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REVIEW

Hideo Yoshida

The wide variety of possible applications of micro-thermofluid control

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Abstract The possible applications of micro-thermofluid control are reviewed here, mainly on the basis of the seventeen proceedings of IEEE International Workshops and Conferences on Micro Electro Mechanical Systems held since 1987. The contents consist of three aspects. The first is thermofluid control in microsystems; particularly, the attention is focused on the various types of micropumps. The second is thermofluid control in miniaturized thermofluid machines such as a microturbine and a microcooler. The third is micro-thermofluid control for conventional-sized flow phenomena such as turbulent shear flows and a flapping-wing micro-aerial vehicle. The author stresses that, in this field, considerable advances have been achieved by relatively young researchers with various backgrounds other than the classical thermofluid dynamics, and many challenging works are in progress which will lead to new possibilities in the field of thermofluid dynamics. Also, the author has gained the impression that the researchers' byword has recently changed from "what can MEMS research do?" to "what should MEMS research do?"

Keywords MEMS · Micro-thermofluid control · Micro-fluidics · Micropump

1 Introduction

There has been marked progress in micro electro mechanical systems (hereafter referred to as MEMS) technology (Gad-el-Hak 2002). The history of MEMS research has been most comprehensively recorded in the IEEE International Workshops and Conferences on MEMS which have been held annually since 1987, the latest of which was held in January 2004. Among the wide range of applications of MEMS technology, several possibilities for practical applications have firmly developed; the most typical applications are micro total chemical analysis systems (μTAS), and bio, optical, wireless, RF and power MEMS.

As the basis for these applications, microfluidics plays an essential role. In the author's understanding, "micro-thermofluid dynamics" is a more appropriate terminology than "microfluidics," because thermal characteristics are inherently as important as fluidic ones. One of the basic roles of micro-thermofluid dynamics is considered to be control. Here, it should be noted that there are various aspects of control by micro-thermofluid dynamics. Figure 1 shows a proposed classification for the objects or systems which can be controlled by micro-thermofluid dynamics. This classification is based on the length scales and functions of the controlled systems.

1. The first is thermofluid control in microsystems such as bio MEMS, μTAS, devices, and other new systems. In this category, thermofluid components such as micropumps, microvalves and micromixers are key items; they are literally components in the systems.
2. The second is thermofluid control in miniaturized thermofluid machines, i.e., power MEMS such as microengines and microturbines, as well as microcoolers. For these miniaturized machines, thermofluid phenomena within themselves should be controlled.
3. The third is micro-thermofluid control for conventional-sized flow phenomena. For these phenomena, micro-thermofluid dynamics is regarded as perturbation. In other words, this kind of control is considered to be an amplification process analogous to that in electrical circuits using transistors.

Although the author does not have experience in fabricating MEMS, as a researcher in thermofluid dynamics, the author has been keeping a steady watch in the progress of the control technology based on micro-thermofluid dynamics. As a result, the author is aware of the wide variety of its possibilities, and is simultaneously

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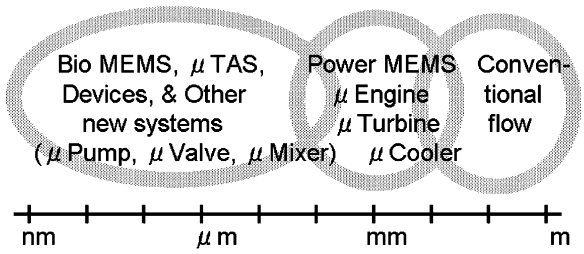

Fig. 1 Objects or systems relating to micro-thermofluid control

impressed by the inexhaustible perseverance of the relatively young researchers whose specialties are not always thermofluid dynamics. In this paper, the possibilities of micro-thermofluid control are discussed in terms of the three aspects above. Although a comprehensive review is impossible because of the limited length of the paper as well as the author's limited knowledge, the promising state of the art in this field will be described, mainly on the basis of the seventeen IEEE International Workshops and Conferences on MEMS held from 1987 to 2004.

2 Thermofluid control in microsystems

As the first aspect of possible applications, thermofluid control in microsystems is discussed in this chapter.

2.1 Various operating principles for micropumps

In microsystems, micropumps and microvalves are the key components, and furthermore, the boundary between them is not very clear because valves frequently function as pumps. The purpose of this section is to systematically describe the various micropumps based on different operating principles. Another comprehensive review on micropumps is also reported by Koch et al. (2000) and Nguyen and Wereley (2002), although their frameworks differ somewhat from the present one.

Here, the following classifications are proposed on the basis of the operating principle and mechanism:

– Rotary type
– Reciprocating type
– Valve-less type
– Electrohydrodynamic (EHD) type
– Acoustic wave or vibration type
– Interfacial tension type

Since the principal motivation here is to demonstrate the enthusiastic efforts in fluid pumping research, detailed comparisons are omitted.

Prior to describing each type of micropump, it should be noted that the functions required of micropumps are as follows:

– Precise control for flow rate
– Small flow resistance in forward direction
– Large flow resistance in backward direction
– Small leakage or low reverse flow rate
– Tolerant to bubbles in the case of liquid flow
– Low power consumption
– Robustness
– Easy fabrication and matching with other components

2.2 Rotary type

This type is the simplest extension of conventional-sized pumps to micropumps, and has potential for smooth fluid delivery. Figure 2 shows the rotary micropump fabricated on a silicon wafer. It is driven magnetically, and has been successfully applied to conductive fluids (Ahn and Allen 1995).

2.3 Reciprocating type

In this type, the reciprocating motion of a membrane drives fluids. Various actuators for the membrane are applicable including:

– Electrostatic
– Magnetic
– Piezoelectric
– Thermopneumatic
– Shape-memory alloy

As is widely known, at the sizes of MEMS, surface forces are much more prevalent than body forces. Therefore, electrostatic force, which is proportional to surface area, is one of the most prevalent forces for actuation. Figure 3 shows a typical silicon micropump developed by Zengerle et al. (1992). The membrane chip

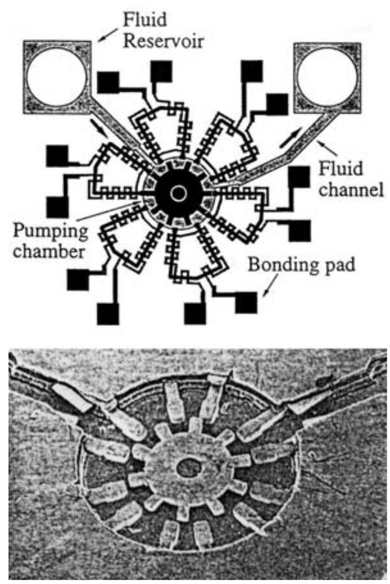

Fig. 2 Magnetically driven rotary micropump (Ahn and Allen 1995 © IEEE)

