# Electrohydrodynamic Micropump Driven by Traveling Electric Fields

Jin-Woo Choi and Yong-Kweon Kim

## Abstract

A novel driving theory on the electrohydrodynamic(EHD) pump driven by traveling electric fields without the temperature gradient is proposed. The equations of the generating pressure and the flow rate are derived. The EHD micropump is fabricated by micromachining technology and tested. The channel heights are 50 $\mu$m, 100 $\mu$m and 200 $\mu$m respectively and the channel width is 3 mm. The spacing and width of the electrodes are both 40 $\mu$m. The maximum pressure is 70.3 Pa, 35.4 Pa and 17.2 Pa at the frequency of 0.2 Hz for each channel height (50 $\mu$m, 100 $\mu$m and 200 $\mu$m) and the maximum flow rate is $0.90\times10^{-1}$ $\mu\ell$/min, $1.88\times10^{-1}$ $\mu\ell$/min and $4.85\times10^{-1}$ $\mu\ell$/min at the frequency of 0.4 Hz for each channel height.

## I. Introduction

Electrohydrodynamic(EHD) pump transports fluid using the interactions between charges induced in the fluid and applied electric fields. EHD pump has such advantages that it doesnt need mechanical actuating parts and its structure of the pump is so simple[1-4].

The theoretical and experimental researches on EHD pump have been widely made since early 1960s. Stuetzer[3] and Pickard [4] proposed and studied the injection type EHD pump and Melcher[1, 2] proposed and studied the induction type EHD pump. Especially the Melchers one fluid temperature gradient model[2] is an interesting topic and many researchers such as Kervin[9], Seyed-Yagoobi[10], Bart[7], Fuhr[5] and Youn[11] have fabricated and experimented the EHD macro- or micropumps based on the Melchers theory. Some of those researchers, however, noted that the fabricated EHD pumps using the Melchers one fluid temperature gradient theory didnt accord to the Melchers theory and Youn[11] pointed out that the flow direction is always same to the direction of traveling electric fields.

In the Melchers temperature gradient driving theory, the fluid cannot flow if there is no temperature gradient and the direction of fluid flow depends on the sign of the temperature gradient between top and bottom of channel. If the geometry of the pump is out of accordance with the Melchers assumption (the electric field along the channel is negligibly small and the vertical direction electric field to the channel is dominant), the Melchers theory is not valid[11].

In this paper, a novel driving theory on the electrohydrodynamic(EHD) micropump is proposed and a micro EHD pump is fabricated on the basis of the proposed theory. The generating pressure and the flow rate are measured and the experimental results are discussed.

## II. Theory

D.C. current conduction and the associated EHD motion in dielectric liquid is a complex process. Generally the current vs. voltage curve is highly nonlinear and can be divided into three different regimes[12]. In the low field region, linear (ohmic) behavior is observed, which is mainly due to dissolved electrolytic impurities. In the intermediate field range around 20 kV/cm, the behavior is subohmic showing only a slightly increased current with increased voltage with a rise in field strength near electrodes. The conduction mechanism is this regime is mainly caused by ionic dissociation and the creation of heterocharges near the electrodes since the ions are no longer in equilibrium with the liquid due to their removal by the field. In the high field regime (about 100 kV/cm), current suddenly increases with increase in voltage due to the injection of ions from the electrodes into the liquid.

The electric field used in the paper is about in the intermediate field range. The heterocharges are generated on the electrodes. When the electric fields are traveling, the charges interact with the electric fields so that the fluid is moving in proportion as the charges are moving. Fig. 1 shows the schematic diagram of the

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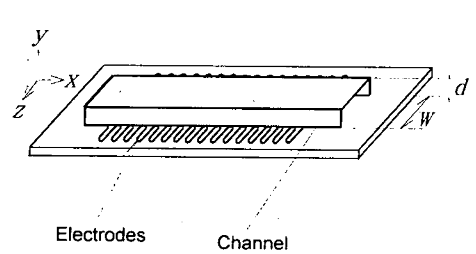



Fig. 1. Schematic diagram of the EHD pump.

