may evenly take place. This paper treats only the charge injection phenomenon. Excess charges generated by charge injection near the emitter electrode of the ion drag pump in Fig. 1 are attracted to the collector electrode by Coulomb's force. The injected charges have the same polarity as the voltage applied to the emitter electrode. As injected charges are drawn to the collector electrode, they drag neutral molecules with them, generating a net flow. Thus, the application of Coulomb force increases the pressure from the emitter electrode to the collector electrode.

Many investigations into ion drag pumps have been conducted, and many types of electrodes have been proposed [2–4,14–17]. The majority of the previous investigations were experimental, and the shape of the electrodes and their arrangement in a tube or duct were determined by trial and error. The shape and arrangement of electrodes are key to the performance of an ion drag pump; therefore, they must be determined by considering the detailed electric and flow fields in such a pump. Recently, the ion drag pump characteristics have been examined using numerical simulations [18–23]. However, the majority of such numerical investigations are limited to cases where the ion drift term dominates over the other terms included in the current density, which is generally described by Eq. (1) [24–26].

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Nomenclature

D_i	diffusion coefficient of ions m^2/s
$\mathbf{E}$	electric field strength V/m
EL	length of emitter electrode m
E_{static}	electrostatic field strength V/m
E_{thres}	threshold electric field strength V/m
f_x	x component of Coulomb force per unit mass m/s^2
f_y	y component of Coulomb force per unit mass m/s^2
f_z	z component of Coulomb force per unit mass m/s^2
H	spacing between collector electrodes m
$\mathbf{j}$	current density A/m^2
k	proportional constant for injected charge density $\text{C}/(\text{V m}^2)$
L	length of collector electrodes m
P	pressure generated by ion drag pump Pa
q	charge density C/m^3
q_e	charge density injected from emitter electrode C/m^3
Q	flow rate generated by ion drag pump m^3/s

u	x component of flow velocity m/s
U_{in}	inlet velocity m/s
v	y component of flow velocity m/s
$\mathbf{V}$	flow velocity m/s
V_e	applied voltage V
w	z component of flow velocity m/s
W	emitter electrode interval m
x	x coordinate m
y	y coordinate m
z	z coordinate m
ϵ	permittivity F/m
ϵ_r	relative permittivity
μ	viscosity Pa s
μ_i	ionic mobility $\text{m}^2/(\text{V s})$
ν	kinetic viscosity m^2/s
ρ	density kg/m^3
σ	conductivity S/m
ϕ	electric potential V

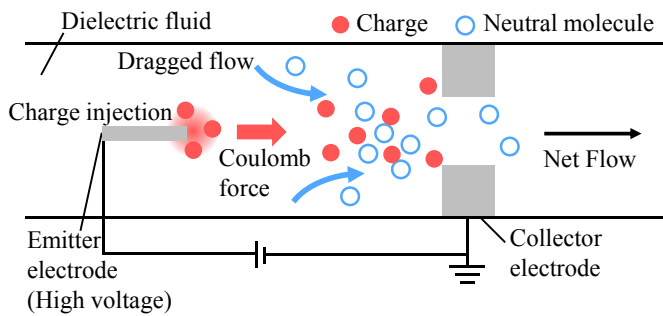


Fig. 1. Schematic of an ion drag pump.

$$\mathbf{j} = q\mu_i\mathbf{E} + q\mathbf{V} - D_i\text{grad}(q) + \sigma\mathbf{E} \quad (1)$$

where $\mathbf{j}$ is the current density, the first term $q\mu_i\mathbf{E}$ is the ion drift term, the second term $q\mathbf{V}$ is the convective term, the third term $D_i\text{grad}(q)$ is the diffusion term, and the fourth term $\sigma\mathbf{E}$ is the conductive term. For gases and some types of liquids, the ion drift term dominates over the other terms. However, for the majority of liquids, the convection term is not negligible when compared with the ion drift term. The majority of EHD literature do not include the conductive term $\sigma\mathbf{E}$. It does not affect the flow and electric fields but affects the current. When simulated currents need to be compared with measured ones, the conductive term is necessary.

The prediction accuracy of the flow fields and ion drag pump characteristics is sensitive to the density of the charges injected from the emitter electrode and to the ionic mobility. Previous studies [27,28] proposed an equation to determine the injected charge density. However, the equation was limited to high symmetry electrodes such as plane parallel plates, coaxial cylinders and concentric spheres. Estimation of ionic mobility is difficult because the produced ions have to be identified, and their motion cannot be distinguished from that of neutral molecules. Yanada et al. conducted numerical simulations of the ion drag flows [18,26] and ion drag pump characteristics [18] taking all of the terms in Eq. (1) into consideration and comparing the simulation results with measured values. They showed that it is important to assign a much larger

value to the ionic mobility than the value calculated by Walden's rule. They also proposed an expression for the density of charges injected from an emitter electrode. Their simulation results agreed relatively well with measured results. However, the effects of the electrode configuration and the physical properties of the fluid on the ion drag pump characteristics have not been fully investigated. This paper investigates the effect of the electrode configuration with a two- or three-dimensional shape on the ion drag pump characteristics. Features of the electric and flow fields, as well as the pressure–flow rate characteristics, under various electrode configurations are presented.

2. Numerical modeling

The computational domain in Fig. 2 surround the emitter in the center and two collectors on the inner wall of a rectangular channel. The ion drag pump in Fig. 2 with an emitter located in the center of the channel generates a higher pressure than one having both the emitter and the collector on wall as in Refs. [19,23] because the electric field is higher when the emitter is located in the center. Because the computational domain is symmetrical about the centerline of the flow channel, computation is made only in the upper half of the channel. Fig. 2(b) shows the y – z plane of a three-dimensional model; the cyclic width is represented as W . Because the three-dimensional domain is symmetric in the z direction as well as the y direction, the computational domain is only a quarter of the channel. In addition to the rectangular collector, a tapered collector and a triangular collector are simulated, as shown in Fig. 2(c) and (d). The continuity equation and the Navier–Stokes' equation including Coulomb's force as the external force under a steady, laminar, and incompressible flow are solved. The charge conservation equation and Gauss' law are solved simultaneously.

2.1. Governing equations and boundary conditions

The governing equations and boundary conditions are presented in this section. The continuity equation is

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \quad (2)$$

and the Navier–Stokes' equations are

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