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Design, Fabrication and Experimental Investigation of a Planar Pump Using Electro-Conjugate Fluid

Woo-Suk Seo[a], Soon-Young Yang[b], Byung-Ryong Lee[b],
Kyoung-Kwan Ahn[b,*], Young-Bog Ham[a]

[a]*Intelligent and Precision Machinery Research Division, Korea Institute of Machinery & Materials, P.O. Box 101, Yuseong-gu, Daejeon 305-343, Korea.*
[b]*School of Mechanical and Automotive Engineering, University of Ulsan, San 29, Muger 2-dong, Nam-gu, Ulsan 680-749, Korea.*

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Abstract

This paper presents the design, fabrication, and experimental investigation of a novel planar pump using electro-conjugate fluid. The electro-conjugate fluid (ECF) is a kind of dielectric functional fluid which generates a powerful jet flow (ECF-jet) when a static electric field is applied via a pair of rod-like electrodes. This phenomenon that ECF can generate jet flows from the positive electrode to the ground electrode in an applied electric field is called the ECF effect, and converts electric energy directly into kinetic energy of the fluid. The ECF-jet acts directly on the working fluids; therefore, the proposed planar ECF pump requires no moving parts and produces no vibration or noise. The fabricated planar ECF pump consists of three parts: a pump base, a top cover, and an electrode substrate with dimensions of 280 mm × 190 mm × 1 mm. In this paper, five different electrode patterns and three different flow channel heights were investigated for the realization of a high-performance planar ECF pump. Each array of electrodes was patterned on the glass epoxy substrates using a wet-etching process, and the flow channel heights were either 200 μm, 300 μm, or 500 μm. The pumping experiments used FF-1_{EHA2} as the working fluid. Experimentation showed that a no-load flow rate of 5.5 cm^3/s, maximum output pressure of 7.2 kPa, and maximum output power of 11.6 mW were achieved at an applied voltage of 2.0 kV.

Keywords: Electro-Conjugate Fluid (ECF); ECF-jet; ECF pump; Planar pump; Functional fluids; Liquid cooling system

1. Introduction

Recent development trends in microprocessor architecture and electronic devices have focused on the increasing integration density, miniaturizing processors, and increasing clock frequencies. As a result of these trends, heat generation rates of the chip and other electronic components have rapidly increased [e.g., the heat flux for a high-performance microprocessor, such as the 3.4 GHz Intel® Pentium® 4 processor, has been projected to be 100 W/cm^2 (Intel Corp., 2005)]. According to the International Technology Roadmap for Semiconductors (ITRS), the maximum power dissipation of the next-generation microprocessors is predicted to increase more than 300 W by the end of 2010s (Semiconductor Industry Association, 2005). Traditional electronics cooling solutions, such as a forced air convection cooling method using conventional fan assembled fin-array heat sinks and heat pipe technology, are unsuitable for counteracting these large heat generation rates (Pastukhov, 2003; Saini, 2003).

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*Corresponding author. Tel.: +82 52 259 2282, Fax.: +82 52 259 1680
E-mail address: kkahn@ulsan.ac.kr

Among current state-of-the-art technologies, forced liquid cooling using a pump and microchannel heat sinks is one promising strategy for dissipating the heat flux from the high-power electronic chips and electronic devices. The pump plays a significant role in the forced liquid cooling system, which is required to drive the flow of working fluids through microchannel heat sinks. In electronics cooling, forced liquid cooling demands a high flow rate and high output pressure. For instance, Tuckerman and Pease (1981) reported a microchannel heat sink on liquid-phase convective cooling that removes 790 W/cm^2 at flow rates of 600 mL/min. Jiang *et al.* (2002) demonstrated a closed-loop cooling system using an electro-osmotic pump and silicon microchannels heat sink, which required a pressure drop of about 10-50 kPa at a flow rate up to 4 mL/min. Although conventional rotary pumps and gear pumps have a large flow rate and output pressure, they are unsuitable for electronics cooling due to their large size, especially for portable computers and mobile electronic devices (Sinhal, 2004).

