Electrohydrodynamic Micropump Modeling for Performance Optimization

Modeling and simulating EHD micropump design to simulate and get optimum values for efficient operation of the pump using COMSOL Multiphysics®

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Abstract: In this paper, we are presenting an optimized and efficient design of an Electrohydrodynamic micropump for high performance in Microscale and biological applications. The Electrohydrodynamic (EHD) micropump works on phenomenon of movement of Microscale particles and fluids by presence of Electromagnetic field. It is found that performance and operation of pump are highly sensitive to changes in voltage, material and positioning of electrodes. We have considered designs from previous attempts to design an EHD micropump and have carried out various tests on the micropump modeled in COMSOL Multiphysics® environment such as changing the Geometrical parameters, physical parameters (electric current, voltage range), material parameters. Some of the tests include - effect on pump temperature with change in voltage and resistivity, effect on magnetic properties with change in voltage and geometrical parameters, effect on particle acceleration with change in geometrical and electrical parameters. The ultimate goal of this paper is to present a set of optimized parameters from each aforementioned sets to design a highly efficient EHD pump for biological & nanomedicine applications. Parylene-C substrate based design is for electrically actuated medicine delivery and silicon based pump design for on-chip cooling of microprocessors and SOCs.

Keywords: EHDpump, ion-drag, Micropump, modeling

1. Introduction and working principle

EHD micropump consists of specifically designed and fabricated pairs of electrodes over a substrate suitable for intended application. The term Electro-Hydro-Dynamic explains that the working principle of the pump is based on movement of liquid or liquid containing micro-particles with the help of dynamically generated electric field. This kind of pump draws major attention because there are no moving parts involved and additionally the simplistic design of fabrication makes it suitable for wide variety of applications. EHD micropump basically works on principle of Coulomb forces. There are total three types of pumping mechanisms based on this principle viz. induction pumping, conduction pumping and ion-drag pumping [3]. We are considering ion-drag EHD pump as it is vastly studied in literature and research [7]. In ion-drag pump, applied electric field sets motion of electrons which create ions in the fluid or it sets already present ions into motion based upon their polarity. If such dielectric liquid contains micro-particles then those particles also get transported along with the flow generated by the field. If an array of such electrode pairs is fabricated then it contributes to total unidirectional flow of the liquid or micro-particles in the medium. This phenomenon makes the working of pump dependent on various physical, chemical and electrical parameters such as conductivity of the liquid, sizing and shape of electrodes, heating effects and voltage range which we are studying in further sections of the paper.

2. Building geometry in COMSOL Multiphysics

The underlying working principle of the designed EHD pump being ion drag, pump was designed with two permeable electrodes in direct contact with the fluid to be pumped. The micropump had following design parameters for in-lab fabrication [3]. This was followed by a 3D-Model design for illustration purpose as shown in the Fig.2. Silicon substrate is built with the dimensions 350 x 5000 with height of 380µm and oxide thickness of 4µm, metal thickness as 5µm. Metal thickness is varied in different studies to observe the effect on results. The major constraint that was encountered while building the geometry was the absence of *hand-tool* in COMSOL

Multiphysics. So it was decided to scale down the model from 200 pairs of electrodes to 2 pairs, since number of electrodes do not affect the pumping ion drag mechanism of the model.

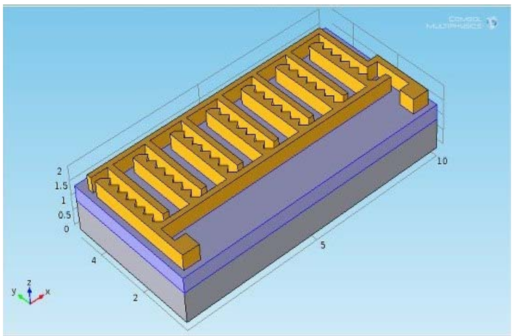
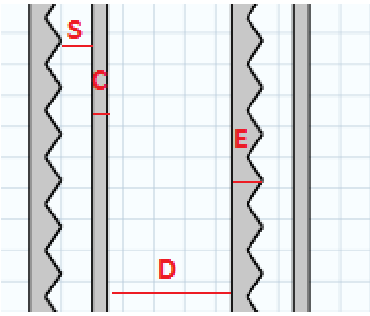


Figure 1. Prototyped Unscaled Model in COMSOL

Each positive electrode consists of around 160 grooves with an area of grounded electrode being 10.8 x 10^{-3} mm^2.



