

BASIC CHARACTERISTICS OF A LIQUID CRYSTAL PUMP

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ABSTRACT

A flow visualization of a liquid crystal was conducted under the application of an electric field in a mini cylinder with electrode strips on the inner surface. Three-phase alternating currents were used as rotation electric fields to generate the rotational flow of the liquid crystal. A pump with a spiral flow channel was designed based on the rotational flow mechanism of the liquid crystal by using the three-phase alternating currents. The pressure-flow rate characteristics of the pump were measured and the characteristics for the length and the shape of the flow channel in the pump were investigated for various amplitudes of electric fields. The pressure increased when we used a liquid crystal with a high dielectric constant and a high kinematic viscosity for the constant voltage. Dimensional analysis was conducted to arrange the characteristics of the present pump simply and the non-dimensional flow rate and pressure were almost on one line. The size of our pump can be decreased by further research. This study contributes to the development of a micro-pump in micro-fabricated systems and our pump eliminates mechanical vibration and noise.

KEY WORDS

Functional Fluid, Pump, Flow Visualization, Pressure, Flow Rate

NOMENCLATURE

D : total length of flow channel, 0.04945m
 E : electric field intensity, ($=V \text{ volt}/(0.9 \times 10^{-3})\text{m}$)
 g : acceleration due to gravity, 9.81m/s^2
 H : total head, m
 p : pressure, Pa
 p_m : maximum pressure, Pa
 Q : flow rate, mm^3/min
 w : channel width, mm
 α : angle between the electric rotation direction and the flow direction in a spiral direction
 ε_{para} : dielectric constant of the parallel direction to longitudinal direction of the liquid crystal molecule, F/m
 ε_{per} : dielectric constant of the vertical direction to

longitudinal direction of the liquid crystal molecule, F/m

ε_1 : dielectric constant of insulating part (polyimide film) in the cylinder electrode, Relative permittivity of 3.57 was used ($\varepsilon_1=3.16 \times 10^{-11}$ F/m), F/m

μ : viscosity, Pa · s

ρ : density, kg/m^3

INTRODUCTION

Research has actively been undertaken to provide a better understanding of pump dynamics. Diaphragm- and micro-syringe pumps are typical examples of a mechanical micro-pump [1,2] and the other mechanical micro-pumps are developed recently[3,4]. The advantage of these pumps over conventional ones is that they can

be used to pump any liquid or gas. However, they are difficult to micro-fabricate and assemble because they contain many parts, so research is currently being conducted to develop low-noise pumps that use functional fluids and have simplified designs with no sliding parts. Such a micro-pump would have various applications. For example, it could be used in power sources of equipment that supply liquid, cooling systems, micro machines, and supplying fuel to the ultra-micro gas turbine. For this wide range of applications, various micro-pumps are needed to enable its use in any environment and under any conditions. Therefore, various micro-pumps are being designed and are actively being studied. The system with fluid control type would be used widely in micro fields because of the decreased number of parts and the sliding part using the fluid drive by the characteristic of the functional fluid. The properties of functional fluids can be controlled by electric or magnetic fields. Typical fluid pumps use some flow mechanisms, including ion drag [5], electro hydro dynamics (EHD) [6,7], electro-conjugate fluid (ECF) jets[8,9] and electroosmotic flow[10].

In this study, we developed a pump based on the flow of liquid crystals [11] in typical functional fluids by applying an electric field. Rotation electric fields were applied to the electrodes in the pump to add voltage to the fluid, and the flow was induced by the dielectrophoresis[12-16] of liquid crystals. We designed the pump based on the mechanism [17] and subsequently measured the pressure and the flow rate. Especially the effect of the length of the flow channel and the angle between the pump axis and the flow channel direction on the flow rate and the pressure is reported in this paper. Our pump can be also used to transport liquid crystal or to fill a gap of panels for a display with a liquid crystal.