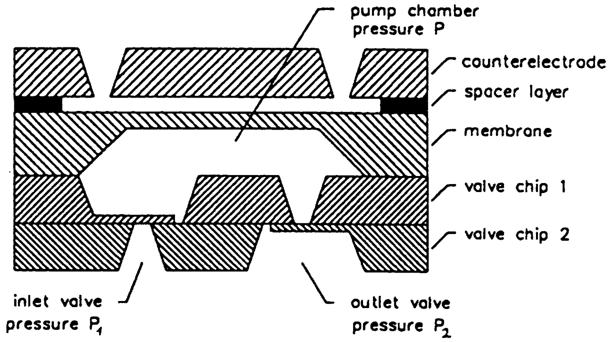

Fig. 3 Electrostatic micropump (Zengerle et al. 1992 © IEEE)

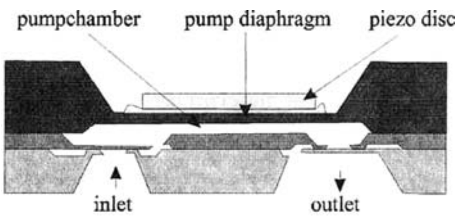

Fig. 4 Piezoelectric micropump (Linnemann et al. 1998 © IEEE)

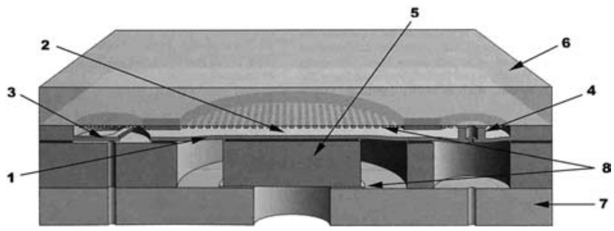

Fig. 5 Reciprocating micropump with various types of actuators (Maillefer et al. 2001 © IEEE). *1* pumping membrane, *2* pumping chamber, *3* inlet check valve, *4* outlet check valve, *5* mesa, *6* upper glass plate, *7* lower glass plate

with the facing counterelectrode forms the actuation unit. Two identical valve chips make up two passive check valves. This type of micropump is popular, and has been applied for both gas and liquid flows by Judy et al. (1991), Messner et al. (2003), Cabuz et al. (2001), and Dubois et al. (2001).

The magnetically actuated reciprocating micropump has also been studied by Shinozawa et al. (1997) and Meng et al. (2000).

As an alternative to electrostatic force, piezoelectric actuators are widely employed for micropumps. As shown in Fig. 4 (Linnemann et al. 1998), a piezoelectric layer is attached to the membrane, unlike the electrostatic actuators where the membrane itself is an electrode. Since the piezoelectric actuators are independent of the main structures of micropumps, the freedom in design is much greater. Consequently, there exist many studies on piezoelectric actuators by, for example, Esashi et al. (1989), Nakagawa et al. (1990), Stehr et al.

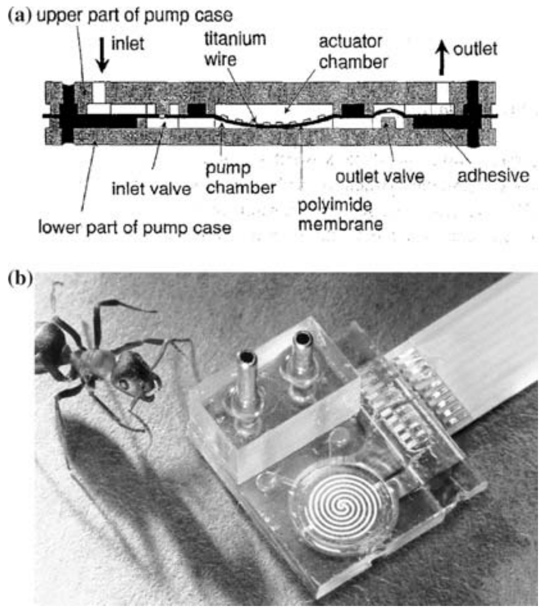

Fig. 6 Thermopneumatic micropump (Büstgens et al. 1994 © IEEE). **a** Schematic view. **b** Photograph (Courtesy of Dr. Walter Bacher of Forschungszentrum Karlsruhe)

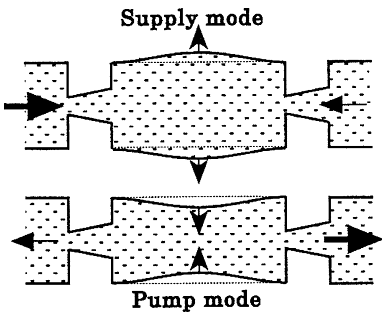

Fig. 7 The operation of a diffuser pump during the supply and pump modes (Olsson et al. 1997a © IEEE)

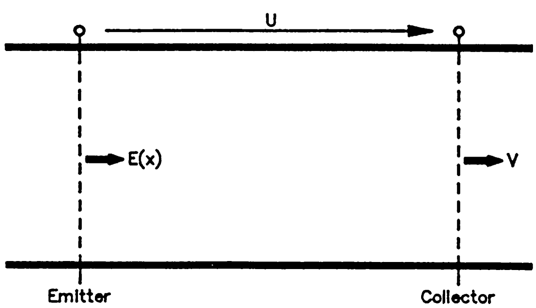

Fig. 8 Geometry of EHD injection pump (Richter and Sandmaier 1990 © IEEE)

(1996), Maillefer et al. (1999) Shinohara et al. (2000), Yang et al. (2003a), and Li et al. (2003a, 2003b).

In addition to piezoelectric actuators, Maillefer et al. (2001) applied various actuators such as direct pneumatic, electromagnetic, and shape-memory alloy actuators for the micropump shown in Fig. 5.

