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MICRO-ELECTROHYDRODYNAMIC PUMP BY DIELECTRIC FLUID: IMPROVEMENT FOR PERFORMANCE OF PRESSURE USING CYLINDRICAL ELECTRODES

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ABSTRACT

This paper presents the improvements for the performance of a micro-electrohydrodynamic (EHD) pump and the fundamental model theory based on unipolar charge conduction. The EHD pump was fabricated with thin stainless wires which are the diameter of 0.3mm. An electrode pair consisted of one emitter electrode and two collector electrodes. The distance between the emitter and the collector electrode in an electrode pair had a 0.2mm. Static pressure tests have been performed with a dielectric fluid. In order to increase the pressure performance, the electrode pair was increased from one to five at the distance between the electrode pairs, 2.0mm. As a result, it is found that the increase of the electrode pairs improve the pressure performance. The EHD pump produces a static pressure about 700 Pa with five electrode pairs using Dibutyl Sebacate. Both experimental and theoretical pressure results show a liner relationship. This linear relationship confirmed the unipolar conduction concept theoretically.

KEY WORDS

Electrohydrodynamic (EHD), Pump, Dielectric Fluid, Static Pressure, Cylindrical Electrode,

NOMENCLATURE

L : length, m
P : pressure, Pa
V : voltage, V
h : height, m
r : radius, m

ε : dielectric constant, F/m
μ_e : Ion mobility, $m^2/V\cdot s$
μ : Dynamic viscosity, $Pa\cdot s$
ρ : Liquid density, kg/m^3
σ : Electric conductivity, S/m

INTRODUCTION

With the advance of micro fabricated electro-mechanical devices, new applications such as micro pumps and micro actuators are expected. In these days, the electronic devices are demanded for reducing both volume and weight while increasing their complexity and power density. The micro pumps will be used in a micro fluidic pump in order to cool the electric devices. In micro-fabricated systems, the pumps without moving parts are of special interest. The electrohydrodynamic (EHD) pumps without vibration and dissipate power are electronically controllable and require no or little maintenance. These advantages make them attractive for applications in micro-systems.

The EHD pumps use the Coulomb force by unipolar charge conduction to produce high pressure in a compact design pump without moving parts. The charges on a dielectric fluid are charged and directly discharged on the surface of electrodes. The fluid molecules are charged with electrodes and derived by the electric field between electrodes in the EHD pump [1].

The fact that dielectric liquids can be pumped by the injection of ions in applied electric field between the electrodes has been known for some time. Indeed, the theoretical and experimental investigations of the EHD pump were widely pursued in early 1960's. Stuetzer [2] and Pickard [3], [4] were the fist researchers who proposed and studied the ion-drag EHD pump. Later, many researchers made further studies of the ion-drag EHD pump.

Crowley et al. [5] showed that high dielectric constant and low viscosity would lead to high flow velocity, while low electric conductivity and mobility would promote high efficiency.

With development of micro-fabricated technology, intense research efforts have been made toward micro-fluidic systems and micro-liquid handling devices [6], [7].

Otsubo et al. [8] used the jet flow produced by the injection of ions in Dibutyl Sebacate as the rotational power of motors. Yokota et al. [9] developed the micro-motors of a millimeter-scale outer diameter using Dibutyl Sebacate.

This paper presents the arrangements of the electrodes made by thin stainless wires to improve the pressure performance of the EHD pump (Figure 1). Also, this paper presents a fundamental model developed to design and characterization of the EHD pump.

EXPERIMENTAL SETUP

A photograph of the EHD pump is shown in Fig. 1. The overall dimensions of the micropump are 30×30×4.9 mm and of the pumping channel are 24×24×0.9 mm. The main body of the pump was made by the acrylic resin.

