A Pump using EHD Fluid

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One of an electrohydrodynamics (EHD) phenomenon is the induced flow of an EHD fluid in the presence of an electric field. In this paper, we describe a small pump in which the flow is generated by such an EHD phenomenon. In the case of pumps based on cylindrical electrodes, which thus far have been the focus of our research on EHD pumps, the total circumference length of the edge of the holes in the electrode that generates the rotational flow is small, leading to a small overall one-directional flow velocity. To investigate the influence of the total circumference length of the edge of the holes in the electrode, the area of the holes and the electric field intensity on pressure-flow rate characteristics, we produced ten different electrode pumps in which the electrode contains multiple holes. We measured the pressure-flow rate characteristics of our pumps and compared their performances.

Keywords: Electrohydrodynamics (EHD), Pump, EHD fluids, Flow visualization

1. Background/ Objectives and Goals

The induction of an EHD fluid flow through the application of an electric field is one of an electrohydrodynamics (EHD) phenomenon. In this paper, we describe a small pump in which the flow is generated by such an EHD phenomenon. Although EHD pumps have been studied in recent years, simplifying their structure to improve their efficiency and compactness remains an important challenge. Many electrode shapes were designed in various research organizations and have been tested. For example, mesh electrode pair was designed by Sakurai et al in Ashikaga Institute of Technology1), and Triangular-slit electrode pair was designed by Gu et al in Tokyo Institute of Technology2). However, it has not been lead to practical use yet and there is still room for the development in the structure of the EHD pump (e.g. electrode shape, distance between electrodes and width of electrode). To this end, in this study we focused our attention on the electrode shape, which is an important element of EHD pumps. Thus far, we have been researching EHD pumps based on cylindrical electrodes developed by our previous study3)4). For such a geometry, the total circumference length of the edge of the holes in the electrode that generates the rotational flow is small, resulting in a small one-directional flow velocity.

Therefor the multi-holes electrodes were developed to increase the circumference length5)6). We designed new pumps containing multiple holes in the electrode pair to produce the rotational flows. As the results, the pressure-flow rate characteristics was modified with the pumps. However the influence of the parameters on the characteristics is not clear because the area of the holes also increased with the length of the edge of the holes in the electrodes.

In the present study, our aim is to investigate the influence of the total circumference length of the edge of the holes in the electrode, the area of the holes and the electric field intensity on the pressure-flow rate characteristics. Our pumps are structurally simple, easy to fabricate, and the flow direction can be reversed by simply swapping the positive and negative electrodes. Previously, we used liquid crystal (MJ-0669, made by Merck company) as the EHD fluid in our pumps; however, due to its high cost, we decided to employ less expensive EHD fluids such as silicone oil and two hydrofluoroethers (HFE-7100 and HFE-7300, made by 3M company) in this study. We compared the behavior of various EHD fluids exhibiting the EHD phenomenon and selected the best performing fluid (HFE-7100) to investigate the pressure flow rate characteristics of the newly designed pumps.

2. Experimental apparatus

Ten types of multi-holes electrode pumps, termed Types I ~ X which are illustrated in Figs 1(a) ~ 1(j) respectively were manufactured. The disk electrodes used in the Type I pump contain seven holes (1 mm diameter), and those used in Type II contain nine holes (1 mm diameter) to reduce the flow resistance.
The distance between the electrodes of Type I and Type II were 1mm. Type III has nine holes (1mm diameter) and the distance between the electrodes was reduced to 0.4mm to increase electric field strength between the electrodes. Type IV has same electrodes of Type II and Type III. However, the distance between the electrodes was 0.2mm. Type V has 18 holes (0.5mm diameter) and distance between the electrodes was 1mm. Type VI has 36 holes (0.5mm diameter) and distance between the electrodes was 1mm. The number and the diameter of holes of Types VI~X are shown in Figs.1(f)~1(j). The electrode material was copper and the flow channel between the electrodes was produced from transparent acrylic resin.

As illustrated in Fig.2, an electric field was generated in the flow channel of the multi-hole electrode pair by connecting the cathode and anode of a DC power supply to electrodes A (left side) and B (right side), respectively. The one-directional flow generated by the electric field is caused by rotational flows.

A schematic depiction of the entire experimental apparatus is shown in Fig.3. In this Figure, H is the total pump head and θ is the angle of the acrylic board with respect to the floor. The multi-hole electrode pumps were connected in series using silicon pipes. The temperature of the EHD fluid was maintained at 30 ± 1 °C using a hot plate. The EHD fluid flow velocity was measured by recording the change in the fluid level in the discharge pipe of the pump with time, and the flow rate Q was calculated by multiplying the measured flow velocity by the cross-sectional area of the pump. When the flow rate was zero, the pressure was at its maximum value.

