Computational modeling and simulation of electrohydrodynamic (EHD) ion-drag micropump with planar emitter and micropillar collector electrodes

Shakeel Ahmed Kamboh1*, Jane Labadin1* and Andrew Ragai Henry Rigit2*
1,2 Faculty of Computer Science & Information Technology, 2 Faculty of Engineering Universiti Malaysia Sarawak, 94300 Kota Samarahan, Sarawak, Malaysia

E-mail: shakeel.maths@yahoo.com, ljane@fit.unimas.my, arigit@feng.unimas.my

Abstract: Computational models can be used to simulate a prototype of electrohydrodynamic (EHD) ion-drag micropump with planar emitter and micropillar collector electrodes. In this study, a simple and inexpensive design of an ion-drag micropump was modeled and numerically simulated. A three-dimensional segment of the microchannel was simulated by using periodic boundary conditions at the inlet and outlet. The pressure and velocity distribution at the outlet and in the entire domain of the micropump was obtained numerically. The effect of the gap between the emitter and the collector electrode, width and the height of micropillar and flow channel height was analyzed for optimum pressure and output flow rate. The enhanced performance of micropump was compared with existing designs. It was found that the performance of micropump could be improved by decreasing the height of micropillar and the gap between both electrodes. The numerical results also show that a maximum pressure head of about 2350 Pa and maximum mass flow rate 0.4 g min⁻¹ at an applied voltage 1000 V is achievable with the proposed design of micropump. These values of pressure and flow rate can meet the cryogenic cooling requirements for some specific electronic devices.

1. Introduction
The prominent features of micropumps inspired their use in a wide variety of applications ranging from biotechnology and chemical analysis to space exploration and cooling of micro electro mechanical systems (MEMS) such as sensors and detectors [1-2]. EHD ion-drag micropump is a non-mechanical type of micropump that uses the electric forces (mainly the Coulomb force) in the liquid bulk. The fluid flow is produced due to the friction between moving ions and the working fluids drag [3-4]. Ion-drag micropumps are preferred for pumping single phase incompressible flows because of their attractive features. These pumps are extensively utilized for the applications of fuel injection loops and cryogenic cooling of microdevices [5]. In the last decade, different designs of ion-drag micropumps have been proposed and developed to enhance the output flow rate and pressure. Unfortunately, with the shrinking size of many electronic products still the high pressure output is required in certain applications. On the other hand, the development of new compatible designs of micropumps becomes more challenging because of microfabrication complexity and instruments cost. In such circumstances, the numerical simulation of micropumps plays important role not only to

* To whom any correspondence should be addressed.
understand the different working principles but also enables to model the designs with better performance.

Numerical models for ion-drag pumping have been developed extensively to simulate and predict the fluid behavior. A number of numerical analyses and simulation of the EHD ion-drag mechanism inside liquids have been reported in literatures. Many [3, 6-11] were used to investigate the performance of different designs of ion-drag micropumps. To understand the effect of the electrode geometry on the electric field and fluid pumping effect, Chaudhary et al. [12] performed numerical simulations using FemLab 2D software. Darabi and Ekula [13] performed a three dimensional electric field analysis using ANSYS/Multiphysics to determine electric field distributions. Benetis et al. [14] did numerical modeling using fluent software to create a hydrodynamic model for the micropump. They found relation between internal pressure drop of micropump and mass flow rate, and investigated the relation between pump pressure head and delivered mass flow rate. Darabi and Rhodes [15] performed a two-dimensional numerical model using commercial CFD software FIDAP to model EHD ion-drag pumping between an array of emitter and collector electrodes. The focus of their simulations was to study the effects of electrode gap, stage gap, channel height, and applied voltage. Lee et al. [16] presented parametric numerical studies on the 3D micropillar electrodes that were performed using commercial Finite Element package COMSOL Multiphysics to model the EHD pumping between one emitter and collector stage. A numerical study using COMSOL Multiphysics was conducted by Kazemi et al. [17-18] and demonstrated for the first time, that an asymmetry in the electrode geometry (both 2D and 3D) will result in significantly higher pressure generation with lower power consumption than conventional symmetric electrode designs. A numerical model was developed by Hasnain et al. [19] for an EHD ion-drag micropump that takes into account the effect of the electric field on the charge distribution at the electrodes. The simulations of model were performed on COMSOL and validated using the experimental data of [18]. Rigit et al. [20] used COMSOL Multiphysics and obtained initial 2D simulation for the planar ion-drag micropump.