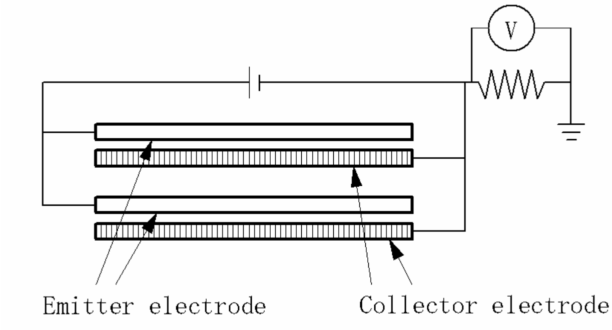
An arrangement of the electrodes is shown in Fig.2. The EHD pump was fabricated with the thin stainless wires which are the diameter of 0.3 mm. An electrode pair consists of one emitter electrode fixed on the center of the channel and two collector electrodes fixed on the channel walls. A distance between emitter and collector electrodes was 0.2 mm. The distance, *L*, between the electrode pairs was changed with 0.6, 2.0 and 3.4 mm. The number of the electrode pairs can be increased from one to five.

The static pumping tests of the EHD pump were performed with a Dibutyl Sebacate. This fluid has a relative dielectric constant, $\varepsilon / \varepsilon_0 = 4.8$ and a low electric conductivity, $\sigma = 4.7 \times 10^{-10}$ (S/m). Other properties of this fluid are listed on Table 1.

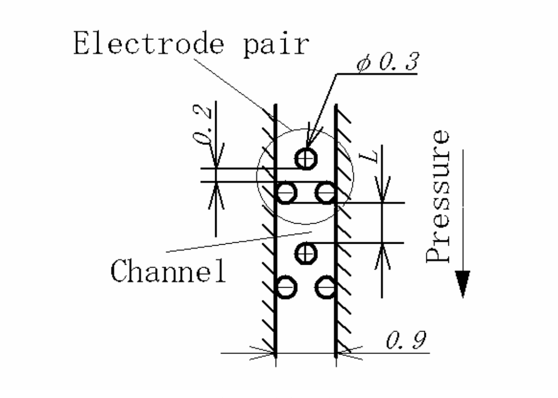
A positive DC-voltage (KIKUSUI Model PHS10K_10) was applied to the emitter electrodes. A voltage drop on a resistance (100 kΩ) inserted in negative electrode is monitored by a multimeter (YOKOKAWA Model 7562) and the electric current of the pump circuit can be calculated from the measured voltage and the resistance.

The outline drawing of static pressure measurement is shown in Fig. 3. The static pressure (zero flow rates) was measured using an inclined-tube manometer. The acrlic tubes for the inclined manometer have the inner diameter of 3 mm and the length of 1 m. All experiments were performed at a room temperature.

Figure 1 Top view of the EHD pump



(a) Top view



(b) Side view

Figure 2 Arrangement of the electrodes

Table 1 Properties of Dibutyl Sebacate

Properties	Dibutyl Sebacate ($C_{18}H_{34}O_4$)
Relative dielectric constant $\varepsilon/\varepsilon_0$	4.8
Electric conductivity σ [S/m]	4.7×10^{-10}
Ion Mobility μ_e [m^2/V·s]	2.1×10^{-9}
Viscosity μ [Pa·s]	9.4×10^{-3}
Liquid density ρ [kg/m^3]	940

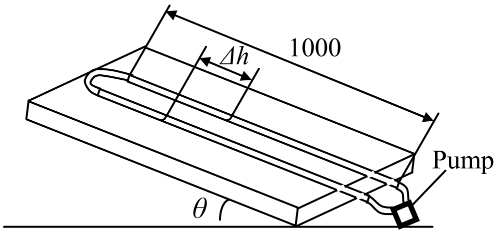


Figure 3 Outline drawing of static pressure measurement

EXPERIMENTAL RESULT

The static pressure of the EHD pump was determined the using Dibutyl Sebacate as working fluid. The electrodes and the pumping channel were cleaned with ethanol to avoid the contamination of the fluid with impurities. The applying voltage was varied such as 0.2, 0.4, 0.6, 0.8 and 1.0 kV. When the voltage was applied to the electrodes, the liquid lifted height was recorded, while the voltage was raised by steps. The maximum point of the liquid height was recorded, since the liquid lifted height tends to decrease with time.

