3D Modeling and Simulation of Electrohydrodynamic Ion-Drag Micropump with Different Configurations of Collector Electrode

[1]Shakeel Ahmed Kamboh, [2]Jane Labadin
Faculty of Computer Science & Information Technology
Universiti Malaysia Sarawak
94300 Kota Samarahan, Sarawak, Malaysia
e-mail: [1]shakeel.maths@yahoo.com
[2]ljane@fit.unimas.my

Andrew Ragai Henry Rigit
Faculty of Engineering
Universiti Malaysia Sarawak
94300 Kota Samarahan, Sarawak, Malaysia
e-mail: arigit@feng.unimas.my

Abstract—**This paper presents 3D simulation work for ion-drag micropump. The commercial simulation software Comsol Multiphysics 4.2 was used to model and simulate ion-drag micropump for three different configurations of collector electrode. The purpose of the simulation was to investigate the ways to improve the performance of the micropump and analyze the effect of the electric field, fluid velocity and pressure gradient on the different design of the micropump. The initial simulation patterns reveal the behavior of the electric field, fluid velocity and pressure gradient in the domain of each of the design of the micropump. From the simulation results it is observed that at the top of the flow channel the fluid flow and pressure field is low because the driving electric body force is stronger near the electrodes surface and weaker at the top regions of the microchannel.**

Keywords-electrohydrodynamics; ion-drag micropump; electrodes; modeling and simulation

I. INTRODUCTION

In recent years, the increasing development in microfluidic and micro electro mechanical systems (MEMS) has gained much attention due to their attractive applications. Micropumps of length scale of order 0.1 mm or smaller but greater than 100nm are considered to be one of the most active components of these devices [1]. The micropumps are capable to transport and manipulate minute quantities of fluids in a number of diverse applications such as chemical and biological analysis, implantable medicine dosage control, cooling of sensors and detectors, fuel injection, space exploration and more [2]. The types and features of micropumps have been reviewed in [2-4] and can be classified into two main classes: *(i) mechanical (or displacement)* and *(ii) non-mechanical (or dynamic)*. Mechanical micropumps use one or more moving boundaries to generate the pressure while non-mechanical micropumps continuously add momentum to the working fluid by converting a non-mechanical energy into kinetic energy. Magneto-hydrodynamics (MHD) and electrohydrodynamics (EHD) micropumps are the most familiar examples of non-mechanical type micropumps. Among the existing micropumps the EHD micropump is highly reliable because it offers advantages of no wearable moving parts or contamination due to lubrication, consumes very low power, requires minimal maintenance and flow rate and pumping pressure can be easily controlled by adjusting the applied voltage.

An EHD ion-drag pump (also known as injection pump) is based on the interaction of electric field and hydrodynamic field with electric charges injected into a dielectric fluid [5-7]. The electric field is established by applying a strong enough electric potential difference V between the metal electrodes called the emitter (anode) and collector (cathode), due to the interaction of electric field with the working fluid. The electric field exerts body forces (mainly the Coulomb force) on the free charges and dipoles that are transmitted directly from emitter into the fluid. As a consequence, the friction between the ions moving from emitter to collector and neutral molecules drags the working fluid and creates a flow. This ion-drag pumping mechanism between a pair of emitter and collector electrodes separated at a distance $x=L$ is schematically demonstrated in Fig 1.