E	C	S	D
20um	10um	20um	80um

Figure 2. Design Parameters

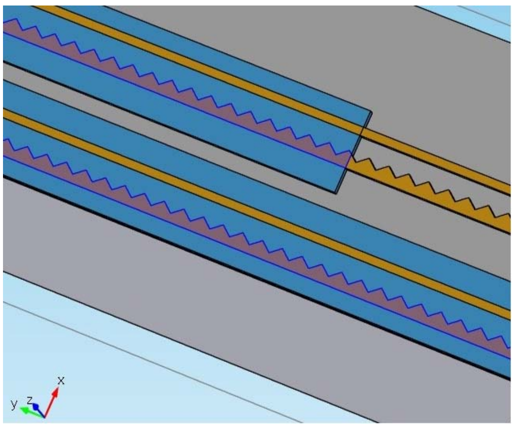


Figure 3. Two pair electrode model with water as fluid

3. COMSOL Multiphysics Simulations

We performed different sets of simulations for varied parameters of the EHD Pump. The simulations were performed with AC/DC, Structural Mechanics, Fluid flow, Heat transfer modules.
Attempt is made to come up with best possible pump design with optimized features.

3.1 Modeling Joule Heating

Joule heating was modeled on Silicon-Gold as well as Silicon-Platinum combination to observe the heating of electrodes and the interacting fluid.

Electrical Conductivity of water	Operating Voltage (V)	Low temperature limit (K)	High temperature limit (K)
σ= 5.5e0	5	295.41	2727.4
	10	303.08	435.19
	20	336.17	896.75
	40	436.61	2727.4
σ= 5.5e-4	20	289.03	296.31
	40	287.48	297.75
	80	291.09	326.95
σ= 5.5e-6	40	287.27	297.7
	200	291.96	465.23
σ= 5.5e-8	80	291.26	326.98
	200	291.26	326.98
σ=5.5e-16	200	291.26	326.98

Table 1. Joule Heating for Si-Au pair

Electrical Conductivity of water	Operating Voltage (V)	Low temperature limit (K)	High temperature limit (K)
σ= 5.5e0	5	$8.08x10^4$	$8.08x10^8$
	10	$3.2238x10^5$	$3.2268x10^{10}$
	20	$1.2886x10^6$	$1.2899x10^{12}$
	40	$5.1537x10^6$	$5.15x10^{12}$
σ= 5.5e-4	20	418.03	418.13
	40	805.23	805.72
	80	2351.8	2353.8
σ= 5.5e-6	40	298.08	298.09
	200	420.21	420.31
σ= 5.5e-8	80	293.55	293.55
	200	291.26	291.26
σ= 5.5e-16	200	293.36	293.36

Table 2. Joule Heating for Si-Pt pair

By varying the conductivity of the water (fluid considered) changes in the temperature were noted and studied for Si-Au *(Table 1)* and Si-Pt (*Table 2*).

It can be concluded from the above results that after a specific electrical conductivity of the fluid the heating of the electrodes takes place independent of the conduction and is negligible. Thus, if the conductivity of the fluid is very less and the operating voltage is kept optimum then heating can be minimized.

Platinum being lesser conductive than Gold creates more heating effect as we can see in the simulations.

3.2 Electric Field modeling

Electric field modeling shows an increasing potential gradient from saw-tooth shaped anode to the cathode. Figure 4 shows the results for σ= 5.5e-8 of water and operating voltage as 40V. The electric potential gradient shows the increase in potential from anode to cathode thus ionizing the liquid in that direction.

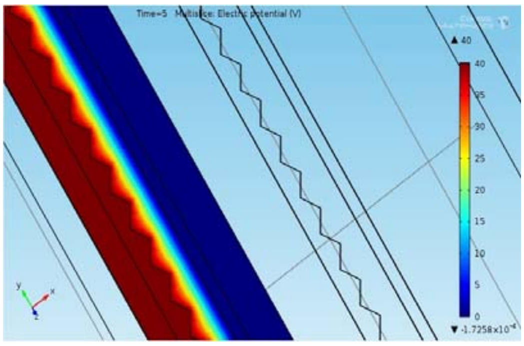


Figure 4. Electric Potential (V) gradient

The electric potential is minimum near the cathode and maximum at the anode. Due to 75-100 numbers of pairs of electrodes, the ion motion set between each pair of electrodes and the effective flow of liquid in that direction pumps the fluid from one direction to other.