The measurement of static pressure for the various distances between two electrode pairs, *L*, is shown in Fig. 4. The distance, *L*, is changed such as 0.6, 2.0 and 3.4 mm. The electrodes layout of the one electrode pair is labeled P1. The distance between the emitter and the collector is 0.2mm (Fig. 1). The other layouts labeled such as P2L0.6, P2L2.0 and P2L3.4, have two electrode pairs with the distance, *L*, of 0.6, 2.0 and 3.4mm, respectively.

The static pressure of P2L2.0 shows the highest performance in these experiments. Therefore, it is evident that the case of L=2.0 indicates the best performance. The static pressure for P2L2.0 is up to 340 Pa at applying voltage of 1 kV.

The static pressure results by increasing the number of electrode pairs are shown in Fig. 5. All of the electrode distance between the electrode pairs, L, is the same as 2.0 mm. The numbers of the electrode pairs are increased one to five in the EHD pump. We believe that the lager number of the pairs is the better pumping performance in this design. The static pressure for P5L2.0 was raised up to 700 Pa at applying voltage of 1 kV.

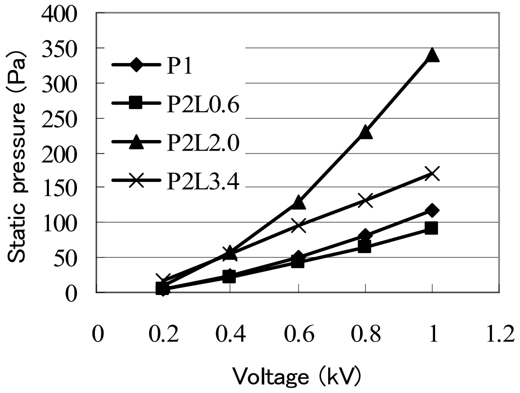


Figure 4 Static pressure as a function of applied voltage for the case of various electrode distances

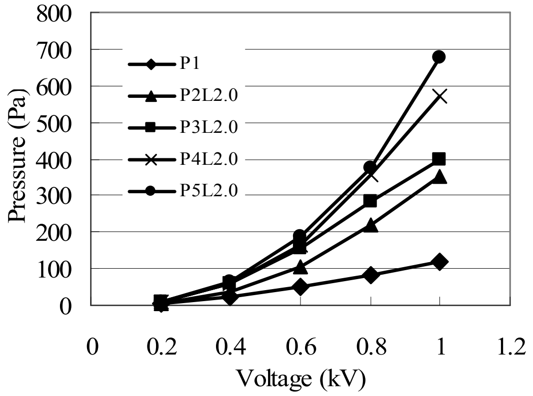


Figure 5 Static pressure as a function of applied voltage for the case of various number of electrode pairs

DISCUSSION

The simple formulas of the EHD pump for plane, cylindrical and spherical electrode were summarized by Stuetzer [2]. Stuetzer derived the static pressure of EHD pump with a cylindrical electrode as:

$$\Delta P \approx \varepsilon \left(\frac{V-V_0}{r}\right)^2 \log\frac{r}{r_0} \qquad (1)$$

where *P* is the pressure within the fluid, *V* is the appling voltage, ε is the permittivity and V_0 is the threshold voltage below which pressure is not obtainable. V_0 is assumed to be zero in this paper. r is the radius of between the electrodes and r_0 is the radius of a electrode. The main dimensional parameters of this arrangement are indicated in Fig. 6.

According to Eq. (1), the pressure of the EHD pump is proportional to the square of the electric field when the electrodes are fixed.

The pressure drop is generated at an electrode pair and between the electrode pairs. The pressure drop between the electrode pairs is generated to the opposite direction of the pressure drop generated at an electrode pair. Although the electric field between the emitter and the collector are slightly affected by the other electrodes, we assumed that the electric field between the emitter and the collector is not interfered by the other electrodes. The total pressure drop is exerted by the electric filed between the emitter and the collector. Then, we have:

$$\Delta P \approx \sum_{n=1}^{N} \varepsilon \left(\frac{V - V_0}{r} \right)^2 \log \frac{r}{r_0} - \sum_{n=1}^{N-1} \varepsilon \left(\frac{V - V_0}{r'} \right)^2 \log \frac{r'}{r_0} \qquad (2)$$

where r' is the radius between the electrode pairs and N is the number of the electrode pairs.

