Experimental investigation of thermal flow in asymmetric micro pulsating heat exchanger using LIF technique

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Abstract Heat and flow visualization has been carried out to investigate the thermal flow in an asymmetric and symmetric micro pulsating heat exchangers (MPHE). With the help of MEMS, the micro heat exchangers were fabricated with a total of 16 parallel rectangular channels, which were interconnected by forming a meandering closed loop. The mixture of ethanol and rhodamine B was used as a working fluid for LIF technique. In order to evaluate the thermal performance of heat exchanger, the thermal resistances with inclination angle were estimated and the effect of filling ratio of the working fluid was considered. As a result of visualization, the vertical orientation has the highest thermal performance even at low filling ratio due to the strongest gravitational force compared with horizontal and reverse orientations. The asymmetric MPHE gives the better performance of heat transfer than the symmetric MPHE due to the active repetitive circulation between the generation and dispersion of slug flows.
Keywords: Pulsating Heat Exchanger, LIF Technique, Annular Flow

1 Introduction

As the electronic component keeps being smaller and denser, the thermal fatigue failure of the component emphasizes the importance of research for small heat transport device [1]. In the several types of heat transport device, heat pipe has been applied to many industrial fields with various methods because of high heat flux and simple fabrication process. As the size of heat pipe becomes smaller, in case of narrow pipe or tube, liquid slug and vapor plug which disturb inner thermal flow causes operating failure of heat pipe [2]. In order to overcome an inoperative state by miniaturization, a new type of pulsating heat pipe based on the slug and plug flows was reported in 1990 [3]. After that, there are so many studies of the MPHE (micro pulsating heat exchanger) for the purpose of thermal control in small electronic devices. Recently, an asymmetric MPHE with different frictional force was invented, and the efficiency of heat exchanger are improved continuously [4]. The approach to evaluate thermal efficiency, however, is confined to the measurement of surface temperature using thermocouple. The measurement of inner thermal flow is quite insufficient. Last year, the wall temperature contacting with inner fluid was visualized by infrared thermometry, where the temperature is not the temperature of fluid itself but the temperature at the outside surface of solid [5].
In this study, the asymmetric MPHE was visualized by laser induced fluorescence (LIF) technique in order to measure the thermal flow phenomenon inside the channel. For experiments, the asymmetric MPHE with the shape of looped micro channels of which the hydraulic diameters are 571, 444 ㎛, was fabricated by MEMS process. First of all, the thermal performance with respect to inclination angles, filling ratios and uniformity of channel diameter are evaluated. The temperature distributions inside the channel were visualized by the LIF technique.

2 Experiments

2.1 Fabrication of MPHE specimen

Fig. 1 shows the fabrication process, the schematic diagram and final specimen of MPHE. MEMS process which is consist of masking, metallization, photo resist, exposure, etching and DRIE was used to form micro channels on silicon wafer. A looped asymmetric MPHE is made up of 16 parallel rectangular channels with the depth of 400 ㎛ and the diameter of 1, 0.5 ㎜, respectively. A looped symmetric MPHE is also fabricated with the channel diameter of 1 ㎜. The whole size of the specimen is 22 x 44 ㎟ and the thickness is 600 ㎛.

In order to visualize inner flows, pyrex glass which is superior in insulation and strength was used for a top plate. Injection halls on the glass were fabricated using a femto-second laser to prevent leakage or crack. The etched wafer and the pyrex glass were completely bonded by an anodic bonding process.

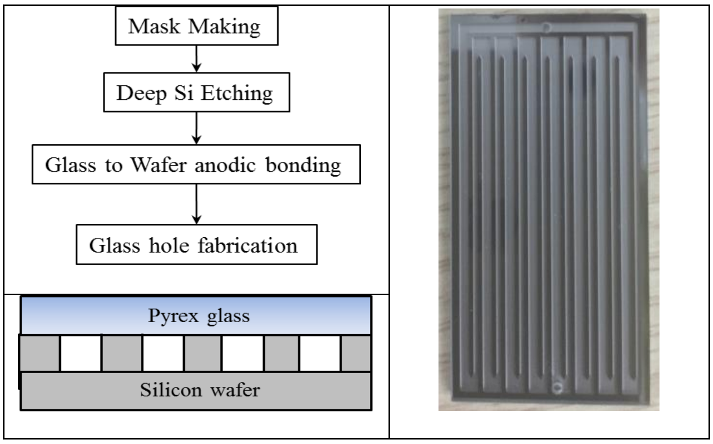

Fig. 1 MEMS process for MPHE and the specimen

2.2 Experimental apparatus

Fig. 2 shows the whole schematic of experimental apparatus. A vacuum pump is used to remove non condensable gas which exists inside a working fluid. At medium-vacuum status ($1x10^{-3}$ torr), ethanol (99.5%) as the working fluid is filled into the channels using a syringe pump. A ceramic heater (155 W/㎠, Watlow) is attached to the evaporator section. A water cooling system with a constant-temperature bath (±0.01℃, PolyScience) is installed to the condenser section. The surface temperature of MPHE is measured by a thermocouple (T-type), the measuring points are located at the evaporator, condenser, inlet and outlet of the cooling water. In order to apply LIF thermometry, the working fluid is mixed with a rhodamine B. A CCD camera with an expansion lens (5.6x) and optical filter (550 nm) was used to capture the images at the resolution of 1280x1024 pixels and at the speed of 1,000 fps.