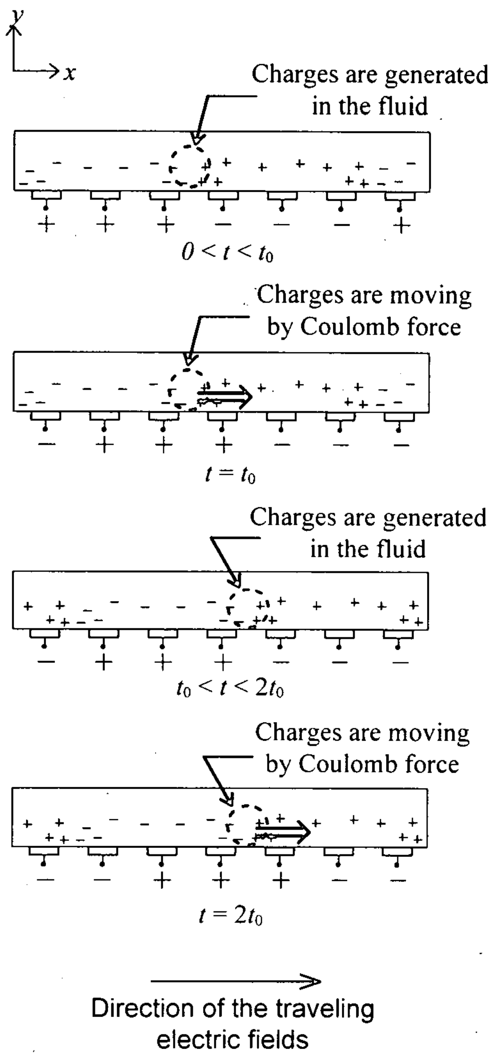



Fig. 2. Conceptual diagram of the EHD pump.

EHD pump and Fig. 2 shows the conceptual diagram about the charge distribution and the applied electric fields.

Six phase, 60 degree delayed, square traveling electric fields are applied. If the electric field is applied at $0 < t < t_0$ in Fig. 2, the volume charges are generated in the fluid around edges of the electrodes. The charges would be relaxed if the applied electric field is removed. Before the charges relaxed, the traveled electric field is applied during $t_o < t < 2t_0$. The induced charges in the fluid interact with the electric field. Also during $t_0 < t < 2t_0$, the new charges are generated around next edges (in Fig. 2, between the first and the second electrodes, the fourth and fifth electrodes etc.) of the electrodes due to the electric field in the time $t_0 < t < 2t_0$. The new induced charges will interact with the traveled electric field during $2t_0 < t < 3t_0$ and these processes take places over again. So the charges are moving continuously with relaxation and the fluid is moving with the charges movement.

The movement of the fluid depends upon how much charges are generated and how fast the electric field travels. However if the electric field travels so fast that the generated charges cannot go with the electric field. If so slowly that the number of times per unit time to move the fluid decreases, the fluid moves slowly. We should, therefore, apply the adequate frequency of traveling electric field, which is determined from the electric conductivity ($\sigma$) and the electric permittivity($\varepsilon$) of the fluid. The ratio the electric permittivity to the electric conductivity($\varepsilon / \sigma$) is the charge relaxation time($\tau$). As the value is smaller, the charges relax faster[2, 11].

Now we derive the theoretical equations. The instantaneous charge density is expressed by (1).

$$\rho(x, y, t) = \rho_0(x, y)(1 - e^{-\frac{1}{\tau}}) \tag{1}$$

where $\rho_0(x, y)$ is an initial charge.

At $t = t_0$ when the next state($t_0 < t < 2t_o$) electric field $\vec{E}(x - x_p, y)$ is applied, the induced charges are interacting with the traveling electric field and are dragged by the Coulomb force ($\vec{F} = \rho\vec{E}$). The generated force density between the induced charges and the traveled electric field is described as (2).

$$\vec{F}(x, y, t) = \rho(x, y, t_0)e^{-\frac{t-t_0}{\tau}}\vec{E}(x - x_p, y) \tag{2}$$

where $x_p$ is a pitch of the electrodes.

