Micro-Electrohydrodynamic Pump by Dielectric Fluid*

Ichiro KANO** and Yoshio KANO***

A Micro-Electrohydrodynamic (EHD) pump is tested experimentally. The EHD pump examined in this paper is fabricated with two cylindrical copper electrodes of the inner diameter 3 mm. The distance between electrodes was changed from 0.6 mm to 1.2 mm. In order to simplify the characterization of the pressure capacity of the EHD pump, the uniform electric field added in the gap between the cylindrical electrodes using aluminum disc electrodes (40 mm outer diameter). The static pressure and the mean velocity in a closed fluidic circuit were measured with Dibutyl sebacate as working fluid. The liquid has a dielectric constant, $\epsilon/\epsilon_0 = 4.8$ and a low electric conductivity, $\sigma = 4.7 \times 10^{-10}$ (S/m). The static pressure results are compared with the theoretical results. The theoretical model is based on the unipolar conduction which generates the space charge in the liquid. In this model, the Coulomb force can contribute to the EHD motion. The static pressure results show a linear relationship with the square of the electric field. This linear relationship supports the assumption that the unipolar conduction generates the pressure driving force. The estimation of the EHD pump efficiency based on the theoretical model is 18% with the electrode gap of 1.2 mm between the electrodes and 5% with the one of 0.6 mm.

Key Words: Pump, Pipe Flow, Electrohydrodynamics (EHD), Dielectric Fluid, Micro Pump, Ion Drag and Unipolar Charge

1. Introduction

The Electrohydrodynamic (EHD) pumps use the Coulomb force by the unipolar charge conduction to produce the high pressure without moving parts. The fact that dielectric liquids can be pumped by the injection of ions in an 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⁽¹⁾ and Pickard^{(2),(3)} were the first 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.⁽⁴⁾ 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-fabrication technology, intense research efforts have been made toward micro-fluidic systems and micro-liquid handling devices. In micro-fabricated systems, the EHD pumps without moving parts are of special interest. The EHD pumps produce no vibration, dissipate power, need no electrical controller and require no or little maintenance. These advantages make them attractive for applications in micro-systems.

Ootsubo et al.⁽⁵⁾ used the jet flow produced by the injection of ions in Dibutyl Sebacate as the rotational power of motors. Yokota et al.⁽⁶⁾ developed the micro-motors having a millimeter-scale outer diameter using Dibutyl Sebacate. However, they did not clear properties of this liquid and the mechanism of this jet flow phenomenon.

This paper presents the static pressure generated by the EHD pump and the mean velocity in a closed circuit pumped by the EHD pump. The EHD pump is fabricated with two cylindrical electrodes at several distances in which the electric field added uniformly. Also, the static pressure results are compared with a fundamental model reported by Pickard⁽²⁾ in order to study the characterization of the EHD. The motivation behind this study is to develop a fundamental understanding for the unipolar conduction pumping mechanism through the experimental results.

* Received 28th February, 2005 (No. 05-4015)

** Department of Mechanical Systems Engineering, Yamagata University, 4-3-16 Jonan, Yonezawa-shi, Yamagata 992-8510, Japan.
E-mail: tk306@dp.yz.yamagata-u.ac.jp

*** Environmental Research Institutes, Yamato Co., Ltd., 118 Furuichi-machi, Maebashi-shi, Gunma 371-0844, Japan.
E-mail: kano_yoshio@yamato-se.co.jp

2. Nomenclature

A	: Cross-sectional area (m^2)
D	: Diameter (m)
E	: Electric field (V/m)
i	: Current (A)
L	: Distance between emitter and collector (m)
P	: Pressure (Pa)
q	: Charge density (C/m^3)
u	: Velocity (m/s)
V	: Applied voltage of emitter (V)
x	: Axial length (m)
ε	: Permittivity (F/m)
η	: Dimensionless parameter
λ	: Pipe friction coefficient
μ	: Dynamic viscosity ($\text{Pa} \cdot \text{s}$)
ρ	: Liquid density (kg/m^3)
σ	: Electrical conductivity (S/m)
μ_i	: Ion mobility ($\text{m}^2/\text{V} \cdot \text{s}$)