On the other hand, the electro-conjugate fluid (ECF) is a kind of dielectric and functional fluid which generates a jet flow (ECF-jet) when a static electric field is applied via a pair of electrodes (Otsubo, 1997; Yokota, 2001). Figure 1 shows the visualization results and schematic diagram of the ECF-jet (Yokota, 2001). The diameter of the rod-like brass electrodes is 300 μm, and the distance between the positive and ground electrodes is 3mm. Dibutyl decanedioate, one kind of ECF, is used as a working fluid. As can be seen in this figure, the ECF-jets are generated when a large DC voltage (5 kV) is applied to the electrodes. This phenomenon, when observed in ECF, is called the "ECF effect," and converts electric energy directly into kinetic energy. Therefore, its use can offer an attractive approach for applications in novel fluidic devices and actuators. Indeed, applications of the ECF for macro- and micro-scale fluidic devices have been experimentally investigated by several researchers (Takemura, 2005; Yokota, 1998; 2001; 2005). Yokota *et al.* (2001, 2005) proposed a simple micromotor using the ECF, consisting of a stator, a rotor, and an array of electrodes. When a DC voltage is applied to the electrodes, the ECF-jet flow can propel the rotor. Takemura *et al.* (2005) fabricated a micro artificial muscle actuator using the ECF-jet as a pressure source. They used a pair of needle and ring-type electrodes to produce a more intense electric field. Moreover, Yokota *et al.*, (1998) developed a shape memory alloy (SMA) driven micropump using ECF-jet cooling and experimentally confirmed the effectiveness of the cooling capability of the ECF. Using this ECF as a working fluid, a simple thin-planar pump that uses no working parts is expected to be realized.

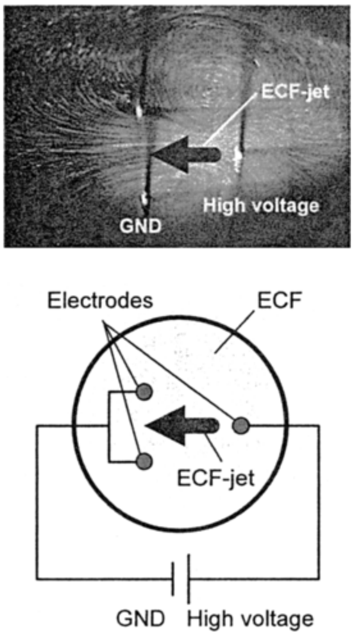


Fig. 1. Visualization and schematic diagram of the ECF-jet. (Yokota, 2001)

The objective of this paper is to realize a pump, which could act as a fluid power source for a forced liquid cooling system. A practical pump system for high-power electronics cooling requires low vibration and noise levels as well as an effective, reliable performance. In particular, a thin-planar pump feature having these qualities is also suitable for the installation in ultra-slim advanced electronic devices, which are increasingly common. In this study, a thin-planar pump using ECF is proposed, fabricated, and experimentally investigated in order to create a suitable liquid cooling system for applications in space-critical portable computers and mobile electronic devices.

2. Proposition of the planar ECF pump

2.1 Pumping principle

The schematic diagram of the pumping principle for the proposed planar ECF pump is shown in Fig. 2.