Most of the numerical models used to simulate and investigate the ion-drag pumping are two-dimensional which restrict to the designs of micropump with 3D geometric features. A 3D modeling and simulation of ion-drag micropump with three different designs of collector electrodes was presented by the same authors of this paper [21]. The simulation was carried out on COMSOL Multiphysics 4.2 and they concluded that a design with planar emitter and 3D micropillar collector may produce better output pressure and flow rate. This paper further analyses and optimizes the works of [21, 17] for enhanced performance and also validates the simulation results by comparing with the recent experimental data of [17].

The paper is arranged by first presenting the motivation of this research and its overview. In the next section, the three dimensional computational model with its boundary conditions is clearly discussed and the values for simulation are also presented. Finally, the numerical results are deliberated where the overall aim is to investigate the effect of various geometric parameters on the performance of a prototype design of ion-drag micropump. Particularly, the dimensions of micropillar collector electrode and the flow channel height were investigated for optimum output pressure and flow rate.

2. Computational Modeling and Simulation

The EHD phenomenon is a complicated process, since various electrostatics and hydrodynamics factors are involved. These factors include geometrical parameters, working fluid and actuator electrodes material properties, electro-chemical reaction factors, electric and fluid dynamics variables and many others. Therefore, the modeling of the EHD phenomenon is quite difficult unless several reasonable assumptions and simplifications are made. The mathematical models that govern the EHD phenomenon are derived from the Maxwell’s general quasi-static electromagnetism equations and fluid flow conservative equations [7,10] and then simplified by using certain realistic assumptions [21]. The complete set of governing equations for incompressible steady state flow in 3D geometry is listed as follows:
\[ \vec{F}_e = -q_e(x, y, z) \left( \frac{\partial V}{\partial x} + \frac{\partial V}{\partial y} + \frac{\partial V}{\partial z} \right) \]

Eq. (1) represents the electric body force \( \vec{F}_e \) (Coulomb force) which is the product of space charge density \( q_e \) and the gradient of electric potential \( V \). Eq. (2) states the Gauss’s law that combines the space charge density with electric potential field. The gradient of electric potential results in electric field \( \vec{E} \) as given in Eq. (3). The conservation of charges is described by Eq. (4) where \( J \) is the current density dominated by the migration current as defined in Eq (5). Eq. (6) is the well-known flow continuity equation with mass conservation and the Eq. (7)-Eq. (9) are the Navier-Stokes momentum equations which describe the fluid flow. Equations (1-9) have to be solved iteratively for potential field \( V \), electric field \( \vec{E} \), current density \( J \), charge density \( q_e \), fluid velocity components \((u, v, w)\) and pressure field \( p \).

The initial values for the entire domain of micropump are set to zero charge, zero current flux, no flow and atmospheric pressure. The boundary conditions are of Dirichlet type and are periodic because only one segment of the whole micropump is simulated. Figure 1 shows the dimensions of a representative segment with emitter and collector shapes. The emitter surface is set to a constant applied voltage and collector is set to ground i.e., zero voltage. The boundary conditions for charge density are not known because the charge injection process is not well understood. Therefore, approximate value for charge boundary condition at emitter surface is calculated from certain experimental value of current [15] that will also provide the boundary conditions for current density between emitter and collector [21-22]. The boundary conditions for fluid flow at both inlet and outlet are assumed equal to zero velocity and pressure. The walls of flow channel are set as no-slip boundary.