PROPERTIES OF LIQUID CRYSTALS AND FLOW VISUALIZATION

The characteristics of the liquid crystals used in our study are listed in Table 1. The MLC6650, K15, and MJ0669 were provided by Merck Ltd., Japan. K15 is a nematic liquid crystal. MLC6650 and MJ0669 are liquid crystal mixtures mixed with some nematic liquid

Table 1 Physical properties of liquid crystals

	MLC6650	K 15	MJ0669
Operating Temperature Region (°C)	-44~99	23.1~35.5	(-10)~45.9
Kinematic viscosity (mm ² /s) (25°C)	59.7	22.4	11.0
Dielectric constant (F/m) (relative permittivity) ϵ_{per} (20°C)	9.0×10^{-11} (10.2)	5.3×10^{-11} (6.0)	3.5×10^{-11} (3.9)
Dielectric constant (F/m) (relative permittivity) ϵ_{para} (20°C)	55.6×10^{-11} (62.8)	23.1×10^{-11} (26.1)	9.9×10^{-11} (11.2)
Density (kg/m ³) (25°C)	1099	1020	947

crystals. The value of the kinematic viscosity, the dielectric constant and the density is large in the order of MLC6650, K15, and MJ0669.

As the first stage of our experiment, a flow visualization of the liquid crystal was conducted under the application of the electric field in the cylinder electrode. The purpose of this visualization is to confirm the generation of the rotational flow and the flow direction of the liquid crystal. The cylinder electrode with 9 electrodes was used. The inner diameter of the electrode for flow visualization is about 6mm.

The cylinder electrode for flow visualization is shown in Fig.1. Three-phase alternating current is applied to the cylinder electrode in order to apply the voltage on the liquid crystal. Three-phase alternating current is shown

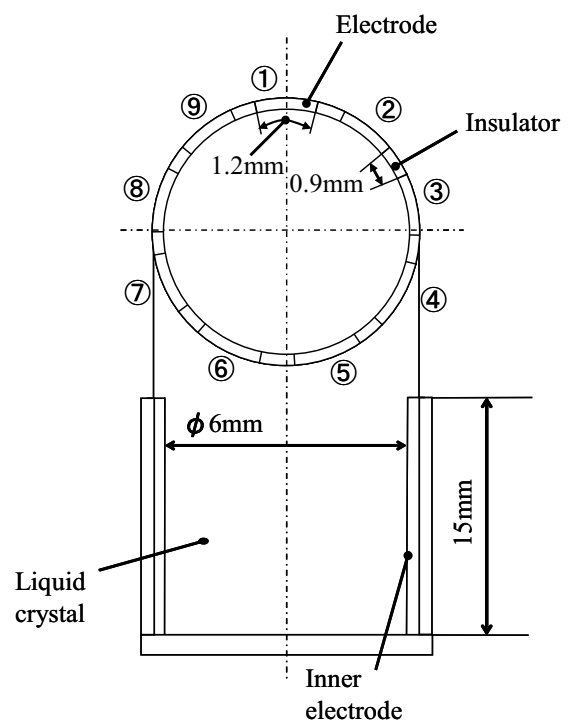


Fig.1 Cylinder electrode

in Fig.2. The voltage curves ①, ② and ③ (④, ⑤ and ⑥ or ⑦, ⑧ and ⑨) come in that order. The voltage is applied in the clockwise direction in Fig.1. Therefore, the electric fields appear to rotate on the cylinder electrode.

The experimental apparatus for flow visualization is shown in Fig.3. In this experiment, the frequency of a voltage wave of three-phase alternating current is 50Hz and the voltage means the effective value. A 50-Hz, 200-V three-phase alternating current is input to a voltage transformer. An output voltage between 0 and 240 V is generated using this voltage transformer. Next, the amplitude of the output voltage is amplified about 15