The parallel rod-like electrodes are patterned on the substrate, and the electrode substrate is inserted into the pumping chamber. The pumping chamber is then filled with the ECF. When a DC voltage is applied to the electrode array, ECF-jets are generated (the ECF effect) from the edge of the positive electrode to the ground electrode. Although the mechanism of the ECF effect has not yet been fully described, the qualitative phenomenon (that dielectric fluids can generate jet flows between a pair of electrodes in an applied electric field) is known as the electro-hydrodynamic (EHD) effect (Ahn, 1998; Fuhr, 1994). Previous studies also show that the velocity of the ECF-jet increases almost proportionally to the applied voltage (Takemura, 2005; Yokota, 1998; 2001; 2005). We hypothesize that the pumping mechanism of the planar ECF pump is as follows: When the ECF effect between a pair of the positive and the ground electrodes is generated by an applied electric field, some of the momentum of ECF-jets is transferred to a stationary fluid through viscosity. If an applied electric field is strong enough, the local flows are created around each pair of electrodes. As the velocity of the ECF-jet is further increased until the local flows exceed certain threshold value for making the uniform fluid flow in the channel, a fluid flow along the whole channel is established, as illustrated schematically in Fig. 2.

In the proposed planar ECF pump, the ECF-jet acts directly on the working fluid; the pump therefore requires no mechanical moving parts and produces no vibration or noise. Moreover, this planar pump can be mounted on, for example, the reverse side of the LCD panel of a portable computer. The heat flux of the CPU would then be transferred to the reverse side of LCD panel via the ECF and then be radiated by the large pump surface through contact with air. In this case, the planar ECF pump simultaneously plays the key roles of fluid power source and radiator in the forced liquid cooling system. These characteristics of the proposed planar ECF pump would seem to suit it well for use as a forced liquid cooling system in next-generation portable computers and mobile electronic devices.

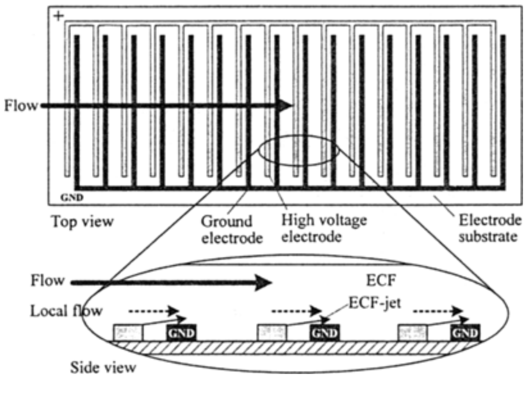


Fig. 2. Schematic diagram of the pumping principle for the planar ECF pump.

2.2 Design and fabrication

We designed and fabricated a planar ECF pump using various electrode patterns and flow channel heights. Figure 3 shows a schematic diagram of the fabricated planar ECF pump. The pump consists of a pump base, a top cover, an electrode substrate, and peripheral devices, such as O-rings and pipes. The pump base and top cover are made of brass and polycarbonate, respectively. The overall dimensions of the fabricated planar ECF pump are selected based on the A4 size (297 mm × 210 mm) LCD display of the portable computers. The glass epoxy substrate with copper electrodes was used as the electrode substrate. The substrate had a length of 280 mm, a width of 190 mm, and a thickness of 1.0 mm. Four acryl spacers, with width 5 mm, were inserted into the pumping chamber to maintain the flow channel height as shown in Fig. 3. The O-ring is used to prevent leakage of the working fluids. The electrical connection lead wires are passed through the pump base and are connected to the external high-voltage power supply.

In a planar ECF pump, the pumping is achieved when ECF-jets are generated around each pair of electrodes. The ECF-jet intensity depends on the applied electric field, and the electric field strength in turn depends on electrode dimensions. The flow cha-

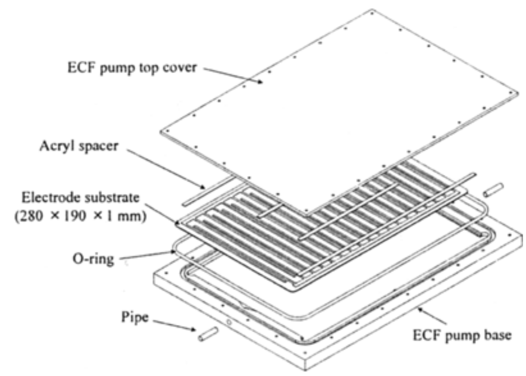


Fig. 3. Schematic diagram of the fabricated planar ECF pump.

