NOTES

Experimental investigation on phase transformation type micropump

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Abstract **The phase transformation type micropump without moving parts was experimentally studied in this note. To analyze the pumping mechanism of the micropump, a simplified physical model was presented. The experimental results indicate that the pump characteristic is mainly dependent on the heating and cooling conditions. For a given system, there exist an optimal combination of heating current and switch time with which the flow rate reaches maximum. Comparing with the natural cooling, the forced convective cooling needs larger heating current to obtain the same flow rate. In our experiments, the maximum flow rate is 33 μL/min when the inner diameter of the micropump is 200 μm, and the maximum pumping pressure reaches over 20 kPa. The theoretical analysis shows that the pumping mechanism of the micropump mainly lies in the large density difference between liquid and gas phases and the effect of gas chocking.**

Keywords: micropump, phase transformation, pumping characteristic.

Micro fluidic system is an important branch of micro-electro-mechanical systems (MEMS). In recent years, it has been a hot research field. The micropump, as an important actuator, is the basic sign of the development level of micro fluidic system. With the micropump being smaller and smaller, the fabrication of the moving parts becomes more and more difficult. Therefore, more attentions have been paid to the micropump without mechanical moving parts. And many micropumps based on new principles came out, such as thermopneumatic micropump[1], electro-hydro-dynamics (EHD) pump[2–4], magnetohydrodynamic (MHD) micropump[5], micro ion drag pump[6], valveless diffuser micropump[7,8], phase transformation type micropump[9,10], etc.

The thermal inertia of the fluid flowing in a channel decreases sharply when the dimension of the channel becomes smaller. This makes the phase changes possible within a very short time. Therefore, by scanning electric current supplied cyclically through the stainless steel microtube, the fluid in a microchannel is easily evaporated/condensed and pumped toward the scanning direction. The basic structure of the micropump is shown in fig. 1.

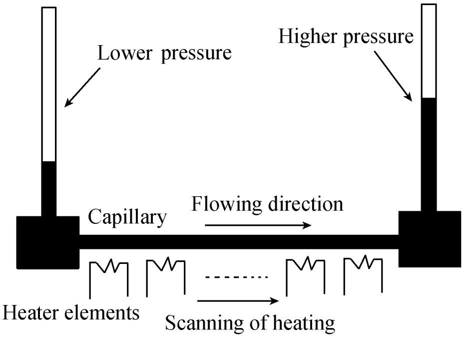

Fig. 1. Structure of the phase transformation type micropump.

Ozaki et al. [9,10] first did creative research on this micropump. They measured the pumping characteristics and analyzed the pumping mechanism of the micropump with a simple model. In the analysis, they assumed that three segments of fluid, which are liquid, gas, liquid respectively, flowed in the channel, as shown in fig. 2, and the flow was time-independent. In Case Ⅰ, no vaporized areas are in the channel. Pressure geadient is constant throughout the channel and the fluid flows from point *O* to point *I*. In Case Ⅱ, there exists a vaporized area and the gas is quiescent relative to the liquid. Then most of the total pressure drop occurs in the vaporized area. In Case Ⅲ, the vaporized area moves towards the point *O*, the inverse direction on the arrows in fig. 2. In this case, pressure drop in the vaporized area is larger than that in Case Ⅱ due to the movement of phase boundary, point *E* and *C*. If the moving velocity of the vaporized area is large enough, the pressure drop in the area becomes bigger than the pressure difference between point *I* and point

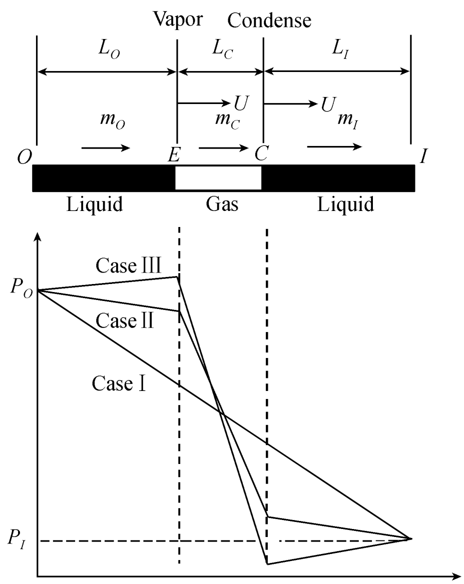

Fig. 2. Analysis of the pumping mechanism.