After setting up the problem, the three dimensional numerical model was performed using commercial finite element based simulation program COMSOL Multiphysics 4.2. The working fluid is selected as HFE-7100 (Hydrofluoroether, \( \text{C}_4\text{H}_9\text{OCH}_3 \)) into the flow channel with density \( \rho \), 1480 kg m\(^{-3}\), viscosity \( \eta \), 6.51\( \times \)10\(^{-4}\) Pa.s, ion mobility \( \mu_e \), 1.31\( \times \)10\(^{-8}\) m\(^2\) V\(^{-1}\).s and dielectric constant \( k \), 7.39; the ambient conditions are set to room temperature 25°C and the atmospheric pressure 101.325 kPa.
Electrode material is set to gold (Au) with predefined default properties. The mesh structure of entire segment of micropump consists of 33194 free tetrahedral mesh elements. The simulation results presented here were performed with extremely coarser grid. First the Electrostatics module was used to compute electric body force and then laminar fluid flow module was used to couple the effect of Coulomb force. The electric current flowing between electrodes is obtained by the relation \( I = \int_j dA \) and the power consumption is computed by \( P = IV \) [23]. Pressure generated within single segment was obtained from the difference between the average pressure at the inlet and outlet [15]. The proposed design of micropump consists of 100 pairs of electrodes, consequently the total generated pressure was computed by multiplying the number of segments by the pressure generated from single segment; the flow rate was calculated by \( \dot{m} = \rho \bar{u} A \). In order to optimize the design, extensive simulation trials were performed by varying the different controlling parameters. The effect of the gap between the emitter and the collector electrode, width and the height of micropillar and flow channel height was analyzed for optimum pressure and output mass flow rate. The simulation results were compared with experimental data of [17].

**Figure 1.** Schematic of a segment of EHD ion drag micropump showing electrode geometry. **Figure 2.** Local electric potential distribution along zx planes.

### 3. Results and Discussion

The electric potential profiles are obtained from the numerical solution of Poisson’s equation (2) and are useful to understand the behavior of electric field, electric current flux and charge density within the entire domain. It is observed that there is a continuous transition of electric potential from emitter to collector (figure 2). The values of electric potential remain higher in zx planes and near the surface of emitter but lower near the collector. It demonstrates that the charge concentration will be higher at the emitter surface and lower at the collector surface. Electric field is the most important factor in the ion-drag pumping because it is responsible for the drag force (Coulomb force). Therefore, in order to understand the electric field behavior, its simulation profiles are obtained. Figure 3 exhibits the electric field direction and contour lines. It can be seen that the direction of electric field lines is from emitter to collector and the field lines converging to the collector surface. It is also shown that the high magnitude of electric field occurs at the edges of emitter and collector near the bottom of flow channel. The behavior of fluid velocity can be understood by the simulated local velocity field profiles (figures 4-6).
Figure 3. Electric field profiles within the entire domain of micropump.

Figure 4. Local velocity field distribution at the outlet.

Figure 5. Local velocity field distribution along xy plane.

Figure 6. Local velocity field distribution along zx plane.