nnel heights also influence the output flow rate and the pressure of the planar ECF pump. Thus, the design of electrode patterns and flow channel heights is of crucial importance to improving the pumping performance. Figure 4 shows a schematic diagram of design parameters for the planar ECF pump. It consists of five parameters: electrode height t_e, electrode width B_e, distance L_e between the positive and ground electrodes, distance L_p between the electrode stage, and flow channel height H_c. In this paper, five electrode patterns and three flow channel heights were used to establish the electrode design rules for improving pump performance of the planar ECF pump. The specifications of the five different electrode designs are summarized in Table 1. In each electrode design, the flow channel heights H_c were varied among 200 µm, 300 µm, and 500 µm. The fabrication of electrodes was performed on a glass epoxy substrate using a wet-etching process. A photograph of fabricated electrode pattern No. 1 is shown in Fig. 5.

Table 1. Specifications of various electrode designs. (see Fig. 4)

Substrate No.	h_e (µm)	B_e (µm)	L_e (µm)	L_p (µm)	No. of stages
1	35	100	200	900	212
2	35	100	300	800	212
3	70	100	200	900	212
4	35	70	200	960	212
5	35	100	200	400	344

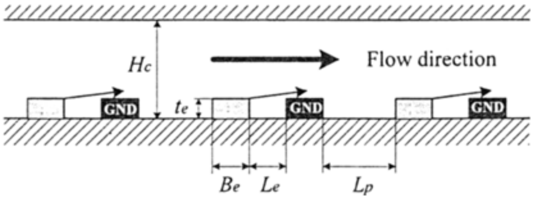


Fig. 4. Definition of the design parameters.

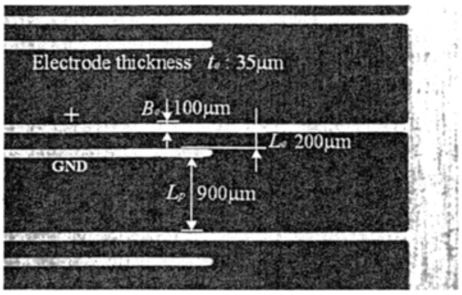


Fig. 5. Photograph of the fabricated electrode pattern No. 1 using wet-etching process.

3. Experimental setup

The experimental apparatus (Fig. 6) consists of the fabricated planar ECF pump, a high-voltage power supply, a shunt resister, and measurement instrumentation. A high-voltage DC power supply (HEOPS-3P10, MATSUSADA Precision Inc., Japan) with output voltage range 0-3 kV and current output range 0-10 mA was used to provide voltage to the substrate electrode of the planar ECF pump. To measure the current, a shunt resister (10 Ω) was installed. The measurement of mass flow rate during a one-minute was performed using a digital balance with a resolution of 0.02 g, and calculated volume flow rate was given by $\dot{Q} = \dot{m}/\rho$ where $\dot{m}$ is the mass flow rate and ρ is the density of the ECF. The maximum pressure head was measured as the height of liquid column rise from the drain liquid level. The load pressure can be applied to the planar ECF pump by means of a rising height of drain port.

All pumping experiments for the fabricated planar ECF pump were performed using FF-1_{EHA2} for the working fluid. The FF-1_{EHA2} is a type of ECF, which

Table 2. Physical properties of FF-1_{EHA2}.