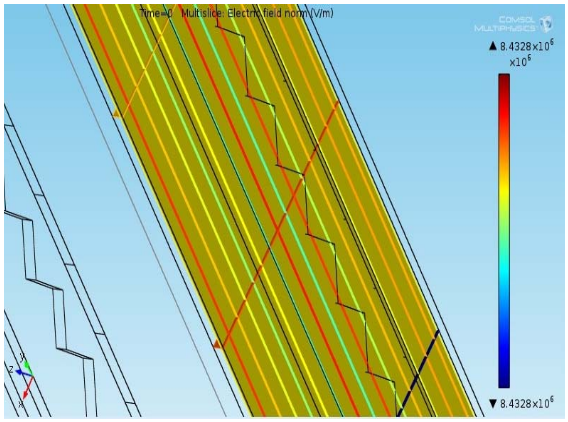


Figure 5. Electric Field (V/M) for Si-Au

Figure 6. Shows the direction of electric field vector for the pump over the surface.

Simulation in Figure 6 gives us minimum and maximum values of the Electric field Emax = 8.43×10^{12} V/m and Emin = 8.43×10^{6} V/m.

3.3 Variation in Electrode Thickness

As electrode thickness is increased, the cross section area of electrode increases. The resistance of a conductor is given as
$R = \rho * L/A$

Increase in A leads to decrease in R but at the same time we should consider the application of the pump and should optimize the thickness accordingly. Too much thick electrodes might not be suitable for some micro-scale applications and sometimes higher electrode thickness can also create obstruction for the flow of fluid or micro-particles.

For 10V, σ= 5.5e0, Au electrode

Metal Thickness (µm)	Tmax (K)	Tmin (K)
5	303.08	435.19
10	293.15	340.66

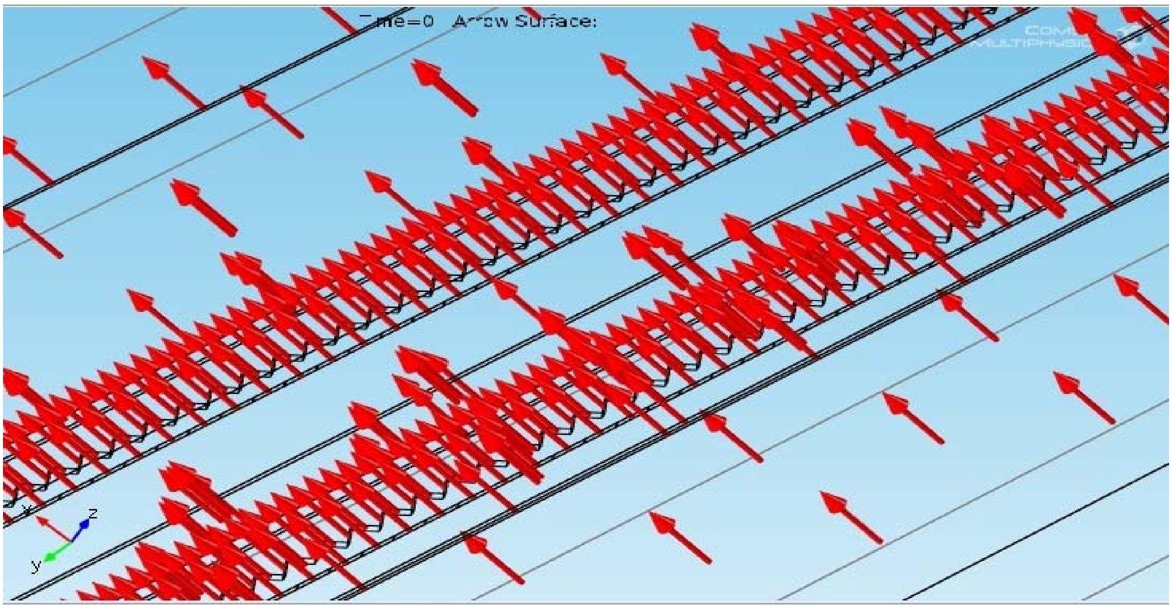


Figure 6. Electric field direction illustrating pumping mechanism

3.4 Calculating analytically approximate velocity of micro-spheres from electric field simulation:

Minimum and maximum electric field values we are getting from the simulations,
Emax = 8.43×10^{12} V/m and Emin = 8.43×10^{6} V/m