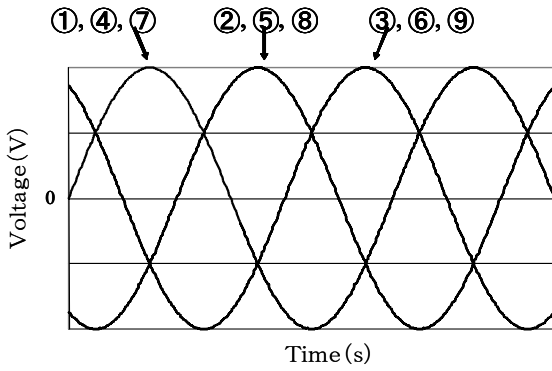


Fig.2 Three-phases alternating voltage

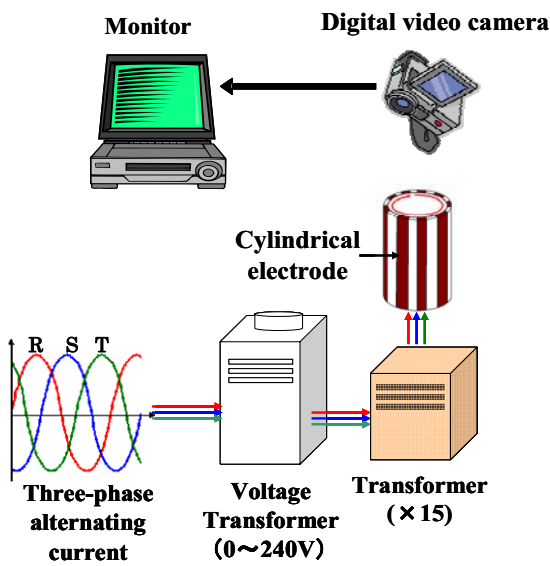


Fig.3 Experimental apparatus for visualization

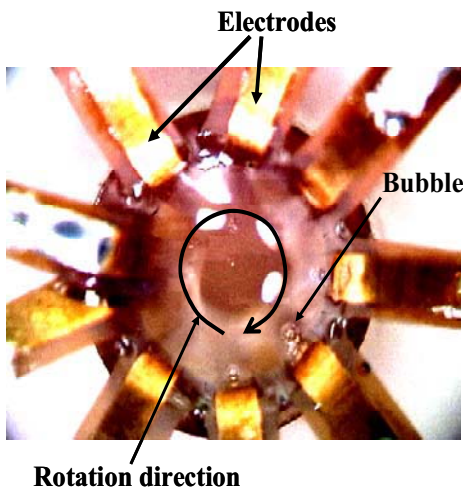


Fig.4 Visualization result for MJ0669

times using the transformer, and the resulting voltage is

applied to the electrodes. The flow of the liquid crystal in the cylinder is observed in the axial direction using a commercially digital video camera. The surface of the liquid crystal is almost flat.

A picture of a liquid crystal flow in cylinder electrode is shown in Fig.4. The voltage is 1000V. A liquid crystal rotated same rotation direction of the electric fields. The

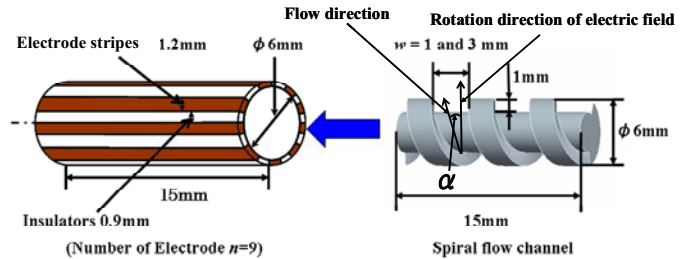


Fig.5 Pump

flow of the liquid crystal is observed by measuring trajectories of bubbles which is indicated by an arrow in the cylinder electrode. The rotational flow and the flow direction of the fluid were confirmed in the present experiment.

EXPERIMENTS FOR PUMP

The electrodes around the flow channel used in the experiment are shown on the left side in Fig. 5. Rotational flow is obtained by applying a three-phase alternating current to the electrodes as described in the previous chapter. The electric fields appear to rotate on the cylinder electrode. The frequency of the voltage wave of the three-phase alternating current is 50 Hz.

The pump consists of a spiral flow channel wrapped inside nine electrodes. The width of the electrodes is 1.2 mm, and the inter electrode distance is 0.9 mm. The