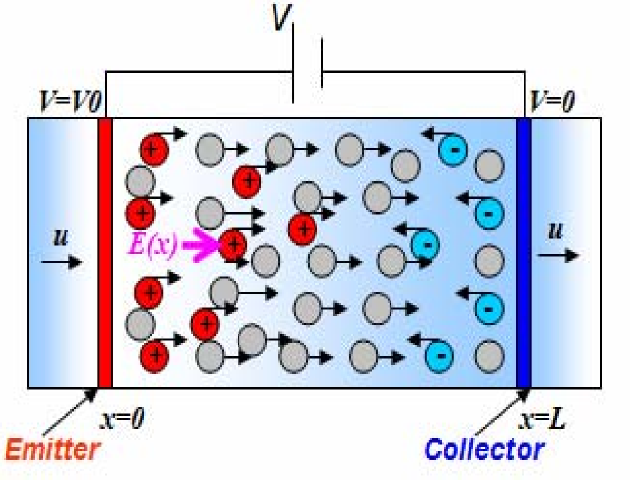

Figure 1. Ion-drag pumping mechanism

978-0-7695-4668-1/12 $26.00 © 2012 IEEE
DOI 10.1109/ISMS.2012.16

II. BACKGROUND

EHD ion-drag pumping phenomenon is known from the early twentieth century but was not utilized till the late 1950s. Stuetzer [8-9] was the first who presented classical theory of ion-drag pumping for both static and dynamic pressure and developed approximate models in Cartesian, cylindrical and spherical coordinates to compute electric field, current, power, force and pressure all depending on the applied electric voltage and the electrode gap. Stuetzer verified his theory with experimental support, where he used needle to ring electrode geometry and obtained a static pressure head of 1600 Pa at an applied electric voltage 17 kV for castor oil. The first operational micropump at mesoscale was fabricated by Richter et al [10] since then different designs of ion-drag pumps at mesoscale and microscale have been developed for specific applications. The performance of micropumps depends upon the proper selection of working fluid and particularly the electrodes designs [11]. Several different electrode designs like grid type emitter and collector, drilled holes plate electrode, ring electrodes, needle-type, screen with needles, wire, blade, circular ring or circular ring with sharp points, sawtooth or sawtooth with 3D bumps, and 3D micropillar electrodes have been proposed to optimize the performance of pump [5-6, 8-10, 12-17]. It was reported by Darabi et al [15] that by using sawtooth electrodes with 3D bumps the pumping capability of ion-drag micropump may increase significantly. Darabi and Rhodes [6] simulated an ion-drag micropump by adding an additional array of planar electrodes to the top cover of the micropump. This kind of arrangement is able to generate pressure and flow rate about three times greater than the pump with bottom electrodes. To increase the uniform electric field Lee et al [16] used 3D micropillar electrodes and showed that the pressure generated by the micropillar electrodes is much higher than the pressure generated by the planar electrode. Kazemi et al [17-18] fabricated and experimentally tested both symmetric and asymmetric designs of planar and 3D micropillar ion-drag micropumps. The pressure output in asymmetric design was about four times greater than the pressure output of symmetric design. With the asymmetric 3D micropillar electrodes designs they obtained maximum pressure of 2240 Pa at an applied voltage of 900V. Although, the performance of micropumps improves by using electrodes with sharp edges or 3D micropillars, it makes the fabrication process very complicated and the manufacturing cost also increases.

III. SHAPE AND POSITION OF COLLECTOR ELECTRODE

In an EHD ion-drag micropump the main driving force is the Coulomb force that is related with the electrical properties of working liquid and the electrodes [11]. Therefore, the micropump performance can be optimized by proper selection of the working dielectric liquid and design of the electrodes. Furthermore, to reduce the fabrication complexity, the collector shape and its position may also play significant role. Instead of using both emitter and collector electrodes as 3D micropillar, a combination of planar and 3D micropillar electrodes may be used. The effect of asymmetric configuration and position of electrodes may also increase the output pressure. In this paper we attempt to investigate further ways to create asymmetry by changing the position and shape of collector electrode.

IV. NUMERICAL MODELING AND SIMULATION

EHD pumping is a complex phenomenon [6] that involves various electrostatics and hydrodynamic forces. In particular, it is required to approximate the output flow and pressure generated as a result of applied electric potential and electric body forces. The electric body force[19] is expressed by

$$\vec{F}_e = \underbrace{q_e\vec{E}}_{\substack{\text{Coulomb}\\\text{Force}}} + \underbrace{\vec{P}.\nabla\vec{E}}_{\substack{\text{Kelvin}\\\text{Polarization}\\\text{Force}}} - \underbrace{\frac{1}{2}\vec{E}^2\nabla\varepsilon}_{\substack{\text{Dielectrophoresis}\\\text{Force}}} + \underbrace{\frac{1}{2}\nabla\left[\vec{E}^2\left(\frac{\partial\varepsilon}{\partial\rho}\right)_T\right]\rho}_{\substack{\text{Electrostrictive}\\\text{Force}}}\,, \quad (1)$$

where $\vec{F}_e$ is the electric body force, q_e is the charge density, $\vec{E}$ is the electric field, $\vec{P}$ is the polarization vector, ε is the fluid permittivity, ρ is the working fluid density and T is the temperature.

The differential form of Gauss's law is used to combine the electric field flux on the closed surface and space charge density and is given by

$$\nabla.\vec{E} = \frac{q_e}{\varepsilon}, \quad (2)$$

where $\vec{E} = -\nabla V$, that always points from the high potential distribution to the low potential distribution. In the absence of magnetic field the electric field is irrotational i.e. $\nabla \times \vec{E} = 0$. The inclusion of electric field in Gauss's law provides the relation between electric potential field and space charge density and takes the form of Poisson's equation. The conservation of charges is governed by

$$\frac{\partial q_e}{\partial t} = \nabla J, \quad (4)$$

where J is the current flux density due to convection, diffusion and migration of charges, i.e.

$$J = q_e\vec{u} + D\nabla q_e + \mu_e q_e\vec{E}, \quad (5)$$

where $\vec{u}$ is the fluid velocity, D is the diffusion coefficient and μ_e is the ion-mobility. The fluid flow and pressure head under the influence of applied electric body