O. Then the direction of pressure gradient in each liquid area changes as shown in fig. 2 and the fluid flows from point *I* to point *O*. It means that the pump works. They ascribed the pumping mechanism to the large difference of kinematic viscosities between liquid and vapor phases.

In order to further study the pumping mechanism and to master the pumping rules of the micropump, the experimental study on the micropump was performed, and a simplified model was presented to analyze the pumping mechanism.

1 Experimental system

The experimental system is shown in fig. 3, which consists of two parts: the pumping system and the controlling system.

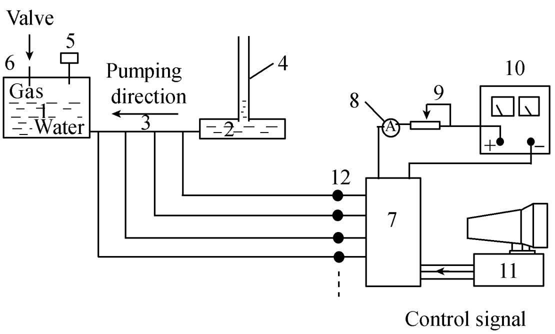

Fig. 3. The experimental system. 1, Vessel with higher pressure; 2, vessel with lower pressure; 3, stainless steel capillary; 4, glass tube with scale; 5, micro pressure sensor; 6, valve; 7, heating controller; 8, amperemeter; 9, resistor; 10, power supply; 11, computer; 12, indicator lights.

The pumping system consists of parts 1—6. The stainless steel microtube is used to pass through DC current to heat and vapor the water flowing in the tube circularly. The working fluid used is distilled water. The dimensions and the subsections of the two stainless steel microtubes used in the experiments are shown in table 1.

Table 1 The dimensions and subsections of the two microtubes used in the experiments

Tube	Inner Diameter/μm	Outer Diameter /μm	Length of tube/cm	Number of subsections	Length of every subsection/cm
1	200	300	30	5	4
2	300	400	30	7	3

The controlling system consists of parts 7—12. The heating controller 7 and computer 11 are used to control the periodical heating. The heating controller is an electronic circuit made up of a set of relays and other electronic components. Indicator lights are used to show the local heated interval.

2 Results and analysis

For the case that the inner diameter of the stainless steel microtube is 200 μm, the experimental results of the averaged volumetric flow rate versus heating current are shown in fig. 4. Here, the so-called switch time is the time interval heating one subsection in a cycle.

It is obviously shown from fig. 4 that the heating condition, embodied by the heating current here, is the key factor affecting the pumping flow rate. For different switch times, the flow rate begins to increase obviously almost at the same heating current. If the heating current is large enough to boil the water in the stainless steel microtube, the flow rate rises rapidly to the maximum. With the current rising on, the cooling condition, which relates to the switch time and the cooling surrounding, becomes the key factor affecting the flow rate. If the thermal energy inserted in the heating region does not dissipate before the next heating circle, the vapor in microtube cannot fully condense. Then the indispensable phase transformation process will not exist. Consequently, the flow rate will drop down. If the current is so large that the whole microtube is full of overheated stream, the pump will not work any longer.