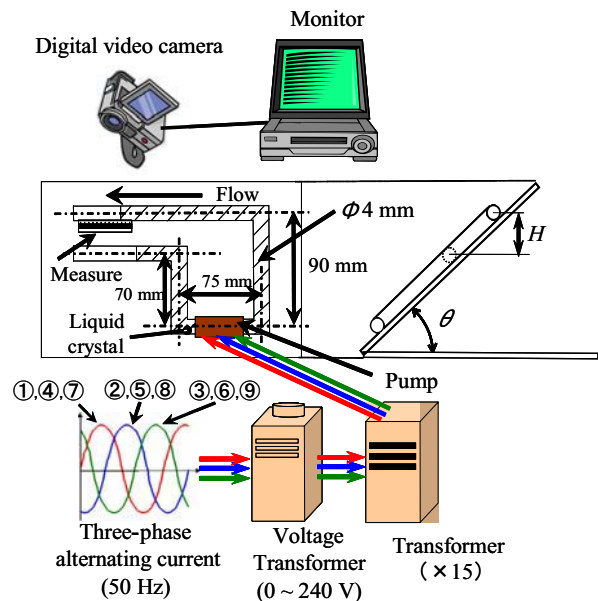


Fig.6 Experimental apparatus for pump

flow channel length in the axial direction is 15 mm, the diameter of the flow channel is 6mm, the channel widths are 1 and 3 mm, and the channel depth is 1 mm. α is the angle between the electric rotation direction and the flow direction. The rotational flow of the liquid crystal is obtained by applying the three-phase alternating current to the electrodes. Therefore, the liquid crystal in the cylinder electrode flows along the flow channel. As a result, the liquid crystal flows in the axial direction of the pump. We designed the pump based on these mechanisms for our study.

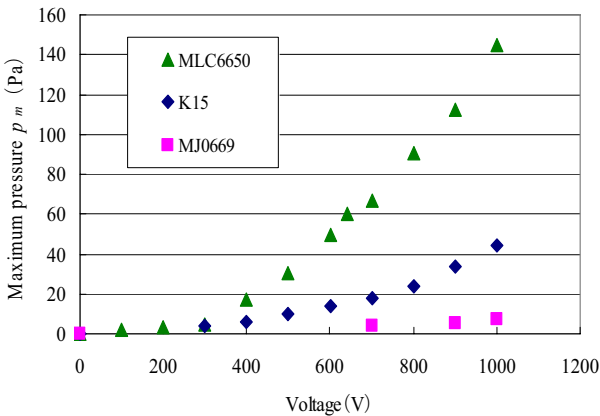


Fig. 7 Relationship between the voltage and the maximum pressure (3turns and $w=3\text{mm}$, $\alpha=17.7^\circ$)

The experimental apparatus is shown in Fig.6. The

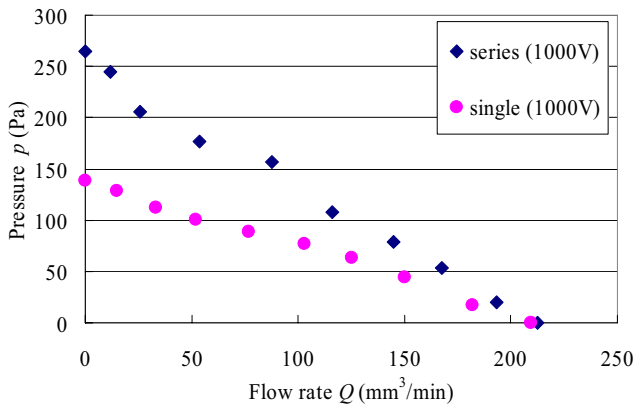


Fig.8 Relationship between the flow rate and pressure (3turns, $w=3\text{mm}$, $\alpha=17.7^\circ$, MLC6650)

electric circuit is the same as the case of the flow visualization test shown in Fig.3. As a maximum total head is 20mm in this experiment, a maximum pressure is about 200Pa. The voltages between 0 and 1000 V were applied to measure in the above pressure range. A maximum total head is 40mm only for series pump. The flow rate was measured when the total head, H , was changed. To measure the flow rate, we first took a video

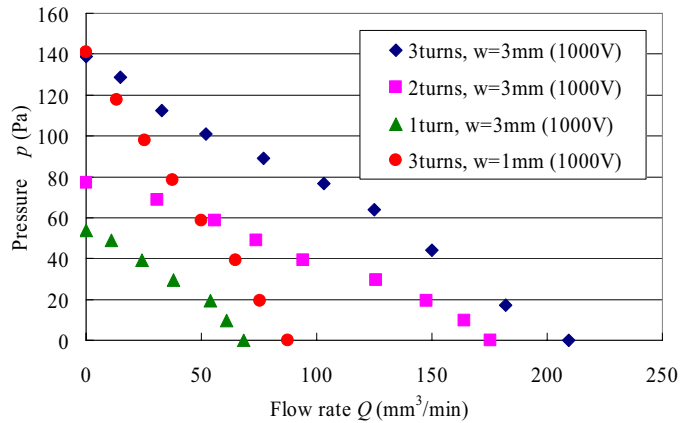


Fig.9 Relationship between the flow rate and pressure ($w=1, 3\text{mm}$, MLC6650)

of the movement of the free surface of the liquid crystal in a pipe whose inner diameter is 4 mm. The video was taken from the direction vertical to the plate. We then enlarged the images in the video to see the flow clearly. The maximum pressure, p_m , is defined without the flow. The maximum pressure is calculated by $p_m = \rho g H$, where ρ is the density, g is the acceleration due to gravity (9.81 m/s^2), and H is the total head.