3. Results

From the flow visualization experiments using several EHD fluids, it is found that HFE-7100 exhibited the highest flow velocity because the relative permittivity is high and the kinematic viscosity is low compared with other EHD fluids. We therefore chose to use HFE-7100 to investigate the
characteristics of the multi-hole electrode pumps, as detailed below.

First, the maximum pressure and maximum flow-rate of Type I ~ Type X was investigated at 3.0kV. The experimental results are summarized in Table 1. However, in Type IV, the dielectric breakdown occurred at 3.0kV. Therefore, Type VI pumps were measured at 2.0kV.

We performed the investigation using two Type I pumps connected in series and measured the pressure-flow rate characteristics at 2.5kV and 3.0kV. We compared the pressure-flow rate characteristics to those previously measured using a cylindrical electrode pair pumps and liquid crystal as the EHD fluid by Tsukiji and Miyahara [4]. The results, shown in Fig.4, reveal that the plot of pressure-flow rate is approximately linear. Furthermore, approximate lines through the data (various dashed lines in the Figure) are translated in the direction of increasing pressure and flow rate when the applied voltage is increased. Therefore, it can conclude that the pressure and flow rate of the pump increase with the applied voltage. In addition, for the same applied voltage, the pressure and flow rate in the Type I pumps using HFE-7100 were higher than those in the cylindrical electrode pair pumps using liquid crystal. It was hypothesized that this is because the total circumference length of the edge of the holes that generates the rotational flow in the Type I pumps was larger (22.0 mm vs. 12.6 mm) than that of the cylindrical electrode pair pump. However, changing the EHD fluid from liquid crystal to HFE-7100 is also thought to have been a major factor.

Next, we performed the experiment using five Type I pumps connected in series and measured the pressure-flow rate characteristics at 3.0kV. A comparison of the results with those previously measured using a cylindrical electrode pair pumps and liquid crystal as the EHD fluid by Tsukiji and Miyahara [4]. The results, shown in Fig.4, reveal that the plot of pressure-flow rate is approximately linear. Furthermore, approximate lines through the data (various dashed lines in the Figure) are translated in the direction of increasing pressure and flow rate when the applied voltage is increased. Therefore, it can conclude that the pressure and flow rate of the pump increase with the applied voltage. In addition, for the same applied voltage, the pressure and flow rate in the Type I pumps using HFE-7100 were higher than those in the cylindrical electrode pair pumps using liquid crystal. It was hypothesized that this is because the total circumference length of the edge of the holes that generates the rotational flow in the Type I pumps was larger (22.0 mm vs. 12.6 mm) than that of the cylindrical electrode pair pump. However, changing the EHD fluid from liquid crystal to HFE-7100 is also thought to have been a major factor.

Next, we performed the experiment using five Type I pumps connected in series and measured the pressure-flow rate characteristics at 3.0kV. A comparison of the results

| No. | Type I | Type II | Type III | Type IV | Type V | Type VI | Type VII | Type VIII | Type IX | Type X |
|-----|--------|---------|----------|--------|--------|---------|----------|-----------|---------|--------|
| The number of holes | 7 | 9 | 9 | 9 | 18 | 36 | 15 | 12 | 16 | 25 |
| Diameter of holes (mm) | 1 | 1 | 1 | 1 | 0.5 | 0.5 | 0.6 | 0.75 | 0.75 | 0.6 |
| Width of electrode (mm) | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Distance between electrodes (mm) | 1 | 1 | 0.4 | 0.2 | 1 | 1 | 1 | 1 | 1 | 1 |
| Length of total circumference (mm) | 22.0 | 28.3 | 28.3 | 28.3 | 28.3 | 56.5 | 28.3 | 28.3 | 37.7 | 47.1 |
| Total area of the holes (mm²) | 5.5 | 7.1 | 7.1 | 7.1 | 3.5 | 7.1 | 4.2 | 5.3 | 7.1 | 7.1 |
| Ratio of the holes (%) | 43.75 | 56.25 | 56.25 | 56.25 | 28.125 | 56.25 | 33.75 | 42.19 | 56.25 | 56.25 |
| Maximum pressure (Pa) | 75.6 | 174.6 | 387.3 | 521.4 (2.0kV) | 178.6 | 223.4 | 175.1 | 175.1 | 193.6 | 208.5 |
| Maximum flow rate (cm³/min) | 9.42 | 10.7 | 28.3 | 33.9 (2.0kV) | 8.07 | 10.8 | 8.31 | 9.42 | 10.7 | 10.7 |
with those of the two-type I setup is shown in Fig.5. Both pressure-flow rate plots are approximately linear, but the maximum pressure was about 2.5 times higher (188.9 Pa vs. 75.6 Pa) for the five-pump setup. We therefore concluded that the pressure is directly proportional to the number of pumps.