σ = 5.5e-4 S/m and V = 40V
q = 1.6×10^{-19} C

The distance between positive and negative terminal of the pump is dx = 20µm

$F = qE$
$F = ma = m \times v^2/(2 \times dx)$
$v^2 = (2 \times dx) \times q \times E / m$
$v = \sqrt{[(2 \times dx) \times q \times E / (m)]}$

For calculation of mass of microsphere, density of Polystyrene DVB microsphere is 1500kg/m^3
For a 5µm particle, m= 7.85x 10-13 kg
Substituting all values, we get,
v_{max} = 8.29m/s and v_{min} = 0.0082m/s

These velocity values are further used to model flow and pressure as shown in Figure 7. And Figure 8.

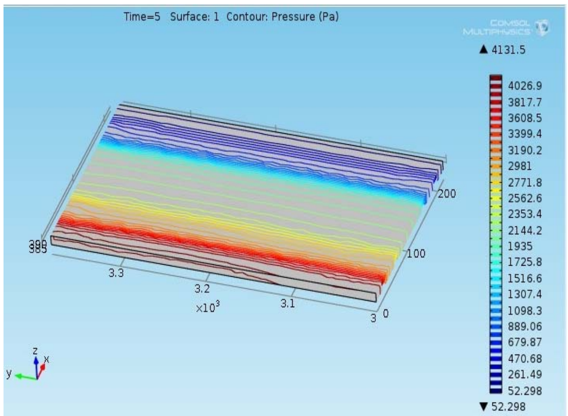


Figure 7. Pumping Pressure

7. Conclusions – Optimum Pump Design

From Joule heating simulations, we can conclude that minimum conductivity leads to minimum joule heating effect and maximum amount of ion-drag should be dynamically created by applied electric field. If any ions or free electrons are already present then they will contribute to increase in conductivity and in turn

Joule heating will occur. Thickness of electrode will help to decrease heating effect but that can put limitation on application and fabrication technology.

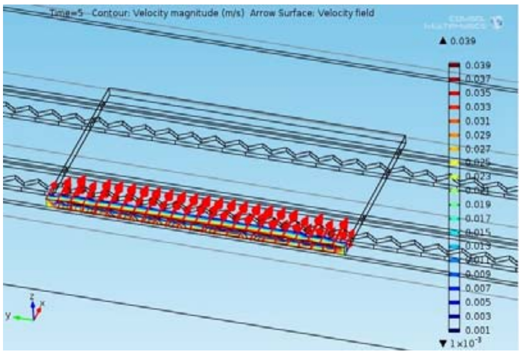


Figure 8. Velocity Direction

As fabricated by Darabi, J. and Wang, H.[9], triangular shaped electrodes lead to maximum electric field at tip of triangle due to less area and high voltage. Also, observed same results in Figure 5. Simulation. Uniform and parallel spacing of electrode pairs will lead to maximum velocity of flow of fluid as we can see in modeling of fluid flow and electric field, directions of electric field, flow and voltage gradient will lead to maximum resultant velocity vector. Material of electrode and substrate should be chosen wisely, after running simulations for desired application and should be suitable for the application environment.

5. Future scope and applications

Simple fabrication masking, low voltage, no moving parts, no vibration and wide variety of materials make EHD micro-pumps an ideal pump for variety of applications some of them include electrically actuated drug delivery, liquid pumping MEMS devices, on-chip cooling for integrated circuits [7]. The design fabricated and tested by Chia-Ling Chen [3] was done on flexible Parylene-C substrate which is suitable for drug delivery in human body. While silicon substrate based design makes it suitable for on-chip cooling applications. Power dissipation density in electronic circuits is increasing exponentially with rise in packaging density, in such cases having an on-chip or over-the-chip cooling device will surely benefit in subsiding the power dissipation. Non-moving MEMS devices will also lead to development of lab-on-chip devices where we can fabricate multiple MEMS devices over a single chip to perform certain desired function.

8. References

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