RESULTS FOR CHARACTERISTICS OF PUMP

The relation between the voltage and the maximum pressure for 3 turn numbers of the spiral flow channel around the axis of the pump and the 3-mm channel width for three liquid crystals is shown in Fig. 7. It is found that the maximum pressure increased when we used a liquid crystal with a high dielectric constant.

The result for two pumps connected in series is shown in Fig. 8. One pump has a 3-mm-wide channel and a three-turn spiral flow channel. Liquid crystal mixture MLC6650 was used because it has highest dielectric

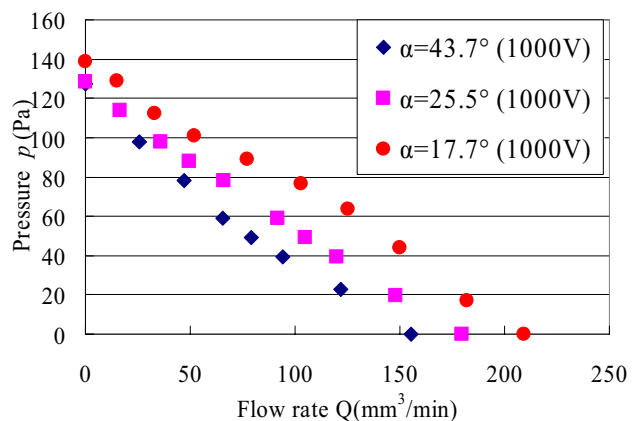


Fig.10 Relationship between the flow rate and pressure ($D=49.45\text{mm}$, $w=3\text{mm}$, MLC6650)

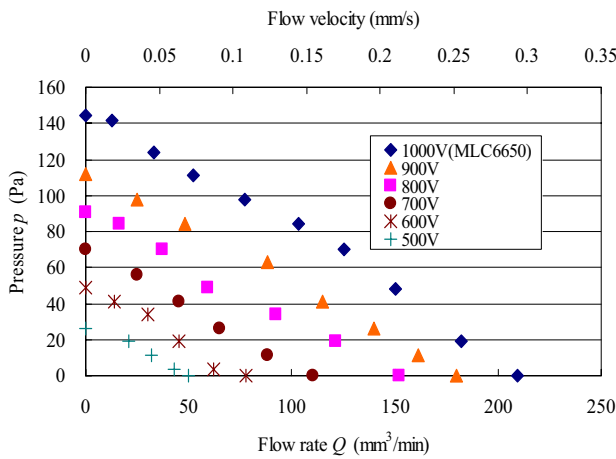


Fig.11 Relationship between the flow rate and pressure (3turns, $w=3\text{mm}$, MLC6650, $\alpha=17.7^\circ$)

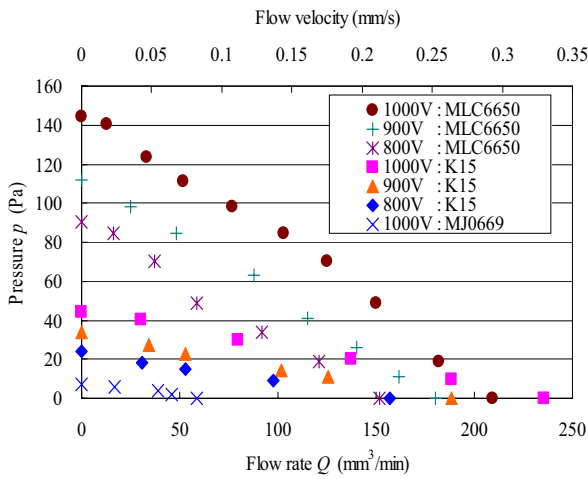


Fig. 12 Relationship between the flow rate and the pressure (3turns and $w=3\text{mm}$, $\alpha=17.7^\circ$)

constant in this experiment. The maximum pressure increased with the voltage and the maximum pressure for the two pumps connected in series is almost twice that of a single pump.