Figure 7 shows the comparison between the experimental and the theoretical values from Eq. (2). The relationships between experimental and theoretical pressure are not a liner except for P2L2.0, while we can expect that all relationships are linear from Eq. (2). The deviation from linear relationship would be caused by the impurities in the liquid.

Figure 8 shows the comparison between the experimental and theoretical pressure. The experimental pressures are the values in Figure 5 and the theoretical ones are from Eq. (2).

There are almost liner relationships between the experimental and the theoretical results. This linear relationship confirmed the concept of unipolar conduction theoretically. The results of pressure obtained with five pairs of the electrodes P5L2.0 show high performance. It is found that increasing the pair of the electrodes improve the pumping performance.

CONCLUSIONS

The improvement for the micro-EHD pump using the thin stainless wires was investigated and the static pressure generated by the pump was quantified. A fundamental theoretical model contributed to guide the design and characterization of EHD pump. The fundamental theory was based on a unipolar conduction model reported by Stuetzer [2]. The electrodes were consisted of several electrode pairs which have one emitter electrode and two collector electrodes. The number of electrode pair increased from one to five. The results of the static pressure demonstrated successfully the capabilities of the EHD pump. The EHD pump with five electrode pairs produced a static pressure drop about 700 Pa using Dibutyl Sebacate.

The relationship between the experimental and the theoretical pressure showed a linear relationship. For the same boundary conditions of the electrode, the static pressures were proportional to the square of electric field strength. This linear relationship confirmed the concept

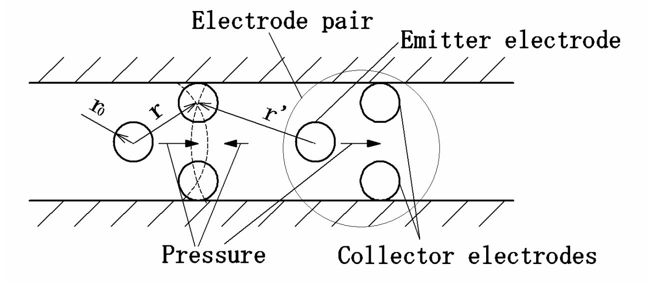


Figure 6 Arrangements and the parameters for cylindrical coordinates

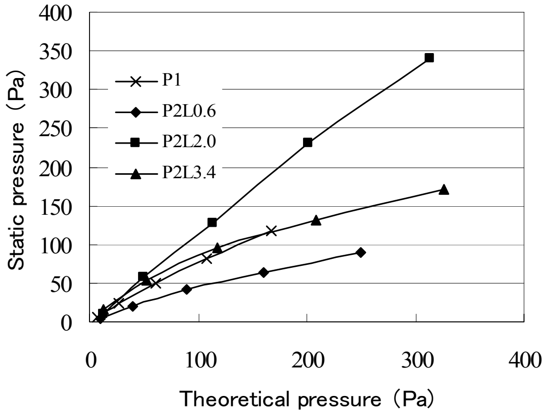


Figure 7 Relationship between experimental and theoretical pressure for the case of various electrode distances

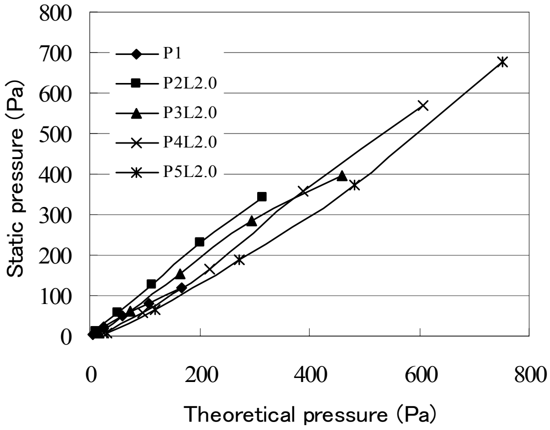


Figure 8 Relationship between experimental and theoretical pressure for the case of various numbers of electrode pairs

of unipolar conduction theoretically. As a result, it is cleared that the theoretical model is useful to design of the high performance EHD pumps.

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