Physical Property	FF-1_{EHA2}
Density [kg/m^3] (at 15 °C)	1.688×10^3
Kinematic viscosity [m^2/s] (at 30 °C)	8.8×10^{-6}
Electric conductivity [S/m] (at 1 kV/mm)	5×10^{-9}
Boiling point [°C] (at 1 atm)	210

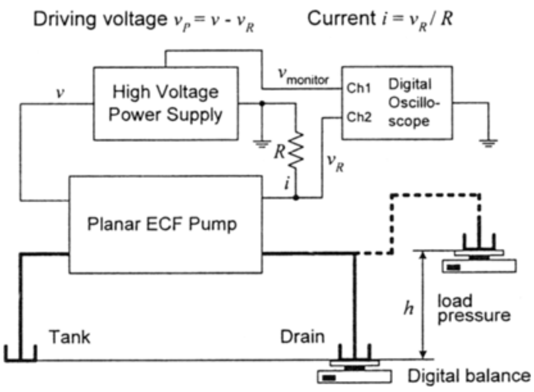


Fig. 6. Experimental apparatus for pumping characteristics of planar ECF pump.

has been known to generate stronger jet flows than the dibutyl decanedioate (DBD). The physical properties of the FF-1_{EHA2} are listed in Table 2.

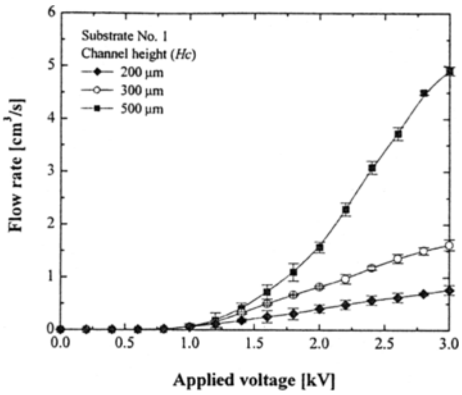
For the pumping experiments, the test devices were cleaned with ethanol to prevent pollution of the working fluid with impurities. The air-stripping process was performed in a vacuum chamber to prevent the breakdown by air.

4. Experimental results

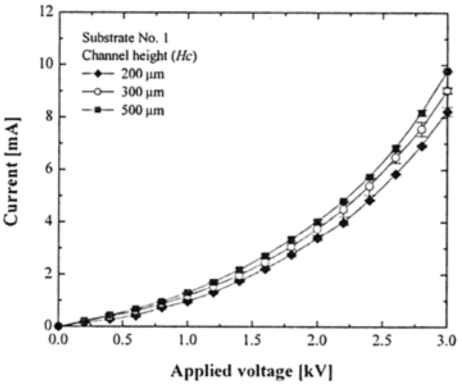
The experiments were performed with three different flow channel heights and five different electrode patterns, as shown in Fig. 4 and Table 1, using the FF-1_{EHA2} as the working fluid. The pumping characteristics, such as no-load flow rate, current, and maximum output pressure, were investigated as functions of the applied voltage. Voltage was applied to the electrodes and was increased in 200 V increments up to 3.0 kV. In pumping experiments, the no-load flow rate, current, and maximum output pressure were measured three times at the same applied voltage. The average values and upper/lower limits of the measured data were denoted on the graphs (see Figs. 7-10).

The effects of the variations in the flow channel height on the pumping performance of the proposed ECF pump were investigated. The flow channel heights H_c were varied among 200 μm, 300 μm, and 500 μm. The measured results of the no-load flow rate and current for the substrate No. 1 are shown in Fig. 7. There, the no-load flow rate and current increased with flow channel height. Also, the results clearly show that the no-load flow rates increased rapidly compared to the increase of the current. Therefore, it is expected that an increment of the flow channel height is effective from a larger flow rate point of view. Figure 8 shows the obtained maximum output pressures for each flow channel height in the case of the substrate No. 1. The results show that the maximum output pressure decreases when the flow channel height increases. This is due to the fact that the cross-sectional area of the flow channel is increased by a higher flow channel height, resulting in a lower output pressure generation.

Another observation from Figs. 7(a) and 8 is that the threshold voltage is observed near the applied voltage of 0.8 kV. This observation is due to the difficulty of making the uniform fluid flow in the channel because the velocity of ECF-jets depends on the applied electric field and thus, the momentum of ECF-jets is insufficient at low applied voltage, as mentioned in Sec. 2.1.