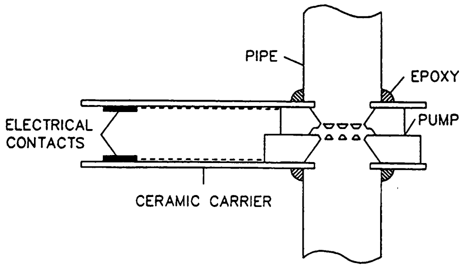

Fig. 9 Packaged EHD injection pomp (Richter et al. 1991 © IEEE)

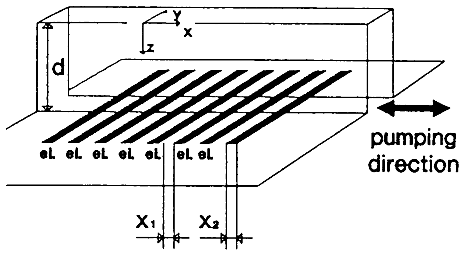

Fig. 10 Traveling wave EHD pump with planar electrodes (Fuhr et al. 1992 © IEEE)

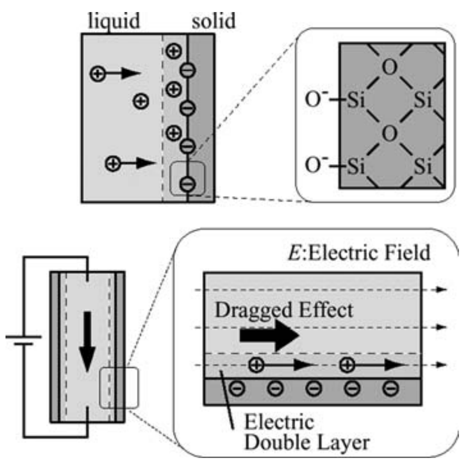

Fig. 11 Electro-osmotic micropump (Chujo et al. 2003 © IEEE)

The working principle of thermopneumatic actuators is the expansion of gas or a phase change of liquid in an enclosed chamber due to heating. In the micropump shown in Fig. 6 (Büstgens et al. 1994), air is heated by an electric current through a titanium wire on the polyamide membrane. On the other hand, Mizoguchi et al. (1992) used the combination of Freon 113 and laser light as the heating source. Recently, Grosjean et al. (2002) and Zimmermann et al. (2004) also presented new micropump systems.

2.4 Valve-less type

Olsson et al. (1996a, 1996b, 1997a, 1997b) proposed a valve-less micropump using diffuser elements. The major

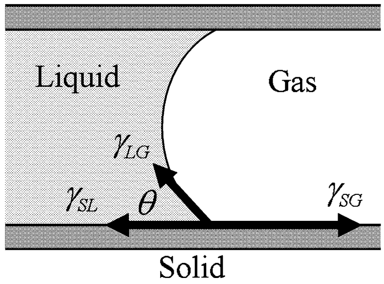

Fig. 12 Liquid in contact with both gas and a solid in a capillary

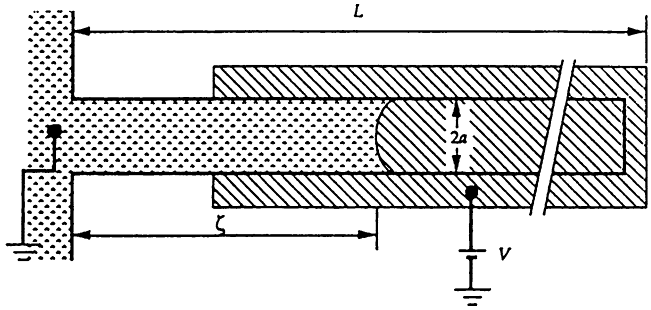

Fig. 13 Reciprocating actuator based on electrical control of solid-liquid interfacial force (Matsumoto and Colgate 1990 © IEEE)

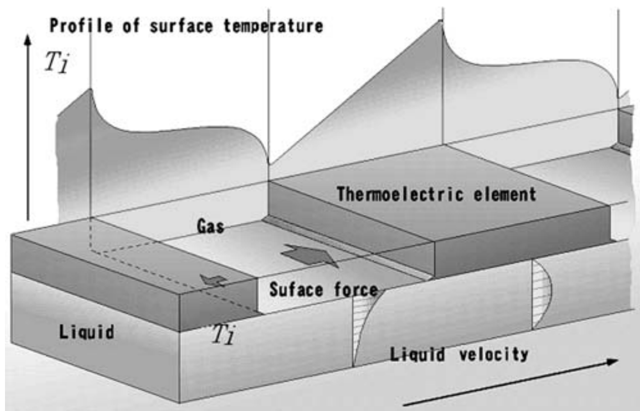

Fig. 14 Marangoni micropump (Yoshida et al. 2002)

advantages of diffuser elements are that the risks of wear and fatigue in passive check valves are eliminated and the danger of valve clogging is reduced. As shown in Fig. 7, two identical fluid-directing elements act as a diffuser in the main pump flow direction with a lower flow resistance in the diffuser direction than in the nozzle direction. Thus, during a complete pump cycle, a net fluid volume is transported from the inlet to the outlet side. Since the difference between forward and reverse flow rates is not so large, the pumping efficiency is not high. However, the extremely simple geometry as well as the aforementioned advantages are preferable for many applications. In addition to Olsson et al., van der Wijngaart et al. (2000), Lee et al. (2000), and Hayamizu

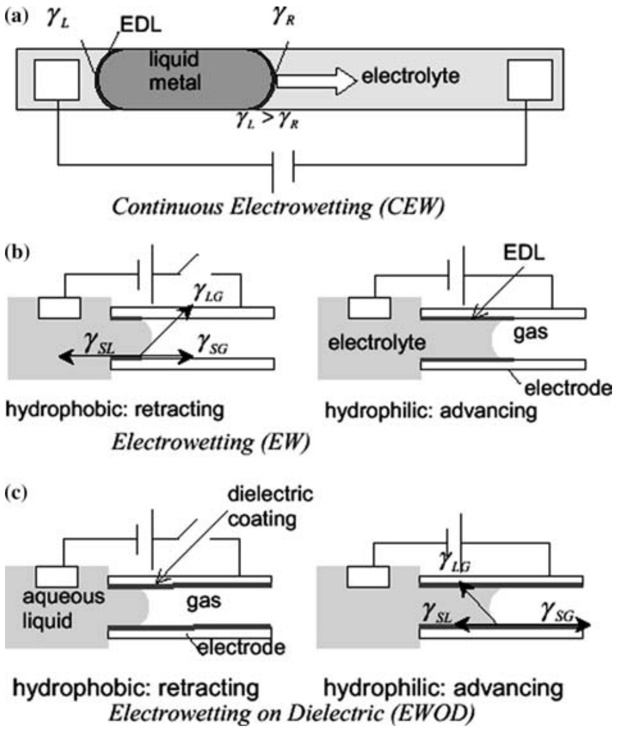

Fig. 15 Liquid driven by electrically controlling surface tension (Lee et al. 2001 © IEEE)

et al. (2002) studied the valve-less micropump with a piezoelectric actuator. Tsai and Lin (2001) applied a thermal bubble (thermopneumatic) actuator to the diffuser micropump.