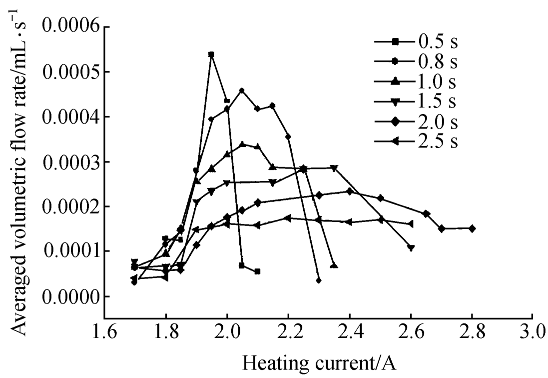

Fig. 4. The flow rate changing with the heating current when the switch time is a constant.

The results of the average volumetric flow rate versus switch time are shown in fig. 5. For different heating currents, the switch times needed to reach the maximum flow rates are different. If the switch time is long enough, the flow rates tend to be accordant although the heating currents are different. Furthermore, the flow rate is nearly inverse proportional to the switch time. The dash line shown in the fig. 5 is a curve of inverse proportion function. This shows that when the switch time is long enough, the flow rate will never vary with the heating current. The reason is that the water in the heating region is fully vaporized due to the long switch time and any further increase of heating current will not make the flow rate in-

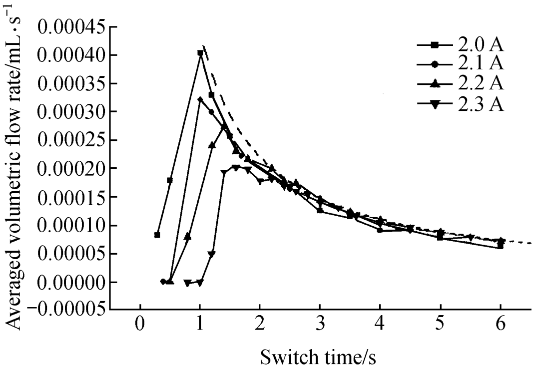

Fig. 5. The flow rate changing with the switch time when the heating current is a constant.

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Fig. 6 shows the pressure head versus the pumping flow rate. When the heating currents are the same, the pressure head for the case of a shorter switch time is higher. When the switch time is the same, the pressure head at zero flow rate for the case of larger heating current is higher. The relations between the pressure and the flow rate in both positive and negative flow rate regions are nearly linear respectively. In the present experiment, the maximum of pressure head is over 20 kPa.

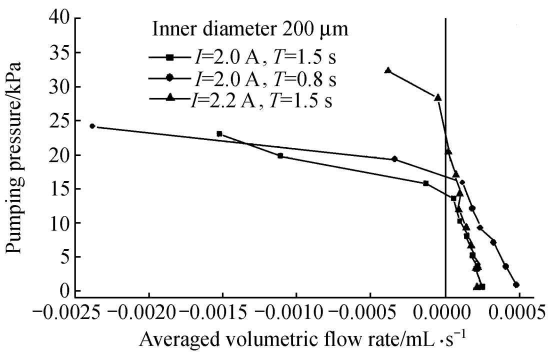

Fig. 6. The pressure head of the pump.

In order to analyze the the effect of inner diameter of the microtube, a micropump with a stainless steel microtube of inner diameter 300 µm is also experimentally studied. The results are shown in figs. 7 and 8. For comparison, the results of the micropump with a microtube of inner diameter 200 µm are also plotted in the corresponding figures.

It is seen from fig. 7 that if the inner diameter of the microtube is larger, the minimum heating current needed for micropump working will be also larger. Fig. 8 shows that the two micropumps have little different features. For the micropump with a microtube inner diameter being 200 µm, the smaller the current, the larger the pumping flow rate, and if the switch time is long enough, the flow rates

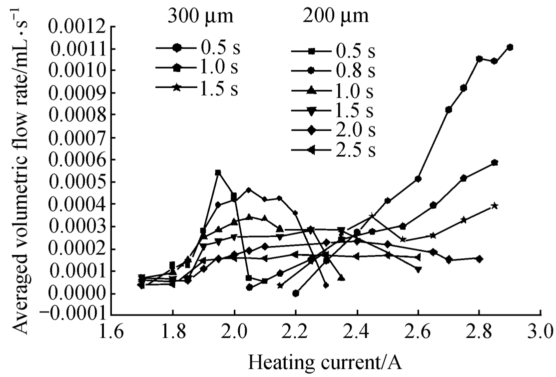

Fig. 7. The flow rate changing with heating current of different inner diameters of the micro channel.