(a) Flow rate



(b) Current

Fig. 7. ECF pump characteristics for various channel height. (without load)

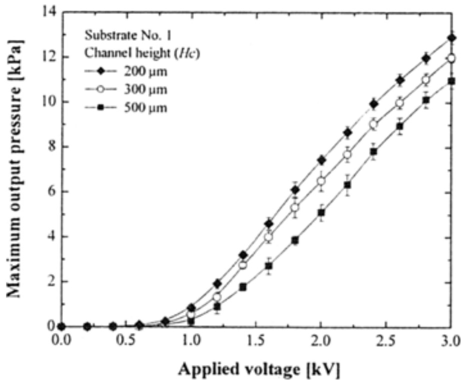
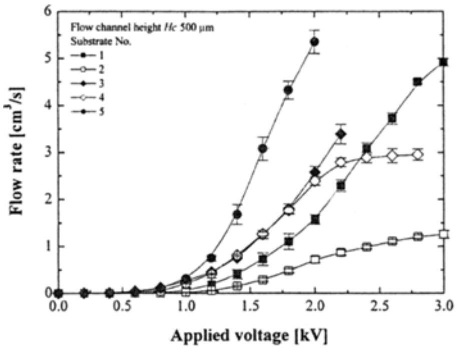
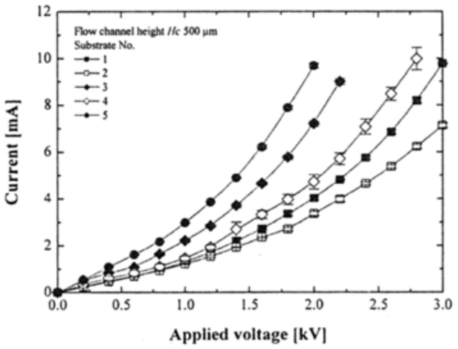


Fig. 8. Maximum output pressure for various channel height.

Based on the results shown in Figs. 7 and 8, the pumping characteristics of substrate Nos. 1-5 at the flow channel height of 500 μm, as shown in Table 1, were experimentally investigated in order to improve the pumping performance. The first electrode pattern, substrate No. 1, consists of rectangular electrodes with an electrode width B_e of 100 μm. The electrode distance L_e is 200 μm, and the distance between each neighboring electrode stage L_p is 900 μm. Substrate No. 1 plays the role of the reference electrode pattern in order to compare the pumping performance of the other electrode patterns. The measured no-load flow rates and currents for substrate Nos. 1-5 are shown in Fig. 9. The obtained maximum output pressures are shown in Fig. 10. For substrate No. 2 (with increased electrode distance L_e), the no-load flow rate and maximum output pressure are lower than those of the substrate No. 1. Considering that the ECF-jet intensity depends on the applied electric field, as mentioned in Sec. 2.2, the increased electrode distance L_e of substrate No. 2 results in lower electric field intensity and thus weaker ECF-jet generation. The no-load flow rate and current of substrate No. 3, which has greater electrode height t_e, are larger than those of substrate No. 1. However, the maximum output pressure of substrate No. 3 is lower than that of substrate No. 1. Substrate No. 4, which has narrow electrode width B_e, exhibited a much higher no-load flow rate and current under an applied voltage of 2.0 kV than substrate No. 1 does. It is believed that this is due to the increase of the non-uniformity of the electric field for the narrow electrode width B_e. At applied voltages of 2.0 kV or greater, however, the fluid vortex and backflow was observed in a pumping chamber, resulting in a lower pumping performance. Finally, in substrate No. 5, the pumping performance was significantly improved by the decrease of the distance L_p between electrode stages. In this case, we believe the larger number of electrode stages (344 pairs of electrodes) in the substrate was responsible for the superior pumping performance. Significant progress in micro fabrication technologies allows distances between electrodes in an electric field to be reduced to a few tens of micrometers; it is expected that the applied voltage can be reduced to lower than kilovolt order. Therefore, reducing the electrode distance and increasing the number of electrode stages are effective ways to improve the pumping performance of the planar ECF pump. The no-load flow rate of 5.5 cm^3/s and maximum output pressure of 7.2 kPa were achieved at an applied voltage of 2.0 kV for substrate No. 5 with a 500 μm flow channel height.