Ozaki (1995) and Matsumoto et al. (1999) proposed micropumps based on the difference in the viscosity of the working fluid; the difference in the former study was due to the phase change, i.e., liquid to vapor, while that in the latter study was due to temperature.

2.5 Electrohydrodynamic (EHD) type

Flow induced by electric field is also effective mainly for liquid with a low electrical conductivity between 10^{-8} and 10^{-6} S/m (Richter et al. 1991). The advantage of

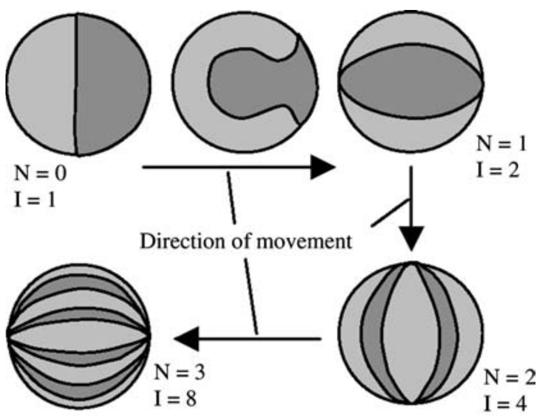

Fig. 16 Mixing pattern by rolling (Fowler et al. 2002 © IEEE)

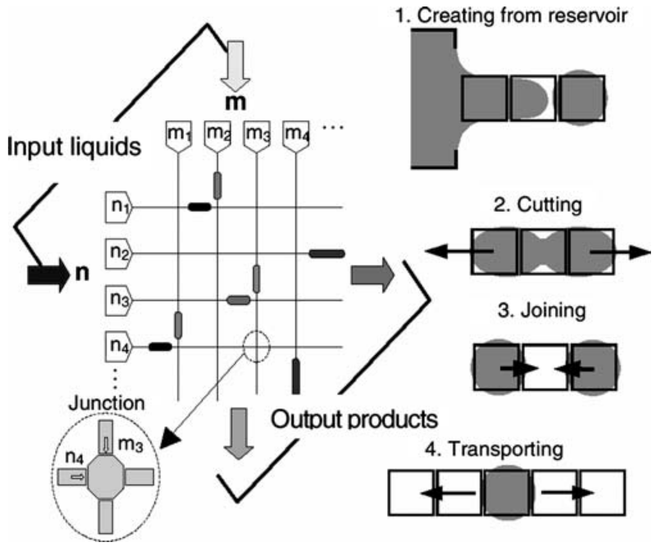

Fig. 17 Envisioned digital microfluidic circuit and the four fundamental droplet operations necessary (Cho et al. 2002 © IEEE)

EHD micropumps is that they do not have moving parts, whereas the disadvantage is that the choice of working fluids is limited by the electrical conductivity.

The body force term for EHD equations **F** is given as

$$\mathbf{F} = q_f\mathbf{E} + (\mathbf{P}\cdot\nabla)\mathbf{E} - \frac{1}{2}E^2\nabla\varepsilon + \frac{1}{2}\nabla\left[E^2\rho\frac{\partial\varepsilon}{\partial\rho}\right] \quad (1)$$

where q_f is the free space charge density, **E** the electric field, **P** the polarization vector, ε the material permittivity and ρ the mass density of the fluid. The terms on the right-hand side correspond to the Coulomb force on free space charge, the Kelvin polarization or dielectrophoretic force, the dielectric or Korteweg-Helmholtz force, and the electrostrictive force, respectively. For EHD micropumps, usually the first and third terms are important.

As shown in Fig. 8, EHD injection pumps based on the Coulomb force require two permeable electrodes in direct contact with the working fluid. The EHD injection pump shown in Fig. 9 drives various polar fluids such as ethanol and propanol (Richter and Sandmaier 1990; Richter et al. 1991). Recently, Yang (2003b) fabricated a more miniaturized EHD injection pump using indium-tin-oxide electrodes.

To overcome the limited applicability to fluids with extremely low electrical conductivity, Fuhr et al. (1992) developed a high-frequency traveling-wave-induced EHD pump, and succeeded in pumping water and weak electrolyte solutions, as shown in Fig. 10. The gradient in natural electrical conductivity or permittivity which is necessary for traveling-wave-induced electroconvection is produced by the traveling waves itself.

In addition to the EHD micropumps, electro-osmotic micropumps have been widely studied (for example, Mutlu et al. 2002; Chujo et al. 2003). As shown in Fig. 11, electric charge near the fluid-wall interface, i.e., the electric double (Helmholtz) layer, is driven by an external electric field.

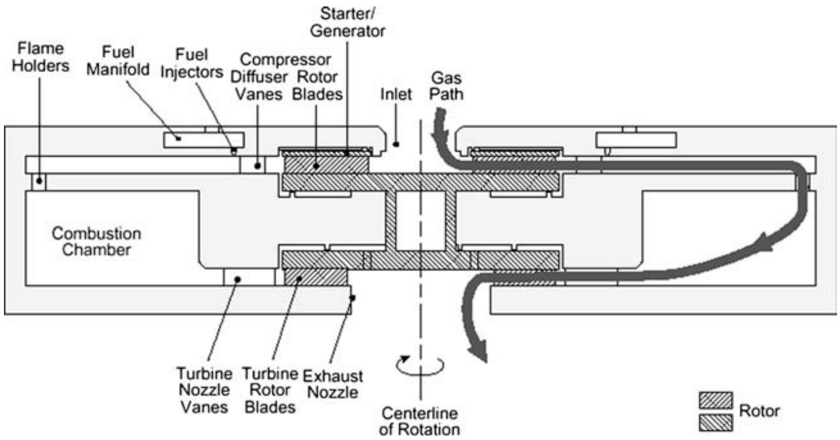

Fig. 18 Radial-flow ultra-microturbine (Epstein et al. 1997. Courtesy of Professor Alan H. Epstein of MIT)

2.6 Acoustic wave or vibration type

Although, to the author's knowledge, the amount of research is highly limited, there exist acoustic-wave or vibration-type micropumps. Moroney et al. (1991) proposed an ultrasonically induced (standing Lamb wave) microtransport system, while Miyazaki et al. (1991) describe a piezoelectric pump driven by a flexural progressive wave.