tend to be accordant although the heating currents are different. It can be explained that the water in the local heating region could be fully vaporized within the selected heating current region (2.0 A—2.3 A). For the micropump with a microtube inner diameter being 300 µm, the pumping flow rate with higher heating current is larger. The reason is that the heating current in the selected region (2.2 A—2.4 A) is not large enough to fully vaporize the water in the heating region. It can be concluded that the flow rates will also tend to be accordant if the switch time is long enough, in other words, if the water can be fully vaporized.

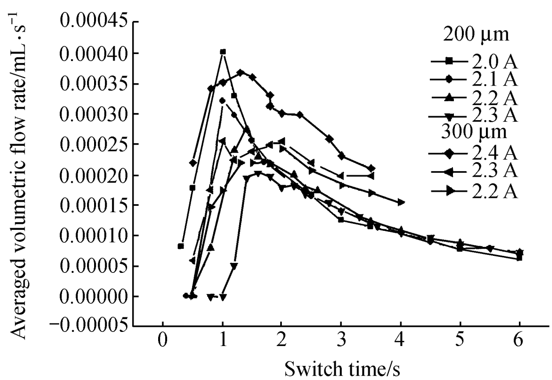

Fig. 8. The flow rate changing with switch time of different inner diameters of the micro channel.

The experiments mentioned above are under natural convective cooling. To study the effect of cooling condi tion on the pumping characteristics, the experiment is also performed under forced convective cooling, which is re alized by a fan. The heat transfer coefficient is much larger than natural convective cooling. The pumping flow rate versus heating current is shown in fig. 9, where the switch time is 2 s. Compared with the natural convective cooling, higher heating current is needed to obtain the same flow rate.

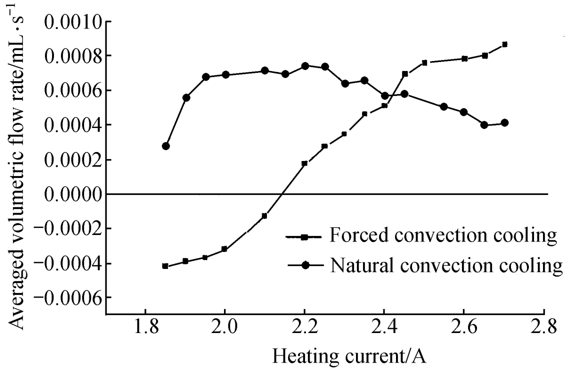

Fig. 9. The flow rate versus heating current under different cooling conditions.

3 Analysis of the pumping mechanism

In general, the fluid flow in the microtube must be a laminar flow due to the small inner diameter and not very high velocity. So a simplified physical model of laminar flow with a continuously moving heat source is established as shown in fig. 10. The heat source moves at a speed of U towards point O, and the fluid is pumped from the lower pressure port I to the higher pressure port O. The liquid is heated up and vaporized at the section E. Cooled by the environment, the vapor is condensed at the section C. The length of the gas section is assumed to be L_C, whose value is dependent on both heating and cooling conditions. If the process is stable, the gas will move at the same speed of the heater, and the length of the gas section remains constant.

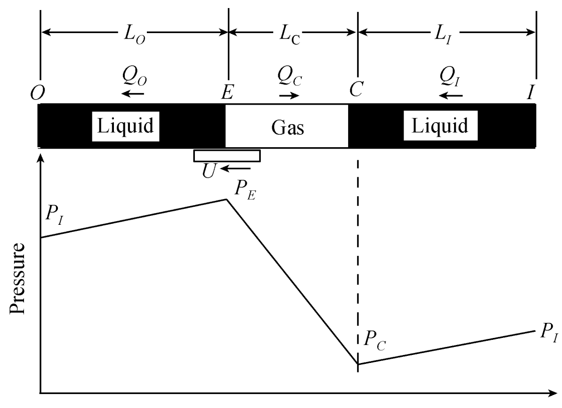

Fig. 10. The simplified model of laminar flow with continuously moving heater of the micropump.