(a) Flow rate



(b) Current

Fig. 9. ECF pump characteristics for various electrode dimensions. (without load)

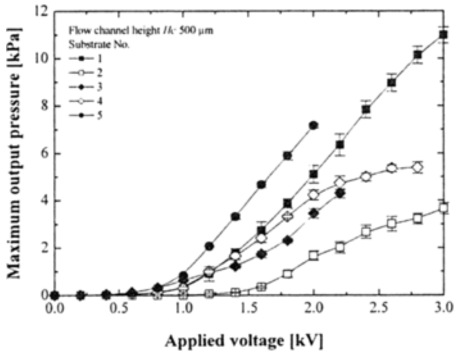


Fig. 10. Maximum output pressure for various electrode dimensions.

The load characteristics of the fabricated planar ECF pump were investigated. The load pressure was applied to the pump by means of a rising height of the drain port. Figure 11 shows the characteristics for the flow rate versus load pressure as functions of applied voltage, using substrate No. 5 and a flow channel height of 500 μm. The applied voltages are 1.6 kV and 2.0 kV. As can be seen in this figure, there is a nearly linear relationship between the flow rate and load pressure. Thus, a maximum output power of 11.6 mW is obtained at an applied voltage of 2.0 kV.

Furthermore, the efficiency of the fabricated planar ECF pump was investigated. The calculated efficiency was given by $\eta = P_{output}/P_{input}$ where P_{input} and P_{output} are the electrical input power and the mechanical output power of the planar ECF pump, respectively. Figure 12 shows the efficiency characteristics for substrate Nos. 1-5 at a flow channel height of 500 μm and an applied voltage of 2.0 kV. As can be seen in this figure, the substrate No. 5 exhibited a much higher efficiency than substrate Nos. 1-4 do. The maximum efficiency of 0.6×10^{-3} is achieved at an applied voltage of 2.0 kV for substrate No. 5 with a 500 μm flow channel height.

However, this planar ECF pump required large quantities of current; for instance, a maximum current of about 10 mA was measured at an applied voltage of 2.0 kV. As a result, the pump consumed a large amount (20 W) of power. A practical pump system for high-power electronics cooling requires low power consumption as well as an effective and reliable performance. Consequently, investigation into higher pumping efficiency and lower power consumption will be needed before use in portable computers and mobile electronic devices is deemed practical.

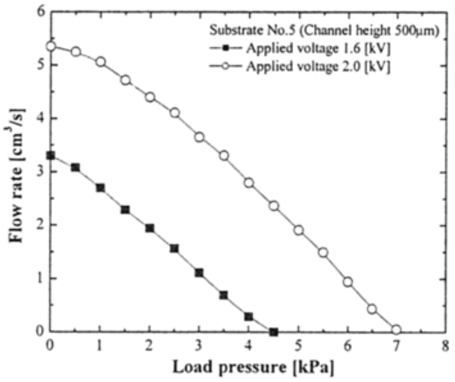


Fig. 11. Flow rate versus load pressure characteristics.

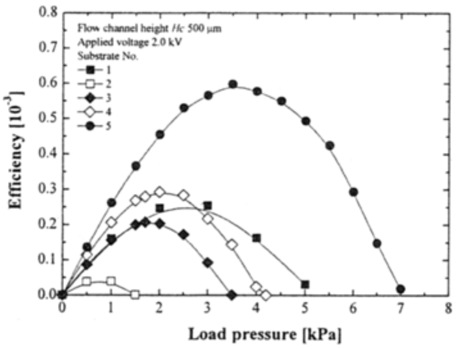


Fig. 12. Efficiency characteristics for various electrode dimensions.