Both the fluid velocity and pressure depend upon the volume forces that create the fluid flow in the direction of electric field. It is observed that the magnitude of fluid velocity varies in different regions of the entire domain. The distribution of fluid velocity changes from inlet towards outlet of flow channel and the high magnitude of velocity is noted at the central regions of the entire domain. The local pressure distribution patterns are shown in figures 7-9. Due to the high electric field near the surface of micropillar collector, the local pressure distribution is higher around the collector and at the centre of outlet. Both the current and power consumption in the micropump increase exponentially as the applied voltage increases linearly as shown in figure 10. Power consumption is of the order of $mW$ (milliwatt) as the current is of the order $\mu A$ (microampere). The average electric field between emitter and collector is approximately linear with respect to the increase in applied voltage (figure 11). The pressure and mass flow rate can be controlled by applied voltage; the generated pressure and mass flow rate rise with the increase in voltage (figure 12).
In order to optimize the design, a parametric study was conducted by analyzing the effect of different controlling parameters on the performance of micropump. Both the mass flow rate and pressure increase with the decreasing of the electrode gap up to a limited extent. In some earlier experimental studies [5], it was noted that the liquid breakdown may occur at very small gap of 5-10 \( \mu \text{m} \) that may affect the life time of the micropump. In this study the electrodes gap is varied from 20 \( \mu \text{m} \) to 120 \( \mu \text{m} \) (figure 13) and as a result the pressure and mass flow rate vary from 2650 to 1840 Pa and 0.45 to 0.32 g min\(^{-1} \), respectively. The width and height of micropillar are also reduced to reduce the possible resistance to flow as shown in figures 14-15. When the width of the micropillar is decreased from 40 \( \mu \text{m} \) to 10\( \mu \text{m} \) the pressure and flow rate have ranges of about 1990-2520 Pa and 0.1-0.4 g min\(^{-1} \), i.e., more thinner micropillar will provide better pressure and mass flow rate will be obtained. Similarly, with the decrease in the height of micropillar from 100 \( \mu \text{m} \) to 10 \( \mu \text{m} \) the pressure range from 1500 to 2200 Pa and mass flow rate from 0.25 to 0.3 g min\(^{-1} \).
and flow rate increase 1490 to 2250 Pa and 0.158 to 0.35 g min$^{-1}$ respectively. The effect of microchannel variation is also analyzed as shown in figure 16. There is an inverse relation between pressure variation and mass flow rate variation as the flow channel height is reduced from 100 μm to 50 μm. The pressure increases however the flow rate decreases. This is due to the fact that the mass flow rate depends upon the area of the outlet. Hence, by decreasing the flow channel height the area of outlet also decreases. On the other hand, the magnitude of the driving force increases with the decrease in the flow channel height that results in high pressure output. A number of simulation trials were done and the simultaneous effects of all four parameters viz. electrode gap, micropillar width, micropillar height and microchannel height were analyzed. It was found that the maximum pressure head ~2350 Pa and flow rate ~0.4 g min$^{-1}$ is achievable at the electrode gap of 40 μm, micropillar width and gap at 10 μm and flow channel height of 100 μm.

![Figure 13](image1.png) **Figure 13.** Variation of pressure and mass flow rate at gap between electrodes.

![Figure 14](image2.png) **Figure 14.** Variation of pressure and mass flow rate at micropillar width.

![Figure 15](image3.png) **Figure 15.** Variation of pressure and mass flow rate at micropillar height.

![Figure 16](image4.png) **Figure 16.** Variation of pressure and mass flow rate at micro channel height.

To validate the model the simulation results were compared with the experimental data of [17] obtained from four different configurations of electrodes. The output pressure achieved from the simulation of proposed design was compared with the planar symmetric, planar asymmetric, 3D symmetric and 3D asymmetric designs of [17] as shown in figure 17. The simulation results are significantly better than the first three designs and clearly, the results are almost equivalently good as the 3D asymmetric design. The proposed design is simple and inexpensive because it uses only one micropillar collector whereas [17] used two wider and thicker micropillars. It can also be deduced that
by increasing the number of micropillars as optimized in the proposed design will increase the pressure and mass flow rate appreciably, unfortunately the fabrication and computational cost may also increase significantly.

Figure 17. Comparison of simulation results with experimental results of Kazemi et al. [17]

4. Conclusions
A modeling and simulation study was performed for a simple prototype design of EHD ion-drag micropump with planar emitter and 3D micropillar collector electrode. The simulation methodology was applied to obtain and understand the behavior of electric potential, electric field, velocity field and pressure field within a representative segment of the micropump. Simulation results were used to optimize the design by analyzing the effect of different geometric parameters. The numerical results reveal that a maximum pressure of about 2350 Pa and a mass flow rate 0.4 g min\(^{-1}\) at an applied voltage 1000 V is achievable with the proposed design of micropump. These values of pressure and flow rate can meet the cryogenic cooling requirements for some specific electronic devices. Finally, the optimized design was compared with experimental results and found that output pressure showed fairly good agreement with experimental data.