2.7 Interfacial tension type

The last type is based on interfacial tension, which is one of the effective surface forces in microscale phenomena. The pioneering study in this field was conducted by Matsumoto and Colgate (1990) on the electrical control of interfacial tension. As shown in Fig. 12, the balance among the horizontal components of interfacial tension is given by

$$\gamma_{SG} = \gamma_{SL} + \gamma_{LG} \cos\theta \tag{2}$$

where γ_{SG}, γ_{SL} and γ_{LG} are the interfacial tensions for solid-gas, solid-liquid and liquid-gas combinations, respectively.

If γ_{SL} can be controlled under the condition that γ_{SG} is constant, the contact angle θ changes, and thus the pressure inside the liquid also changes. On the basis of this mechanism, the horizontally reciprocating system shown in Fig. 13 was proposed.

From the viewpoint of surface tension control by temperature, the author proposed a micropump based on the Marangoni effect (Yoshida et al. 2002). Figure 14 shows a conceptual view of the micropump system using thermoelectric elements as temperature controllers. Thermoelectric elements are distributed inside a channel, and an appropriate amount of gas is trapped between the elements; the gas-liquid interfaces formed between the elements are the source of the pumping power. Each thermoelectric element simply depicted as a box in Fig. 14 has two junctions which absorb and discharge heat according to the Péltier effect; the left and right sides of the element correspond to the cold and hot junctions, respectively. Since heat transfer from these junctions to the working liquid imposes temperature

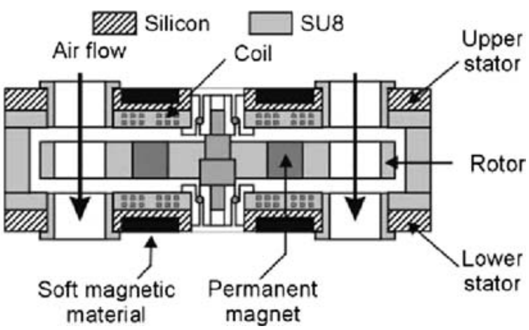

Fig. 19 Axial-flow ultra-microturbine (Holmes et al. 2004 © IEEE)

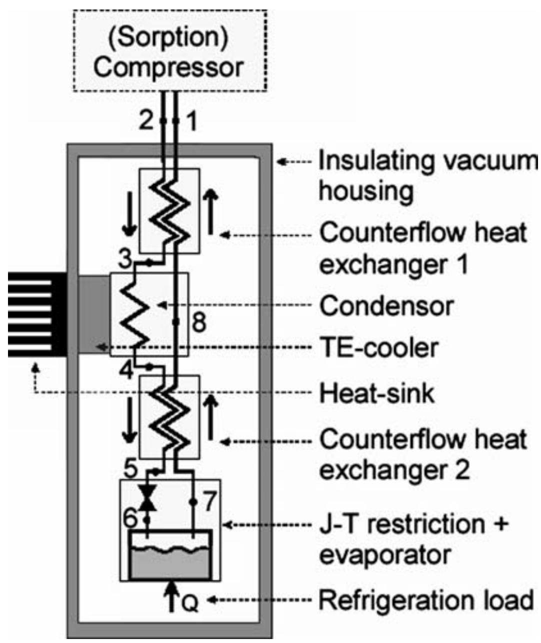

Fig. 20 Schematic diagram of microcooler (Burger et al. 2001 © IEEE)

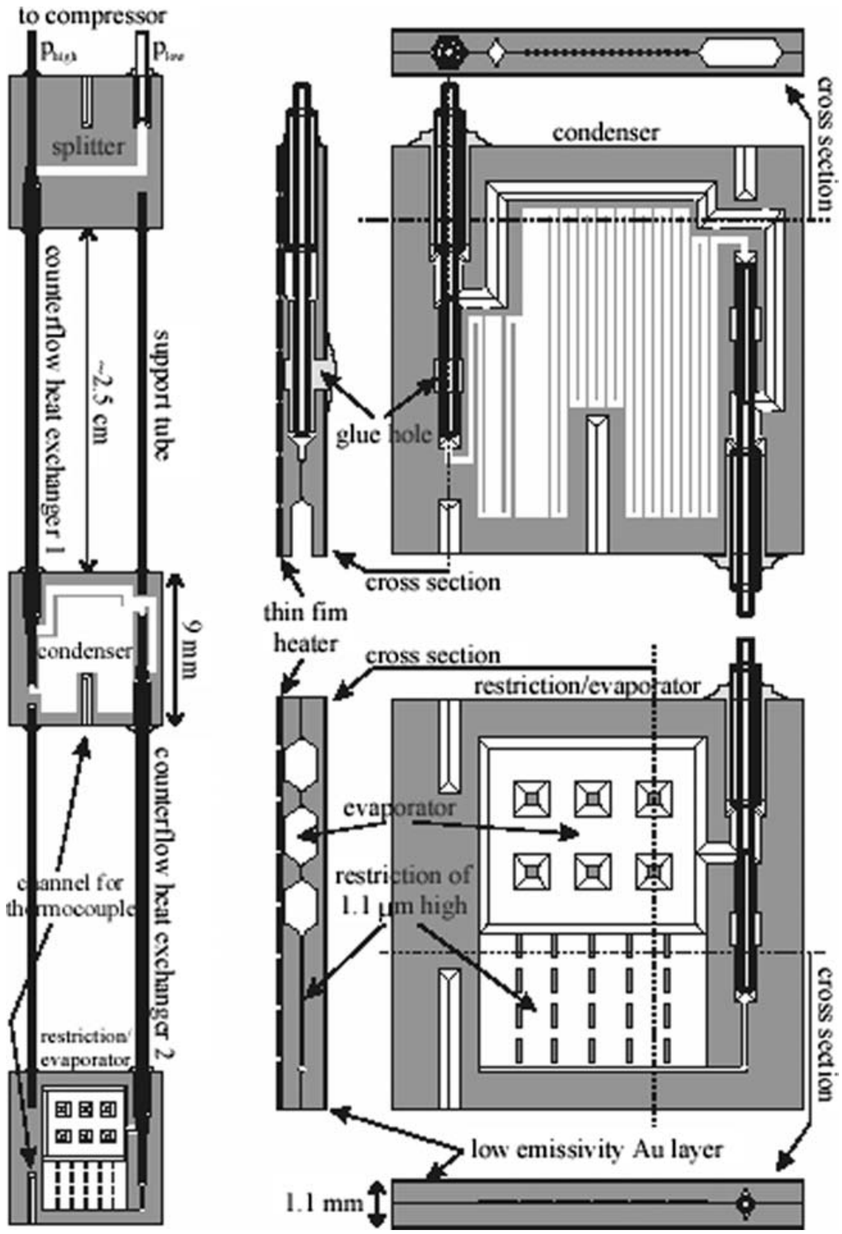

Fig. 21 Microcooler design (*left*) with enlargement of the condenser and restriction/evaporator structure (*right*) (Burger et al. 2001 © IEEE)

gradients along the gas-liquid interfaces, the flow from the hot-liquid side to the cold-liquid side is induced by the Marangoni effect. In order to boost the flow, many thermoelectric elements are distributed along the flow circuit. The following are the features of this system:

- The system does not contain any moving parts, and has a very simple structure.
- There is no flow pulsation, unlike the reciprocating pump.
- There is no limitation on the electrical conductivity of the working liquid as encountered in EHD pumps.
- Flow is easily controlled by the electric voltage applied to the thermoelectric elements.

Furthermore, reversal of flow direction is also possible by reversing the applied electric voltage. Although the author only conducted a numerical analysis, DeBar and Liepmann (2002) fabricated a thermocapillary pump.

2.8 New system based on interfacial tension

As sophisticated extensions of the micropump based on the interfacial force, new systems have been proposed by Kim's group at UCLA. Figure 15 shows a family of liquid actuation principles using electrically varied surface tension (Lee et al. 2001); Fig. 15b is basically the same as Fig. 12. While continuous electrowetting (CEW) involves the changes in liquid-liquid surface tension, electrowetting (EW) and electrowetting-on-dielectric (EWOD) involve the changes in solid-liquid surface tension, γ_{SL}, at the solid-liquid-gas interface. In both EW and EWOD, the change in γ_{SL} results in a change in

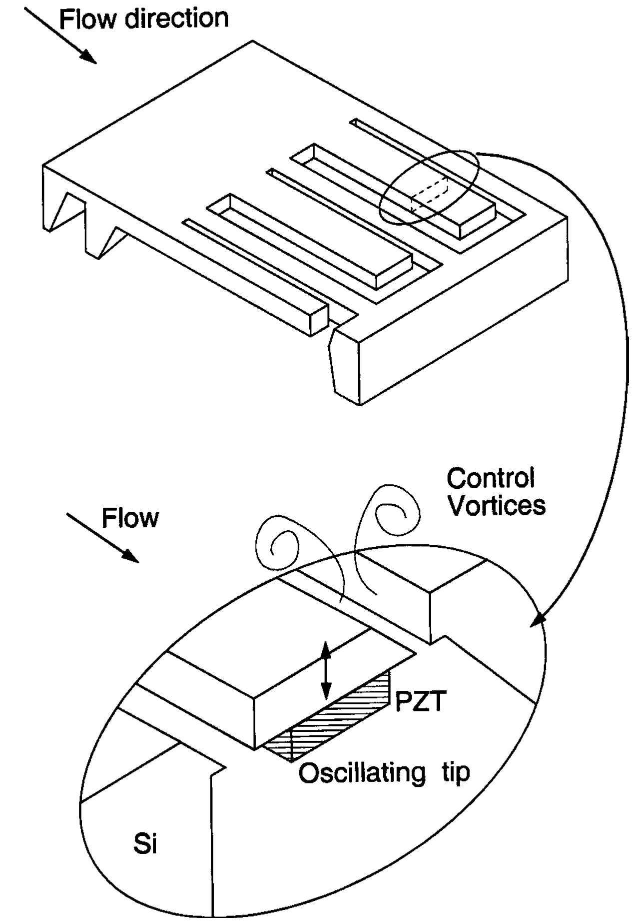

Fig. 22 Actuator concept (Kumar et al. 1999 © IEEE)

the contact angle and leads to liquid flow into and out of the channel. In EW, the electrical double layer (EDL) between the electrode and aqueous solution acts as a capacitance element to balance surface energy with electrical energy. In EWOD, the hydrophobic dielectric polymer acts in the same way as the EDL for EW.

On the basis of CEW, a micropump was fabricated (Yun et al. 2001); whereas using EWOD, the concept for mixing enhancement of droplet rolling was proposed as shown in Fig. 16 (Fowler et al. 2002). Furthermore, the group at UCLA proposed the concept of a digital microfluidic circuit, however, as illustrated in Fig. 17, four fundamental droplet manipulation mechanisms must first be established: (1) creating, (2) transporting, (3) cutting, and (4) merging of droplets in the fluid path (Cho et al. 2002). The most recent state of this research is reported by Cho and Kim (2003), Fan et al. (2003), and Gong et al. (2004).

3 Thermofluid control in miniaturized thermofluid machines

As the second aspect of possible applications, topics relating to miniaturized thermofluid machines are discussed in this chapter.

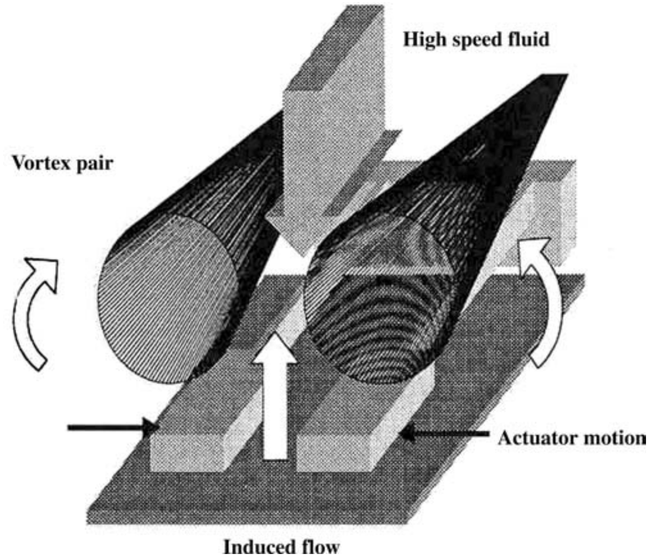

Fig. 23 Streak formation (Sherman et al. 1998 © IEEE)

For mechanical engineers, fabrication of miniaturized thermofluid machines, such as microengines, microturbines and microcoolers, is a simple but exciting dream. Although complete machines which can work independently by themselves have not yet been developed, studies concerning their components are currently in progress. Perhaps, the most well-known project is the MIT microengine project (Epstein et al. 1997; Epstein 2003). Figure 18 shows an ultra-microturbine with radial flow whose output power is designed to be 10–50 W. On the other hand, Holmes et al. (2004) at the Imperial College London, designed an axial-flow ultra-microturbine, shown in Fig. 19.