The generating instantaneous pressure $p(t)$ per one wavelength to the flow direction(positive $x$-direction) of the fluid is calculated by integrating the $x$-component of the force density,

$$p(t) = \frac{1}{d}\int_0^d \int_0^\lambda F_x(x, y, t)dxdy \tag{3}$$

where $\lambda$ is the wave length of the traveling electric field and d is the height of the channel. Because the instantaneous pressure has maximum values at $t = t_0, 2t_0, 3t_0, \cdots nt_0$, $p(t_0)$ could represent the generating pressure. We apply six phase (60 degree delayed) traveling electric field,

$$t_0 = \frac{T}{6} = \frac{1}{6f} \tag{4}$$

where $T$ and $f$ are the period and the frequency of the traveling electric fields, respectively. Hence from (2) to (4) $p_{max}$ is described as (5).

$$p_{\max} = (1-e^{-\frac{1}{6f\tau}})\frac{1}{d}\int_0^d \int_0^\lambda \rho_0(x, y)E_x(x-x_p, y)dxdy \quad (5)$$

In (5), we could introduce a constant $A$, defined as (6), which includes the charge density, the electric field and the geometry of the pump.

$$A = \frac{1}{d}\int_0^d \int_0^\lambda \rho_0(x, y)E_x(x-x_p, y)dxdy \quad (6)$$

Hence, we obtain the relation between the frequency and the pressure as (7).

$$p_{\max} \propto (1-e^{-\frac{1}{6f\tau}}) \quad (7)$$

Next, we derive the flow rate. The electrical stress tensor, $Txy^e$, in the channel is described as (8).

$$F_x(x, y, t) = \frac{\partial T_{xy}{}^e(x, y, t)}{\partial y} \quad (8)$$

The time average of the force density is calculated from (2).

$$\langle F_x(x, y, t)\rangle = \frac{\tau}{t_0}(1-e^{-\frac{t_0}{\tau}})^2\rho_0\vec{E}(x-x_p, y) \quad (9)$$

The velocity of the fluid is derived from (10).

$$\mu\frac{dv_x}{dy} + \langle T_{xy}{}^e(x, y, t)\rangle = 0 \quad (10)$$

where $\mu$ is viscosity of the fluid and $v_x$ is the x-component velocity of the fluid at height $y$ in the channel. From (8) to (10), the average velocity of the fluid is obtained as

$$v_{x,avg} \propto 6f\tau(1-e^{-\frac{1}{6f\tau}})^2 \quad (11)$$

Therefore the flow rate $Q$ is described as

$$Q = v_{x,avg}\cdot w\cdot d \propto 6f\tau(1-e^{-\frac{1}{6f\tau}})^2 \quad (12)$$

where $w$ and $d$ is the width and the height of the channel, respectively.

Fig. 3 shows theoretical relations of pressure and flow rate to a relaxation time and a frequency($f\tau$) of six phase traveling wave voltage applied to the pump.

In Fig. 3, as the frequency becomes low, the generating pressure increases. At low frequency the time is so long that much charges are generated in the fluid and they increase the force density. On the other hand, at high frequency, the time is too short to generate enough charges.

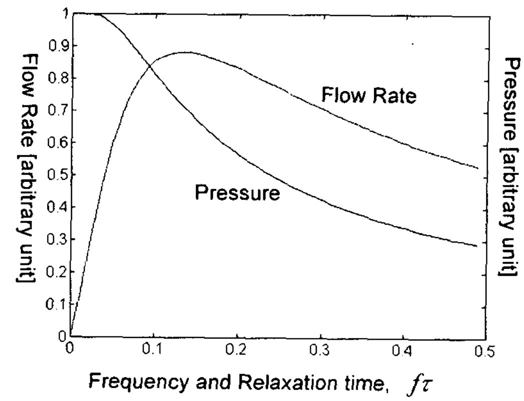



**Fig. 3.** Theoretical relations of pressure and flow rate to a frequency and a relaxation time.

As the frequency increases, the flow rate increases and has a maximum as shown in Fig. 3. It means that much charges are generated at low frequency so the force is strong but the number of times which drags the charges is small. At high frequency, the number is large but less charges are generated so the force is weak. Therefore the small flow rate appears at the both low and high frequency regions. The maximum flow rate is obtained at the frequency which is the same as the relaxation time of the fluid [2, 11].

## Ⅲ. EHD Micropump

An EHD micropump is fabricated using micromachining technology. The pump is composed of sixty electrodes and a channel. The electrodes and the channel are made of aluminum and etched silicon, respectively.