3. Experimental Apparatus

The geometry and assembly of the EHD micro-pump are shown in Fig. 1. The EHD pump is fabricated with two pieces of copper tubes (3 mm inner diameter and 5.2 mm outer diameter). These electrodes are fixed to an acrylic pipe (8 mm outer diameter). In order to generate uniform electric field, two aluminum disk plates (40 mm outer diameter) are fixed to the acrylic pipe with the same distance between two copper cylindrical electrodes. The distances between the emitter and collector electrode are changed with 0.6, 0.9 and 1.2 mm. A voltage drop across the resistance (100 k Ω) inserted between the collector electrode and the ground is monitored by a multimeter (YOKOKAWA Model 7562) and the electric

Fig. 1 Schematic diagram of the pump

current through the pump can be calculated from the measured voltage and the resistance.

The static and dynamic pumping tests are performed using a Dibutyl Sebacate. This fluid has a 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 Table 1.

A positive DC voltage is applied to the emitter electrode by a electric power supply (KIKUSUI Model PHS10K-10) and the collector electrode is grounded. The power supply (1 000 V – 4 000 V DC) provides the necessary voltage to the EHD pump.

The closed fluidic circuit measurement system of the pressure under the static conditions (zero flow rates) and of the mean velocity under the dynamic conditions is shown in Fig. 2. When high voltage is applied, the working fluid is driven by the EHD pump. The static pressure is measured when the closed fluidic circuit is set inclined, that is, the inclined tube manometer. When the closed fluidic circuit is set horizontally, the mean velocity is measured by tracing a bubble flowing in the closed fluidic circuit. The inclined manometer is made by acrylic pipe of

Table 1 Properties of Dibutyl Sebacate

Fluid properties	Dibutyl Sebacate
$\varepsilon/\varepsilon_0$	4.8*
σ (S/m)	4.7×10^{-10} **
μ_i ($\text{m}^2/\text{V} \cdot \text{s}$)	2.2×10^{-9} ***
μ ($\text{Pa} \cdot \text{s}$)	9.3×10^{-3} ****
ρ (kg/m^3)	940****

*data entrusted to KEYCOM Corp.

** JIS C2101

*** based on Walden's Rule⁽⁴⁾: $\mu_i = \frac{2 \times 10^{-11}}{\mu} \text{ m}^2/\text{V} \cdot \text{s}$

**** data from ENCYCLOPAEDIA CHIMICA⁽⁸⁾

(b) Mean velocity measurements in a closed fluidic circuit

Fig. 2 Arrangements for the static pressure and velocity measurements

inner diameter 3 mm and of length 1 m. The length of tracing bubble is 50 mm. All experiments were performed at ambient temperature.

4. Results and Discussions

The static pressure and mean flow velocity in a closed fluidic circuit measurement were performed with the EHD pump using Dibutyl Sebacate as working fluid. The electrodes and the acrylic pipe were cleaned with ethanol to avoid the contamination of the fluid with impurities. When the voltage is applied to the electrodes, the liquid height and the velocity of the bubble were recorded.

Figure 3 shows the typical long-performance study of the static pressure for $L = 0.9$ mm and $V = 2.0$ kV. The static pressure is generated in the direction of the collector electrode. In order to investigate the effect of invisible vapor bubbles, the degassed and non-degassed liquid are compared in this figure. The static pressure of the non-degassed liquid shows significant long term degradation. The heat generated by the passage of the current between the electrodes can cause the formation of invisible small vapor pockets⁽³⁾. The vapor pockets generated in the non-degassed liquid affect either the pressure performance or the electrode emission. On the other hand, the pressure using the degassed liquid slightly decreases after three minutes. The slight decrease is provably due to the organic film. It is well known that the organic film is made on the surface of the electrodes by cationic and anionic polymerization⁽¹⁰⁾.