As shown in Figs. 20 and 21, Burger et al. (1999, 2001) of the University of Twente, fabricated the cryogenic micromachined cooler that is suitable for cooling from ambient temperature to 169 K and below. The microcooler operates by means of the vapor compression cycle with Joule-Thomson expansion. It consists of a silicon micro-machined condenser, a flow restriction/evaporator and two miniature glass-tube counterflow heat exchangers. Using a sorption compressor, the system was tested with ethylene gas from 20 to 1 bar, and produced a cooling power of 200 mW at 169 K with a mass flow of 0.5 mg/s.

4 Micro-thermofluid control for conventional-sized flow phenomena

As the third aspect of possible applications, topics relating to conventional-sized flow phenomena are discussed in this chapter.

Is it possible to control the macroscopic flows around conventional machines by MEMS? The answer to this question should be affirmative. This is because, fortunately, flow around a body is governed by a very thin

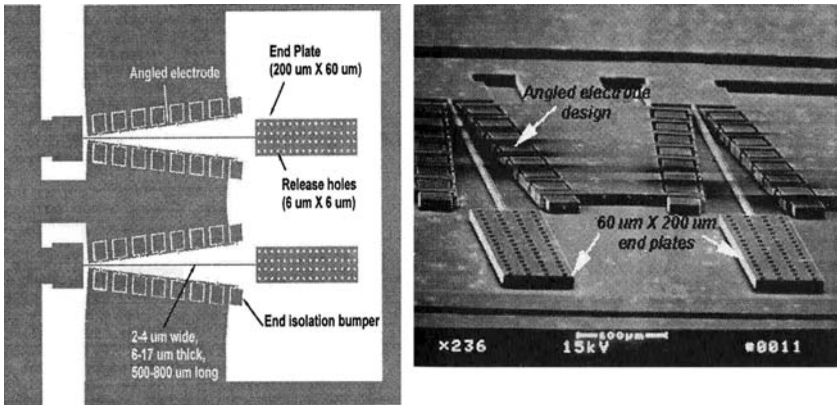

Fig. 24 **a** Design layout of in-plane microactuators. **b** SEM image of the fabricated in-plane microactuators (Sherman et al. 1998 © IEEE)

boundary layer. Furthermore, for turbulent flows in which fine eddy structures exert a decisive influence on the entire flow field, we can expect some additional possibilities of triggering new flow processes. If this is the case, control by MEMS would be considered to be one of the amplification processes in which a natural phenomenon and an artificial perturbation interact.

4.1 Boundary-layer control

It is widely known that for wall turbulent shear flows streaky structures near the wall are the key phenomena; these streaky structures are expressed in various ways using, for example, longitudinal vortex, ejection, sweep, and bursting phenomena. Although the detailed eddy structures near the wall have been clarified from direct numerical simulations, much remains unknown concerning the overall flow responses to various external

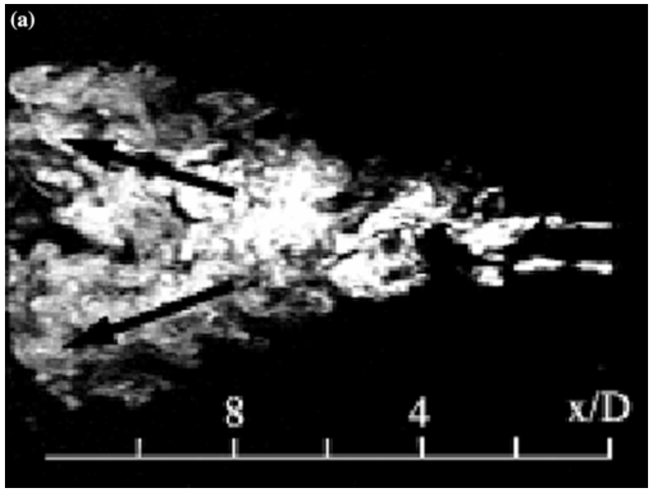

Fig. 26 Bifurcating jet excited with the two halves of flaps out of phase (Suzuki et al. 1999 © IEEE)

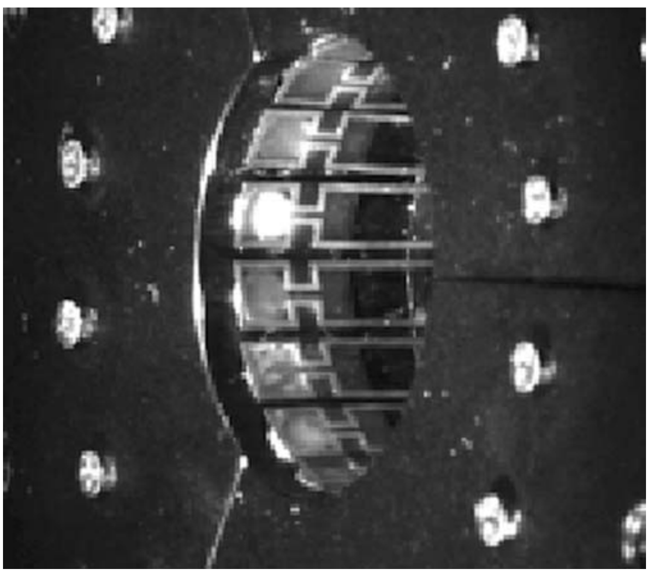

Fig. 25 Nozzle exit with 18 flap actuators (Suzuki et al. 1999 © IEEE)

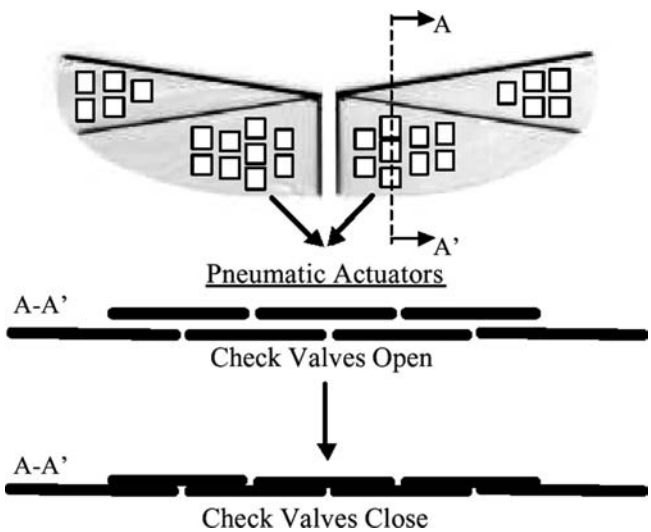

Fig. 27 Integrated actuator MEMS wing concept (Pornsin-Sirirak et al. 2002 © IEEE)