Nomenclature:

| Symbol | Definition |
|--------|------------|
| \(A\)  | Area of outlet \(\left(\text{m}^2\right)\) |
| \(\bar{u}\) | Average velocity at outlet \(\left(\text{m/s}\right)\) |
| \(q_e\) | Charge density \(\left(\text{C/m}^3\right)\) |
| \(J\)  | Current density \(\left(\text{A/m}^2\right)\) |
| \(I\)  | Current \(\left(\text{A}\right)\) |
| \(k\)  | Dielectric constant |
| \(\eta\) | Dynamic viscosity \(\left(\text{Ns/m}^2\right)\) |
| \(F_e\) | EHD body force density \(\left(\text{N/m}^3\right)\) |
| \(\varepsilon\) | Electric permittivity \(\left(\text{F/m}\right)\) |
| \(\vec{E}\) | Electric field intensity \(\left(\text{V/m}\right)\) |
| \(\mu_e\) | Ion-mobility \(\left(\text{m}^2/\text{V s}\right)\) |
| \(\rho\) | Mass density \(\left(\text{kg/m}^3\right)\) |
| \(\dot{m}\) | Mass flow rate \(\left(\text{kg/s}\right)\) |
| \(P\)  | Pressure \(\left(\text{Pa}\right)\) |
| \(V\)  | Voltage \(\left(\text{V}\right)\) |
| \(S\)  | Surface area b/w electrodes \(\left(\text{m}^2\right)\) |
| \((u,v,w)\) | Velocity components \(\left(\text{m/s}\right)\) |

Acknowledgment
This work is supported by the Ministry of Science, Technology and Innovation (MOSTI), Malaysia, under the Sciences project 06-01-09-SF0066. The research is carried out at the Faculty of Computer Science and Information Technology, University Malaysia Sarawak.
References
[1] Laser D and Santiago J 2004 J Micromech. Microengineering 14 35
[2] Tsai N C and C Y Sue 2007 Sens. Actuators A Phys. 134 555
[3] Stuetzer O M 1959 J. Appl. Phys. 30 984
[4] Antonio R 2007 Microfluidic Technologies for Miniaturized Analysis Systems. New York: Springer
[5] Darabi J and Wang H 2005 J. Microelectromech Syst. 14 747
[6] Pickard W H 1963 J. Appl. Phys. 34 246
[7] Melcher J R 1981 “Continuum Electromechanics,” Cambridge: MIT Press
[8] Crowley J M, Wright G S and Chato J C 1990 IEEE Trans. Ind. Appl. 26 42
[9] Bryan J E and Yagoobi J S 1992 IEEE Trans. Ind. Appl. 28 310
[10] Castellanos A 1998 International Centre for Mechanical Sciences, p 363
[11] Darabi J, Rada M, Ohadi M and Lawler J 2002 J. Microelectromech Systs. 11 684
[12] Chowhury S, J. Darabil M, Ohadi and Lawer J 2002 IEEE Trans. Compon. Packag. Technol. 31 1
[13] Darabi J and Ekula K 2003 Microelectron J. 34 106
[14] Benetis V, Shoushtari A, Foroughi P and Ohadi M 2003 Annu. IEEE Semicond Therm. Meas. Manage Symp. 236
[15] Darabi J and Rhodes C 2006 Sens. Actuators A Phys. 127 94
[16] Lee C K, Robinson A J and Ching C Y 2007 13th International Workshop on THERMal Investigation of ICs and Systems p 48
[17] Kazemi P Z, Selvaganapathy P R and Ching C Y 2009 IEEE Transactions on Dielectrics and Electrical Insulation 16 483
[18] Kazemi P Z, Selvaganapathy P R and Ching C Y 2009 J. Microelectromech. Syst. 18 547
[19] Hasnain S M, Bakshi A, Selvaganapathy P R and Ching CY 2011 J Fluids Eng. Trans. ASME 133
[20] Rigit A R H and Chiong M C 2010 Sens Actuators A Phys 134 650
[21] Kamboh S A, Labadin J and Rigit A R H 2012 Intelligent Systems, Modeling and Simulation (ISMS) p 417
[22] Rada M 2004 Mechanical Engineering University of Maryland
[23] Grant IS, Phillips WR 2008 Manchester Physics. John Wiley& Sons, Second edition