The relation between the flow rate and the pressure for the number of turns (1 and 3) of the spiral flow channel around the axis of the pump is shown in Fig. 9. The pressure increased with the voltage. Moreover, the pressure increased with the turn number of the spiral flow channel. The flow rate for $w=3\text{mm}$ is larger than for $w=1\text{mm}$ because the area of the flow channel is large compared with $w=1\text{mm}$.

In Fig.9, both the angle α between the electric rotation direction and the flow direction and the flow channel length D are changed by changing the turn number. So it is not clear that the difference of the results comes from α or D .

The measurement is conducted by keeping the length D constant and changing the angle α to investigate the effect of α . From Fig.10, the flow rate increase with

decrease of the angle α . Therefore, as the direction of the flow approaches the direction of the electric field, the flow rate increases.

The relation between the flow rate, Q , and the pressure, p , is shown in Fig. 11 for liquid crystal mixture MLC6650. The pressure is calculated by $p = \rho g H$. The flow rate increased with the voltage when the pressure was the same. Furthermore, the flow rate was a maximum when the pressure was 0, and the pressure dropped off nearly linearly with the flow rate.

The relation between the flow rate and the pressure of each liquid crystal is shown in Fig. 12. The flow rate increased with the voltage for each liquid crystal when the pressure was the same. The flow rate increases with the kinematic viscosity and the dielectric constant except zero pressure for same pressure and voltage. As the flow resistance is high with the kinematic viscosity, the flow rate can be increased using a liquid crystal with high dielectric constant.

The results of the non-dimensional analysis of the pump properties for all liquid crystals are shown in Fig. 13. The pump has a 3-mm-wide channel and 3 turn spiral flow channel.

All relations between $\mu Q / \{D^3(\epsilon_{per} - \epsilon_1)E^2\}$ and $p / \{(\epsilon_{per} - \epsilon_1)E^2\}$ derived by the π theorem almost

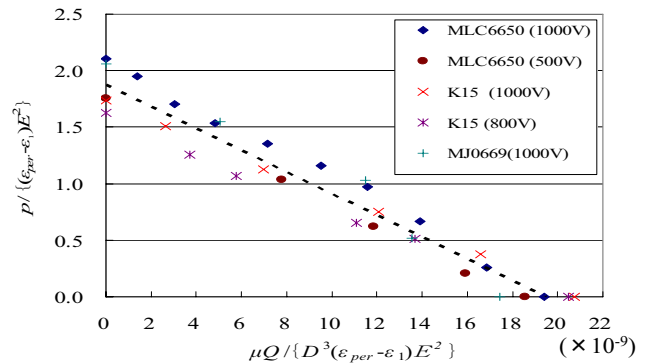


Fig. 13 Nondimensional analysis (3turns, $w=3\text{mm}$, dielectric constant= ϵ_{per} , $\alpha=17.7^\circ$)

become the same line. The above symbols should be referred to nomenclature. The pressure-flow rate characteristics of the pump can be guessed from this result when the liquid crystals with different properties are used in the present pump. $(\epsilon_{per} - \epsilon_1)$ means the difference between the dielectric constant of the vertical direction to longitudinal direction of the liquid crystal molecule and the dielectric constant of insulating part. The difference was used for the present non-dimensional analysis because the difference is found to be very important factor, which acts on the characteristics of the liquid crystal under application of the voltage [18].

CONCLUSIONS

In the present study, rotation electric fields were applied to the cylinder electrodes to add the voltage on the liquid crystals, and flow was induced by the property of the liquid crystal. A pump with a spiral flow channel using the above mechanism was designed, and the pressure-flow rate characteristics of the pump were measured. We made the following findings.

1. The maximum pressure increased when we used a liquid crystal with a high dielectric constant and a high kinematic viscosity for the constant voltage.
2. The pressure of two pumps connected in series was almost twice that of a single pump.
3. As the flow direction approaches the direction of the rotational electric field, the flow rate increases.
4. For the dimensionless parameters calculated using the π theorem, all relations between $\mu Q / \{D^3(\varepsilon_{per} - \varepsilon_1)E^2\}$ and $p / \{(\varepsilon_{per} - \varepsilon_1)E^2\}$ almost become the same line.