All the repeated data are required the fresh and degassed liquid for accuracy. In order to measure the stable static pressure value, the liquid height of the inclined manometer through all experiments is recorded at three minutes later from when the certain voltage is applied.

The static pressure results are shown in Fig. 4. The electrode gaps are 0.6, 0.9 and 1.2 mm, respectively. These pressure results are the average of three or more

Fig. 3 Typical long-term performance of the static pressure for $L = 0.9$ mm and $V = 2.0$ kV

measurements. The static pressure increases with increasing the applied voltage. For the electrode gap of 0.6 mm, the pressure shows higher performance as compared with the other electrode gaps of 0.9 and 1.2 mm above 3.5 kV. On the other hand, the pressure for the gap of 0.9 mm shows higher performance as compared with the other electrode gaps below 3.5 kV. Although the electric field, $E = -V/L$, for the electrode gap of 0.6 mm is higher than the other electrode gaps of 0.9 and 1.2 mm, the static pressure for the electrode gap of 0.6 mm shows lower performance below 3.5 kV. The lower performance of the static pressure for $L = 0.6$ mm is due to the lower pump efficiency based on the fundamental model. The relationship between the static pressure and the electric field and the pump efficiency will be discussed later. The maximum static pressure for the electrode gap of 0.6 mm is 130 Pa at applied voltage of 4.0 kV.

The measured current results as a function of the applied voltage are shown in Fig. 5. The current is measured simultaneously with the pressure measurements shown in Fig. 4. Although the measured current contains quite a bit of leak current flowing the surface of the acrylic resin between electrodes, we are able to recognize the char-

Fig. 4 Static pressure as a function of the applied voltage

Fig. 5 Measured current as a function of the applied voltage in case of the static pressure measurement

acteristic behavior of the current. The measured current increases in proportion to the applied voltage. For $L = 0.6$ mm, the current suddenly increases above 3.5 kV. The sudden increase of the measured current would appear to be that the change such as corona emission in vicinity of electrode surface is occurred because of the high electric field. The region of the sudden current increase would be considered as the prebreakdown region.

The mean velocity in the closed fluidic circuit for the electrode gap of 1.2 mm is shown in Fig. 6. In this measurement, the bubble velocity of the length of 50 mm flowing in the strait acrylic pipe is measured at three minutes later from when the certain voltage is applied. The mean velocity increases in proportion to the magnitude of the applied voltage. The mean velocity is about 1.2 mm/s at 3.5 kV.

The measured current as a function of applied voltage is shown in Fig. 7. The current is measured simultaneously with the mean velocity measurements shown in Fig. 6. The measured current increases in proportion to the applied voltage. The maximum current is 63 nA.

Fig. 6 Mean velocity as a function of the applied voltage for $L = 1.2$ mm

Fig. 7 Measured current as a function of the applied voltage for $L = 1.2$ mm in case of the mean velocity measurement

4.1 Fundamental theory of ion drag pumping

The electric body force, $\vec{f}_e$, can be expressed as follows⁽⁷⁾,

$$\vec{f}_e = q\vec{E} - \frac{1}{2}E^2\nabla\epsilon + \frac{1}{2}\nabla\left[E^2\left(\frac{\partial\epsilon}{\partial\rho}\right)\rho\right], \quad (1)$$

where q is the net electric charge density, $\vec{E}$ is the electric field, ϵ is the electric permittivity and ρ is the fluid density. The first term represents Coulomb force, which is the force acting on the free charges in an electric field. The second term is related to the electric permittivity gradient. The third term is relevant only for compressible fluids. In an isothermal single phase liquid, $\nabla\epsilon$ vanishes and Coulomb force result in the only mechanism for generating a permanent EHD motion.

There are two main mechanisms for generating a space charge in isothermal liquid. The first one is associated with the process of dissociation of the neutral electric species and recombination of the ions⁽⁹⁾. However, the dissociation and recombination process would not contribute the pumping effect since Dibutyl Sebacate shows low electric conductivity shown by Table 1. Furthermore, the liquid should be electrically neutral unless an impurity such as water or small bubbles is in the liquid. The second one is associated with the unipolar conduction^{(1)–(3)}. The unipolar conduction, which is usually called ion emission or ion drag, is the most plausible.