Fig. 4 shows fabrication processes of the electrodes and the channel. Aluminum is deposited on the Pyrex glass substrate and patterned using photolithography to make electrodes whose widths and distances are respectively 40 $\mu$m (Fig. 4 (a)-i) and thickness is 2000 Å. Polyimide is coated about 2 $\mu$m thickness as an insulating layer and patterned (Fig. 4 (a)-ii). To interconnect six phase electrodes (Fig. 4 (a)-iii), aluminum is deposited up to 8000 Å, and patterned (Fig. 4 (a)-iv). The channel of the pump is fabricated by etching of silicon wafer. Three types of channel are fabricated whose width is 3 mm and height is respectively 50 $\mu$m, 100 $\mu$m and 200 $\mu$m. The channel of the pump is fabricated by etching of silicon wafer. The glass substrate and the etched silicon wafer are bonded to make up the micropump. After the bonding process glass tube, whose inner diameter is 1 mm, is fixed at the inlet and outlet of the etched silicon channel.

Fig. 5 shows schematic view of the electrodes part of the pump and Fig. 6 shows the photograph of the fabricated EHD micropump.

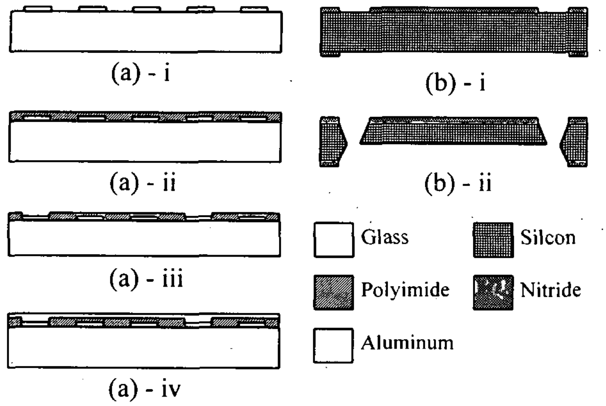



**Fig. 4.** Fabrication processes of electrodes and the channel.

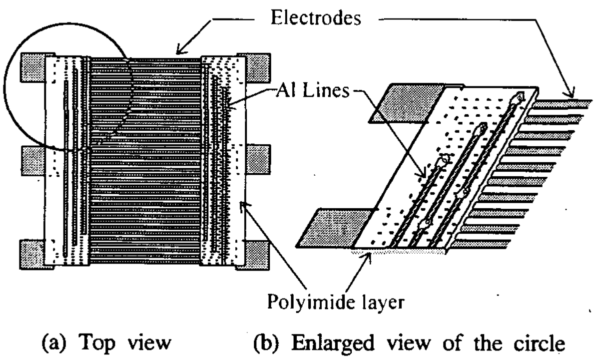



**Fig. 5.** Electrodes part of the EHD micropump.

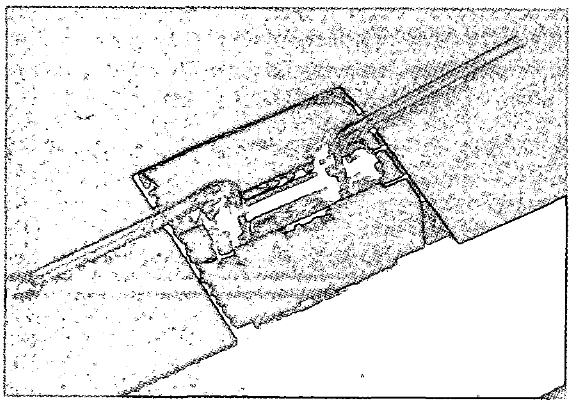


**Fig. 6.** Photograph of the fabricated EHD micropump.

## IV. Results and Discussion

The pressure and the flow rate are measured by observing the movement of the fluid-air interface in the glass tube through the microscope.

In Fig. 7, the pressure is measured from the displacement of height($h$, in Fig. 7) and in Fig. 8 the flow rate is measured from the displacement of the fluid-air interface per unit time. In both