5. Conclusions

A thin-planar pump using electro-conjugate fluid (ECF) was proposed, designed, and fabricated. The proposed planar ECF pump has no mechanical moving parts and produces no vibration or noise. To realize high performance, the pumping characteristics for various flow channel heights and electrode patterns were experimentally investigated. The experiments were performed with three different flow channel heights and five different electrode patterns, using FF-1_{EHA2} as a working fluid. The fabricated planar ECF pump achieved the no-load flow rate, maximum output pressure, and maximum output power of 5.5 cm^3/s, 7.2 kPa, and 11.6 mW, respectively, at an applied voltage of 2.0 kV and using substrate No. 5 with a 500 μm flow channel height. The experimental results indicated that reducing the electrode distance and increasing the number of electrode stages were effective ways to improve the pumping performance of the planar ECF pump.

Future work will focus on realization of low power consumption, improvement of the pumping efficiency, and application of the forced liquid cooling system to advanced notebook computers.

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References

Ahn, S. H. and Kim, Y. K., 1998, "Fabrication and Experiment of a Planar Micro Ion Drag Pump," *Sens. Actuators. Phys. A*, Vol. 70, pp. 1~5.

Fuhr, G. *et al.*, 1994, "Travelling Wave-driven Microfabricated Electrohydrodynamic Pumps for Liquids," *J. Micromech. Microeng.*, Vol. 4, pp. 217~ 226.

Intel Corp., 2005, *Intel® Pentium® 4 Processor on 90 nm Process Datasheet*, pp. 63~66.

Jiang, L. *et al.*, 2002, "Closed-Loop Electroosmotic Microchannel Cooling System for VLSI Circuits," *IEEE Trans. Comp. Packag. Technol.*, Vol. 25, No. 3, pp.

347~355.

Otsubo, Y. and Edamura, K., 1997, "Dielectric Fluid Motors," *Applied Physics Letters*, Vol. 71, No. 3, pp. 318~320.

Pastukhov, V. G. *et al.*, 2003, "Miniature Loop Heat Pipes for Electronics Cooling," *Applied Thermal Engineering*, Vol. 23, pp. 1125~1135.

Saini. M. and Webb, R. L., 2003, "Heat Rejection Limits of Air Cooled Plane Fin Heat Sinks for Computer Cooling," *IEEE Trans. Comp. Packag. Technol.*, Vol. 26, No. 1, pp. 71~79.

Semiconductor Industry Association, 2005, *International Technology Roadmap for Semiconductor (ITRS) 2005 edition.*

Singhal, V. *et al.*, 2004, "Microscale Pumping Technologies for Microchannel Cooling Systems," *Appl. Mech. Rev.*, Vol. 57, No. 3, pp. 191~221.

Takemura, K. *et al.*, 2005, "A Micro Artificial Muscle Actuator Using Electro-Conjugate Fluid," *Proc. of the IEEE Int. Conf. Robotics and Automation*, pp. 534~539.

Tuckerman, D. B. and Pease, R. F. W., 1981, "High-Performance Heat Sinking for VLSI," *IEEE Electron Device Letters*, Vol. EDL-2, No. 5, pp. 126~129.

Yokota, S. *et al.*, 1998, "An SMA-Driven Micropump Using Electro-Conjugate Fluid Jet Cooling," Proc. of the Mechatronics'98, pp. 453~458.

Yokota, S. *et al.*, 2001, "A Micro Motor Using Electro-conjugate Fluids (ECF): Proposition of Stator Electrode-type (SE-type) Micro ECF Motors," *Int. Journal of JSME: Ser. C*, Vol. 44, No. 3, pp. 756~762.

Yokota, S. *et al.*, 2005, "High Integration Micromotor Using Electro-Conjugate Fluids (ECF)," *Jour-nal of Robotics and Mechatronics*, Vol. 17, No. 2, pp. 142~148.