The liquid used in this paper has a characteristic of a positive unipolar conduction which is shown by experimental results in Fig. 4. In this figure, the static pressure is generated towards the collector electrode. The space charge is generated by the fluid molecules positively charged on the surface of the emitter electrode. Therefore, the pressure is generated by Coulomb force.

Pickard⁽²⁾ arrived at the following relation between the static pressure and the electric field intensity for the EHD pumping using a simplified model:

$$P = 9/8\eta\epsilon \cdot E^2 \quad (2)$$

$$E = -V/L \quad (3)$$

where P is the pressure, η , bounded between 0 and 1, is a coefficient which takes in account the influence of several factors, mainly the charge emission laws at the electrode, ϵ is the permittivity, E is the electric field, V is the potential differences between the electrodes and L is the electrode gap. The basic assumption in deriving the above equation was to use the two plane parallel electrodes.

The EHD pump model which is made reference to the experimental setup of Fig. 1 is arranged as shown in Fig. 8. The two axisymmetric circular plane electrodes with a hole are placed parallel to each other. The outer diameter of the circular plane electrode is 5.2 mm and the hole diameter is 3 mm. The dielectric liquid is filled between the electrodes. Neglecting the space charge effects, the electric

Fig. 8 Boundary arrangement

field is uniform between electrodes. Then, Eqs. (2) and (3) are applicable in the present model.

The pressure drop in the closed fluidic circuit shown in Fig. 2 (b) is generated mainly in two long straight pipes. Although the pressure drop is generated in the EHD pump and in the bend which connected between the two straight pipes, the pressure drop in both the EHD pump and the bend is smaller than the one in the straight pipe. Neglecting the pressure drop in both the EHD pump and the bend, the pressure drop of a laminar flow in the two straight pipes by the law of Hagen-Poiseuille is,

$$\Delta P = \frac{L}{D} \lambda \frac{1}{2} \rho \bar{u}^2, \quad (4)$$

$$\lambda = \frac{64}{Re}, \quad (5)$$

where D is the diameter of the straight pipe, λ is pipe friction factor, ρ is liquid density, $\bar{u}$ is the mean velocity in the pipe and Re is the Reynolds number.

4.2 Discussions

Equation (2) predicts a linear relationship between the static pressure and the square of electric field. In order to examine this linear relationship, we compare the static pressure in Fig. 4 with the square of electric field. The static pressure and the square of electric field at $V = 4.0$ kV are chosen as a reference value for both $L = 1.2$ mm and 0.9 mm. For $L = 0.6$ mm, the static pressure and the square of electric field at $V = 3.0$ kV are chosen as a reference value, since the current above 3.5 kV in Fig. 5 illustrate the pre-breakdown region. As shown in Fig. 9, there is a linear relationship between the static pressure and the square of the electric field. This linear relationship support that the unipolar conduction generates the pressure driving force.

Figure 10 shows the proportional factor of η calculated by Eq. (2) as a function of electrode distances, L . Each point represents a mean of data taken at different electrode distances. The proportional factor, η , increases in proportion to L . The proportional factor, η , is 18% at $L = 1.2$ mm and is 5% at $L = 0.6$ mm. This behavior was also reported by Picard⁽³⁾. Picard described that η is sensitive to the electrode distances in case of the small electrode distances because the space charges in vicinity of the emitter and collector electrode surface would overlap and reduce the pressure. In this case, the space charges were generated by the organic film which does not contribute

Fig. 9 Relationship between the static pressure and the square of the electric field

Fig. 10 Effect of the proportional factor η by the electric gaps Fig. 11 Pressure drop in the closed fluidic circuit compared with the static pressure for $L = 1.2$ mm

the generation of the pressure.