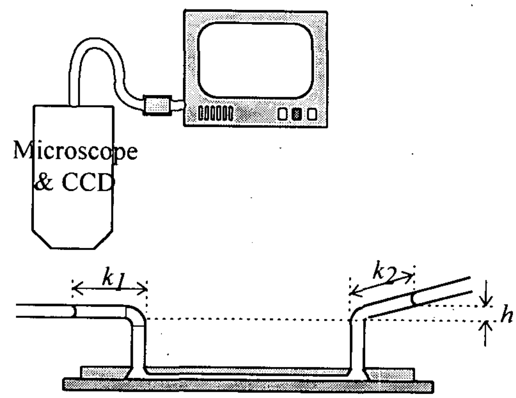



**Fig. 7.** Measurement system for the pressure to the frequency.

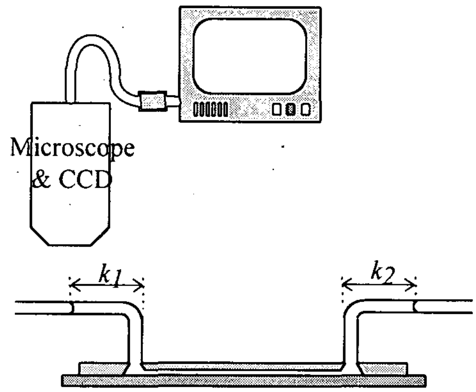


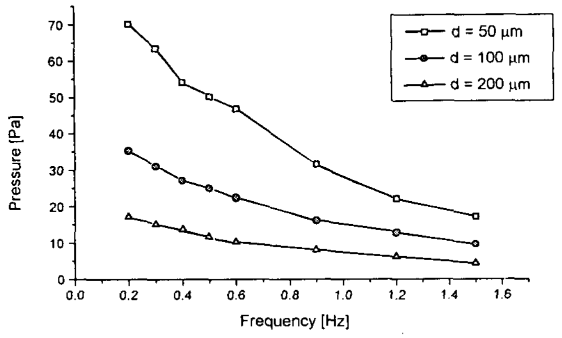

**Fig. 8.** Measurement system for the flow rate to the frequency.

Fig. 7 and Fig. 8 the length which is filled with the fluid, that is, $k_1 + k_2$ is maintained constantly through the experiments. Because the fluid in the glass tube works as only load that has an effect on experimental results.

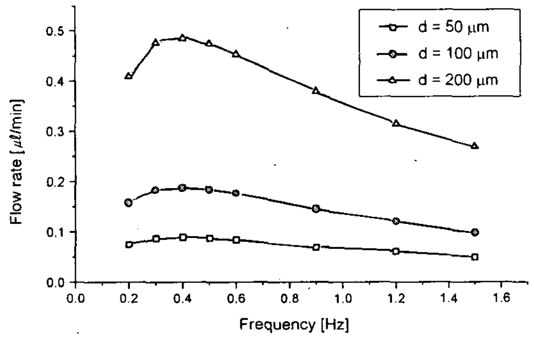
The pump is driven by six phase traveling electric fields. The magnitude of the voltage is 120 V, and the frequency varies from 0.2 Hz to 1.5 Hz. The electrical field strength between the electrodes is 60 kV/cm. The working fluid is corn oil. Its electrical conductivity and electric permittivity measured at 23℃ are $7.5 \times 10^{-11}$ mhos/m and 3.0, respectively[11]. The time constant $\tau$ (= $\varepsilon / \sigma$) is 0.34 sec at 23℃, and the flow rate has the maximum at 0.39 Hz.

The experiment is carried out at the temperature of 23℃. The measured pressure and flow rate to the frequency are shown in Fig. 9. The maximum generating pressure and the maximum flow rate are summarized in table 1. We observed that the flow direction of the fluid was the same direction to the traveling electric fields as mentioned in our previous work[11].

The pressure increases and the flow rate decreases as the channel height decreases. The low channel increases the force density because most charges in the fluid are generated near electrodes. On the other hand, the flow rate in a low channel




(a) The pressure vs. the frequency




(b) The flow rate vs. the frequency

**Fig. 9.** Experimental results of pressure and flow rate.

**Table 1.** The maximum pressure and flow rate to the various channel heights.

| Channel height | Maximum pressure (at 0.2Hz) | Maximum flow rate (at 0.4Hz) |
|---|---|---|
| 50㎛ | 70.3 Pa | $0.90\times10^{-1}$ μℓ/min |
| 100㎛ | 35.4 Pa | $1.88\times10^{-1}$ μℓ/min |
| 200㎛ | 17.2 Pa | $4.85\times10^{-1}$ μℓ/min |

decreases because a small amount of a fluid flows in a small cross sectional area of the channel.

## V. Conclusion

Non-uniform electric fields induce the volume charge density in the fluid, and the charges interact with traveling electric fields so that the fluid is transported with the movements of the charges. The flow direction of the fluid is the same as the direction of the traveling electric fields.

The EHD micropump was fabricated on the basis of the novel theory. The pressure and the flow rate were measured and discussed. The measured pressure was high and the measured flow rate was low in the low channel height.

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