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REFERENCES

1. Enomoto Micropump Co.,Ltd,
<http://www.emp.co.jp/structure.htm>
2. Shinano Kenshi Co.Ltd,
<http://www.skj.co.jp/motor/category8.html#02>
3. Sakai, Y., Maki, M., Ogata, S., Sato, K., Yokota, K. and Itoh, M., Influences of Duct Height on Flow Fields and Pressure Performances of a Viscous Micropump Modes Using a Cylindrical Rotor in a Rectangular Duct, Transactions of the Japan Society of Mechanical Engineers, 2006,72-718, pp.1513-1521 (in Japanese).
4. Kilani, M., AI-Salaymeh, A. and AI-Halhouli, A., Effect of Cannel Aspect Ratio on the Flow Performance of a Spiral-Channel Viscous Micropump, Transactions of the ASME J.of Fluids Engineering, 2006, 128, pp.618-627.
5. Yamada, H., Hakama, S., Miyashita, T. and Zhang, N., An Investigation of an Ion Drag Pump Using a Needle-mesh Electrode Configuration, Proc. Instn Mecha. Engrs., 216 Part C, J.Mechanical Engineering Science, 2006, pp.325-335.
6. Feng, Y. and Seyed-Yagoobi, J., Control of Liquid Flow Distribution Utilizing EHD Conduction Pumping Mechanism, IEEE Transactions on Industry Applications, 2006, 42-2, No.2, pp.369-377.
7. Kano, I., Mizuochi, K. and Takahashi, I., Micro-Electro Hydrodynamic Pump by Dielectric Fluid. Improvement for Performance of Pressure Using Cylindrical Electrodes, Proceedings of the Sixth International Symposium on Fluid Power Tsukuba,2005, pp.575-579.
8. Yokota, S., Seo, W., Yoshida, K. and Edamura, K., A Planar Pump Using Electro-Conjugate Fluids (ECF) (Proposition of an ECF Pump for Liquid Cooling of Electronic Chips), Robotics and Mechatronics Division of the Japan Society of Mechanical Engineers, 2004, No.04-4,2P1-L1-61(1-4) (in Japanese).
9. Sakurai, Y., Kadoi, H., Nagata, T. and Edamura, K., Development of Printed Circuit Board Multi-layered Typed ECF-pump and Its Application to Liquid Colling System, Transactions of the Japan Society of Mechanical Engineers,2006, C, 72-715, pp.991-996 (in Japanese).
10. Okazaki, T.,Miyazaki, K. and Tsukamoto, H., Development of an Electroosmotic Flow Driven Liquid Mirco-pump, The preprint of the Mechanical Engineering Congress in Japan(MECJ-06),2006, No.06-1,No.2, pp.291-294 (in Japanese).
11. Tsukiji, T., Koyabu, E., Tsuji, T. and Chono, S., Influence of Electric Fields on the Flow of a Liquid Crystal Mixture in Circular Pipe Electrodes, JSME International Journal, 2005, 48-3, pp.517-523.
12. Tsukiji, T., Murata, Y. and Ito, J., Flow of a Liquid Crystal Mixture in a Mini-Cylinder under Rotating Electric Fields, Proceedings of the Sixth International Symposium on Fluid Power Tsukuba,2005, pp.595-600.
13. Jones, T., Gunji, M., Washizu, M. and Feldman, M., Dielectrophoretic liquid actuation and nanodroplet formation, Journal of Applied Physics,2001, 89-2 ,pp.1441-1448.
14. Jones, T. and Melcher, J., Dynamics of Electromechanical Flow Structure, The Physics of Fluids, 1973, 16-3, pp.393-400.
15. Jones, T., Hydrostatics and steady dynamics of spatially varying Electromechanical Flow Structures, Journal of Applied Physics, 1974, 45-4, pp.1487-1491.
16. Melcher, J. amd Guttman, D., Dielectrophoretic Orientation", AIAA Journal, 1969, 6-1, pp.25-32.
17. Tsukiji, T., Suzuki, K. and Sato, H., Study on Liquid Crystal Pump, Trans. of the Japan Fluid Power System Society, 2008,(in press).
18. Suzuki, K., 2007,"Study on Functional Fluid Pump", Master thesis in Sophia University, Japan.