Figure 11 shows the pressure drop in two straight pipes calculated by Eq. (4) which is compared with the static pressure of $L = 1.2$ mm in Fig. 4. The mean velocity data in the closed fluidic circuits shown in Fig. 6 is used for calculating the pressure drop. The Reynolds number is from 0.07 to 0.4. It is clear that the static pressure is utilized for pressure drop in two straight pipes. However, the pressure

drop exceeds the static pressure at the high applied voltage. In case of the velocity measurement systems, impurities such as organic film in vicinity of the electrode surface produced by cationic and anionic polymerization will be swept out of the interelectrode volume⁽³⁾. This should tend to increase ion emission which increases the space charge density with the result that pressure drop exceed the static pressure.

5. Conclusions

The effect of the EHD pump performance based on unipolar conduction phenomenon has been investigated. The EHD pump was fabricated with two cylindrical copper electrodes. In order to compare the fundamental model, the uniform electric field added to the gap between the cylindrical electrodes using aluminum disc electrodes prepared near the cylindrical electrodes. The distance between electrodes has been changed from 0.6 mm to 1.2 mm. The pump provided a maximum pressure performance of 130 Pa at applied voltage of 4.0 kV. The mean velocity in the closed fluidic circuit which is consisted of two long strait pips provides a maximum mean velocity performance of 1.2 mm/s at 4.0 kV.

The measured current which was measured simultaneously with the static pressure measurement suddenly increases at the high applied voltage. This sudden increase indicated that the high electric field induced the prebreakdown phenomenon such as corona emission between the electrodes. Below this prebreakdown region, the static pressure and square of the electric field had a linear relationship. This linear relationship supported the assumption that unipolar conduction generated the static pressure.

The estimation of the EHD pump efficiency based on

the fundamental model was studied. It is cleared that the small electrode gap reduced the efficiency. The efficiency was 18% with the electrode gap of 1.2 mm and 5% with the one of 0.6 mm.

References

- (1) Stuetzer, O.M., Ion Drag Pressure Generation, *J. Appl. Phys.*, Vol.30, No.7 (1959), pp.984–994.
- (2) Pickard, W.F., Ion-Drag Pumping: I theory, *J. Appl. Phys.*, Vol.34, No.3 (1963), pp.246–250.
- (3) Pickard, W.F., Ion Drag Pumping: II Experiment, *J. Appl. Phys.*, Vol.34, No.2 (1963), pp.251–258.
- (4) Crowley, J.M., Wright, G.S. and Chato, J.C., Selecting a Working Fluid to Increase the Efficiency and Flow Rate of an EHD Pump, *IEEE Trans. Ind. Appl.*, Vol.26, No.1 (1990), pp.42–49.
- (5) Otsubo, Y. and Edamura, K., Dielectric Fluid Motors, *Appl. Phys. Letter*, Vol.71, No.3 (1997), pp.318–320.
- (6) Yokota, S., Kondoh, Y., Sadamoto, A., Otsubo, Y. and Edamura, K., A Micro Motor Using Electro-Conjugate Fluids (Proposition of Stator Electrode-Type (SE-Type) Micro ECF Motors), *JSME Int. J., Ser. C*, Vol.44, No.3 (2001), pp.756–762.
- (7) Melcher, J.R., *Continuum Electromechanics*, (1981), pp.3.1–3.26, MIT Press, Cambridge, MA.
- (8) Kagaku-Daijiten-Hensyuu-linkai, *ENCYCLOPAEDIA CHIMICA*, (in Japanese), Vol.5, (1993), p.369, Kyoritsu Press, Tokyo, Japan.
- (9) Atten, P. and Seyed-Yagoobi, J., Electrohydrodynamically Induced Dielectric Liquid Flow through Pure Conduction in Point/Plane Geometry, *IEEE Transactions on Dielectric and Electric Insulation*, Vol.10, No.1 (2003), pp.27–36.
- (10) Bockris, J. O'M., Devanathan, M.A.V. and Muller, K., On the Structure of Charged Interface, *Proc. Roy. Soc. London, Ser. A*, Vol.274, No.1356 (1963), pp.55–79.