![Fig.4 Influence of voltage on pressure](image)

![Fig.5 Influence of the number of pumps on pressure](image)

The pressure-flow rate characteristics of the two pumps also were measured at an applied voltage of 3.0 kV using HFE-7100 as the EHD fluid. Typical results comparing Type I and Type II pumps are shown in Fig.6. From the results shown in Fig.6, it was noticed that when the number of holes was increased, both the pump pressure and flow rate increased. Therefore, we can conclude that the pressure and flow rate of Type II pump were larger than those of Type I pump because the total circumference length of the edge of the holes to generate rotational flows of Type II pump was also larger.

![Fig.6 Flow rate-pressure data comparing Type I and Type II pumps](image)

The pressure-flow rate characteristics of the two pumps also were measured at an applied voltage of 3.0 kV using HFE-7100 as the working fluid. Typical results comparing Type II and Type III pumps are shown in Fig.7. Both pumps were produced using the electrode of nine holes (diameter 1 mm). Type II has 1 mm of the distance between the electrodes, however, Type III has only 0.4 mm of the distance between the electrodes. Thus, electric field strength of Type III pump was stronger than that of Type II pump. Therefore, it was expected that the pressure and flow rate of Type III pump was larger than those of Type II pump. From the results shown in Fig.7, as expected the pressure and flow rate of Type III pump was larger than those of Type II pump. It was noticed that when the distance of between the electrodes was decreased, both the pump pressure and flow rate increased. The electric field strength increases when the distance of between the electrodes is reduced. Therefore, it can conclude that the pressure and flow rate increased because the electric field strength increased. In addition, it was noticed that the plot of pressure-flow rate is approximately linear. Furthermore, approximate lines through the data (various dashed lines in the Figure) are translated in the direction of increasing pressure and flow rate when the distance of between the electrodes is reduced.

![Fig.7 Flow rate-pressure data comparing Type II and Type III pumps](image)

Next, results of maximum pressure and flow rate comparing Type II, Type III and Type IV pumps are shown in Fig.8 and Fig.9. However, in Type IV, the dielectric
breakdown occurred at 3.0kV. Therefore, Type IV pumps were measured at 2.0kV. Because applied voltages were different, it was evaluated by electric field strength not the distance between the electrodes. Electric field strength was determined by dividing applied voltages by distance between electrodes. From the Fig.8 and Fig.9, it was found that the maximum pressure and maximum flow-rate were increased almost linearly by increasing electric field strength. It is possible that maximum pressure and maximum flow-rate is increased by increasing electric fields strength.

![Fig.8 Maximum pressure on the electric field strength](image)

Next, typical results comparing four pumps (Type II, Type VI, Type IX and Type X) with different total areas of the holes are shown in Fig.10. Maximum pressure of four pumps for no flow are almost same, however maximum flow rate are different.

The relation between the total area of the holes of the electrodes and maximum pressure is shown in Fig.11. From comparative results of the Type II, Type VI, Type IX and Type X, it was found that it is possible to increase the maximum pressure by increasing length of total circumference of the holes of electrode under condition of same total area of the holes of the electrodes.

From the above results, it can be concluded the pressure and flow-rate of multi-holes electrode pair pump can be increased by increasing length of total circumference of the holes of electrode, increasing the total area of the holes of the electrodes and decreasing the distance between the electrodes.

These pumps are aimed at small-size liquid-cooled cooling system. For this purpose, it is necessary to pressure

![Fig.10 Flow rate-pressure data](image)

![Fig.11 Total area of the holes-maximum flow rate data](image)
of at least a few kPa. However, these pumps have not reached its pressure. Therefore the further improvement of the pump shape is necessary.

**Fig.12 Flow rate-pressure data**

**Fig.13 Length of total circumference -maximum pressure data**

**4. Conclusions**

We produced multi-hole electrode EHD pumps, and investigated the pressure-flow rate characteristics using HFE-7100. The conclusions of this study are as follows:

1. Using HFE-7100 as the EHD fluid in the multi-hole electrode pair pump, an approximately linear relationship was found between the pressure and flow rate. Both of these quantities increased proportionally with an increase in the applied voltage.

2. The pressure and flow rate of the multi-hole electrode pair pumps using HFE-7100 were larger than those of the previously studied cylindrical electrode pair pumps using liquid crystal for the same applied voltage.

3. The maximum pressure of the five Type I pumps connected in series was about 2.5 times that of the two Type I pumps connected in series. In other words, the maximum pressure is directly proportional to the number of pumps.

4. When the distance of between the electrodes was decreased, both the pump pressure and flow rate increased because the electric field strength between the electrodes increased.

5. It is possible to increase the maximum flow rate of the pump by increasing the total area of the holes of the electrodes at the constant length of total circumference of the holes.

6. It is possible to increase the maximum pressure of the pump by increasing length of total circumference of the holes of the electrodes at the constant total area of the holes of the electrodes.

**Acknowledgments**

The authors thank the Techno center of Sophia University for their generous support.

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