Using the relations of laminar flow in circular tube and mass conservation equations both of the whole tube and at the interfaces between liquid and gas, the flow rate can be derived as follows:

$$Q = \frac{-F\Delta P + AU(\rho_L - \rho_G)L_C v_G}{\rho_L\left[L_{v_L} + L_C(v_G - v_L)\right]}, \tag{1}$$

where $F = \pi r^4/8,\ A = \pi r^2,\ \Delta P = P_O - P_I$.

Eq. (1) is an idealized result. In order to compare with the experimental results, it is modified according to the experimental condition. It is noticed that in the theoretical analysis the gas section is assumed to exist, therefore, the water pumped in a cycle is not the total volume of the tube, the volume of the gas should be cut out from the total tube volume. The modified expression of the averaged flow rate is

$$Q^* = \frac{-F\Delta P + AU(\rho_L - \rho_G)L_C v_G}{\rho_L\left[Lv_L + L_C(v_G - v_L)\right]}\left(1 - \frac{L_C}{L}\right). \tag{2}$$

It is seen from eq. (2) that if the micropump does work, the following qualification should be met, i.e.

$$U > \frac{F\Delta P}{A(\rho_L - \rho_G)L_C v_G}. \tag{3}$$

Ineq. (3) shows that the heat source should move faster than a critical speed, otherwise, the micropump cannot work. If the density difference between liquid and gas is too small or the kinematic viscosity of the gas is not large enough, the qualification of pumping is hard to meet. As a result, the pumping mechanism of the micropump mainly lies in the large difference of densities between liquid and gas and the chocking function of the gas section. Also, it is seen that the critical speed is proportional to the square of the diameter of the tube. It means that this kind of micropump is suitable for micromation.

When the pressure drop between inlet and outlet is so small that it can be ignored, eq. (2) can be simplified as in the following:

$$Q^* = \frac{AU}{1 + \frac{v_L}{v_G}\left(\frac{L}{L_C} - 1\right)} \cdot \left(1 - \frac{\rho_G}{\rho_L}\right)\left(1 - \frac{L_C}{L}\right). \tag{4}$$

It indicates that the flow rate is relative to the moving speed of the heat source and the length of gas section if the working fluid and the dimension of the micropump are given. And if the moving speed of heat source does not change, there exists an optimal length of gas section L_C with which the flow rate reaches maximum. The value of L_C is determined by both heating and cooling conditions. In general, heating condition is the main factor of affecting the flow rate if the heating current is small. For this case, the larger the heating current, the larger the L_C and the flow rate. If the heating current is large enough, the cooling condition is the main factor. For this case, larger heating current could result in a smaller flow rate. These phenomena are experimentally proved by figs. 4 and 7.

4 Conclusion

The most important factors that affect the pumping characteristic are heating and cooling conditions. For a given system, there are an optimal heating current and a switch time corresponding to the maximum pumping flow rate. If the switch time is unchanged, the flow rate will first rise up and then drop down with the increasing heating current. For a given heating current, the flow rate is nearly inverse proportional to the switch time if the switch time is long enough. Compared to the natural convective cooling, a larger heating current is needed under the forced convective cooling condition.

The theoretical analysis based on the simplified physical model shows that the pumping mechanism of the phase transformation type micropump mainly comes from the large difference of densities of liquid and gas and the chocking function of the gas section.

Acknowledgements This work was supported by the National Natural Science Foundation of China (Grant No. 59995550-2) and the National Key Project of Fundamental R&D of China (Grant No. 1999033106).

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(Received November 2, 2001)