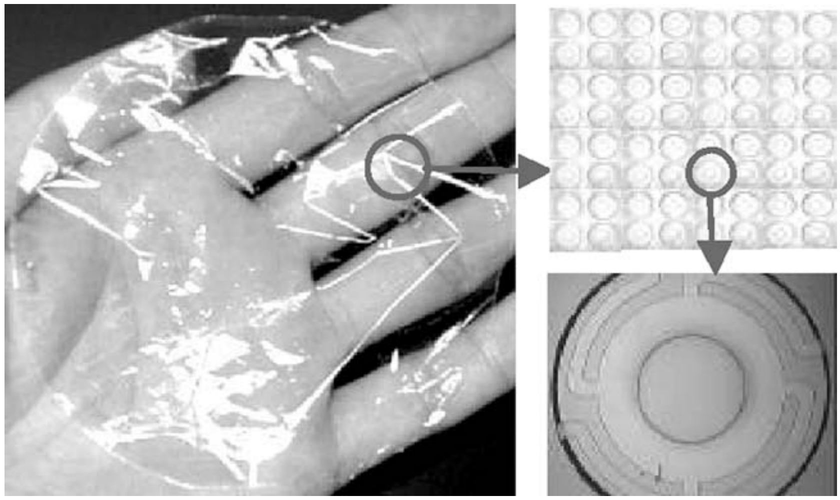

Fig. 28 Flexible parylene-valved actuator skin (Pornsin-Sirirak et al. 2002 © IEEE)

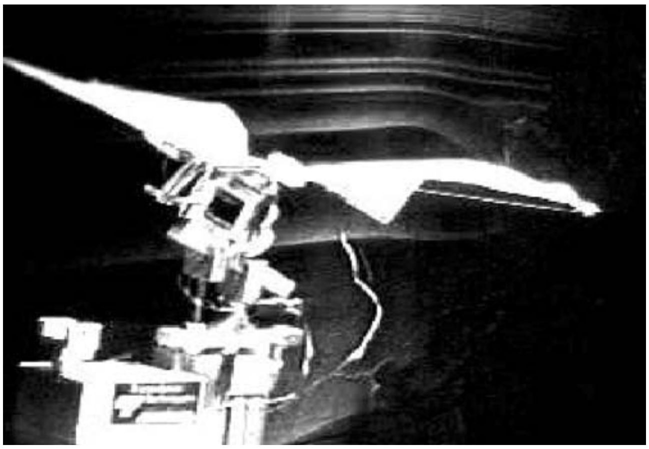

Fig. 29 Wind tunnel aerodynamic test (Pornsin-Sirirak et al. 2002 © IEEE)

perturbations. Therefore, experimental studies using actuators and sensors based on MEMS technology are very important. For both laminar and turbulent boundary layers, Kumar et al. (1999) of Stanford University performed active control experiments using vortex generators, as shown in Fig. 22; the array consists of individually addressable piezoceramic-silicon cantilevers with integrated cavities and unequal side gaps. On the other hand, as shown in Figs. 23 and 24, Ho's group at UCLA fabricated an electrostatically driven microactuator moving in the in-plane direction such that form drag of the actuator can be eliminated (Sherman et al. 1998).

4.2 Free-jet control

Since the eddies generated in free shear flows are larger than those in wall shear flows, larger actuators are considered to be suitable for flow control. For an axisymmetric jet, Kasagi's group at the University of Tokyo installed a row of 18 miniature electromagnetic flap actuators on the nozzle exit, as shown in Fig. 25 (Suzuki et al. 1999). When upper and lower halves of the 18 flaps are driven out of phase, the jet bifurcates into two branches, as shown in Fig. 26.

4.3 Flight control

Although flight control for an actual plane by MEMS may be a distant dream, a challenging project on a flapping-wing micro-aerial vehicle (MAV) is being carried out by Ho's group as described by Pornsin-Sirirak et al. (2000, 2001, 2002). Since control of the wings' pressure distribution is very important for achieving optimal aerodynamic performance, they introduced devices on the wing membrane that can regulate the wing load. Furthermore, they fabricated wafer-sized flexible parylene actuator membranes, which they call "skins," and integrated these skins onto the MEMS wings. Since parylene has a very low Young's modulus, it is frequently used as structural material for MEMS, as reported by Wang et al. (1999).

The above concept is illustrated in Fig. 27. For each flapping cycle, pressure loading either pushes the valve caps open or closed, which controls the air movement through the vent holes. The opening of the valves equalizes the pressure between the upper and the lower surfaces of the wings. When the valves are closed, the existence of the pressure difference can affect the aerodynamic performance, i.e., lift and thrust. The fabricated parylene-valved actuator skin is shown in Fig. 28. The vent holes are 1.5 mm apart; the vent holes and valve caps have diameters of 0.5 and 0.9 mm, respectively. The thickness of the bottom parylene is about 10 µm.

As shown in Fig. 29, the actuator skins were integrated onto the MEMS wings and tested in a low-speed wind tunnel. The test results have shown very significant effects on the aerodynamic performance. Compared to the reference MEMS wings (no actuators), both the lift and thrust of the parylene check-valved wings were improved by more than 50%.

5 Concluding remarks

Possible applications of micro-thermofluid control have been overviewed in terms of the three aspects classified in Fig. 1. To the author, it has been an exciting experience to confirm the dynamic activities in this field through the research history of the IEEE International Workshops and Conferences on MEMS.

Although the author did not investigate all the fields of MEMS research, the author has gained the following impression. In the early period of MEMS research, there existed a tendency for divergent concerns or efforts to show the unlimited possibilities of MEMS; that is, the researchers' byword was "what can MEMS research do?". Recently, however, the activities have been focused on necessity; that is, the researchers' byword has changed to "what should MEMS research do?"

As a researcher basically based in heat transfer, the author is highly stimulated by the state of the art in micro-thermofluid control. The author hopes that this review will relay the vibrant atmosphere of micro-thermofluid control research to the readers.

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