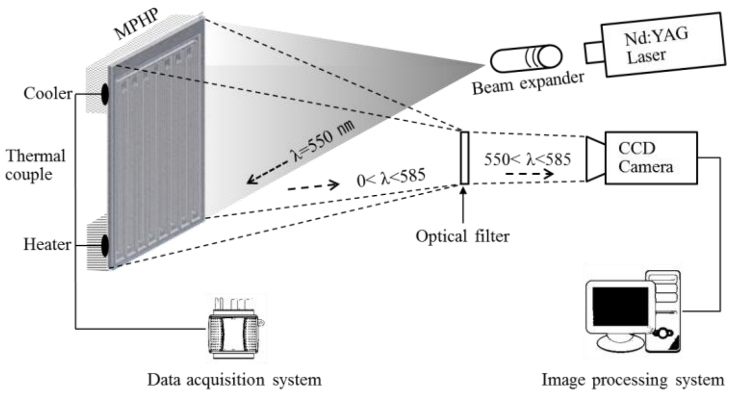

Fig. 2 Schematic of measuring system

2.3 Evaluation of thermal performance

To evaluate the thermal performance of multi-channels type heat exchanger, the heat transfer rate is calculated by the Fourier's law as follows;

$$R_{total} = \frac{T_e - T_c}{Q_{exchanger}} \tag{1}$$

$$Q_{exchanger} = Q_{cooler} \tag{2}$$

$$Q_{cooler} = \dot{m}C_p(T_{out} - T_{in}) \tag{3}$$

where, R_{total} is the thermal resistance and Q is the heat transfer rate, which can be evaluated at the condenser section based on the heat transferred from the condenser to the cooling water. T_e and T_c are the temperature at the evaporator and the condenser of the MPHE, respectively. T_{out} and T_{in} are the temperature at the inlet and the outlet of cooling water, respectively. At the evaporator section, the heating power according to input voltage is calculated on the basis of ohm's law as shown in Table 1.

Table 1 Heating power at the evaporator section

Voltage	0.0	3.0	6.0	9.0	12.0	15.0	18.0	21.0	24.0
Heating power(W)	0.0	0.3	1.3	2.8	5.0	7.8	11.3	15.3	20.0

2.4 Temperature calibration of LIF images

The basic principle of LIF technique for temperature measurement is to convert image intensity into temperature. Temperature is inversely proportional to the intensity of fluorescence image of rhodamine B excited by laser irradiation. In order to calibrate the relationship between the temperature and image intensity, maximum and minimum intensities are extracted from whole captured images. Fig. 3 shows the sample images for calibration at the maximum (90℃) and minimum (10℃) temperatures. The temperature between maximum and minimum values is linearly interpolated based on the linear LIF method.

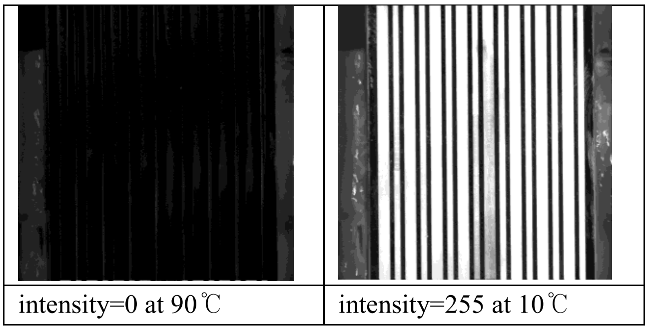

Fig. 3 Calibration of temperature using LIF images

3 Results and discussion

3.1 Estimation of thermal performance

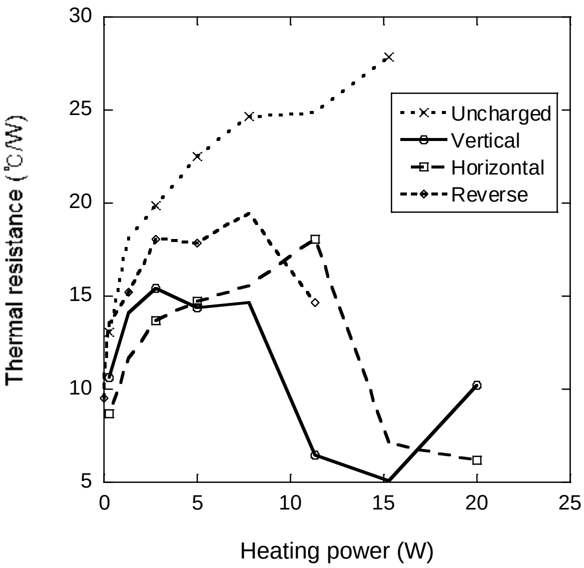

Fig. 4 Variations of thermal resistance according to heating power and inclination angle

In order to estimate thermal performance, Fig. 4 shows the variations of thermal resistance according to heating power and inclination angle. In all cases except for the uncharged case, the filling ratio of working fluid with rhodamine B is 50%. On the whole, the thermal resistances at the charged cases are lower than the uncharged case, irrespective of the inclination angle. After the heating power exceeds 10W, the difference in thermal resistance between the uncharged case and the charged case becomes bigger and bigger. Thus, it can be said that heat transport by convection becomes more dominant than by conduction, when the MPHE is charged. With regard to the inclination angle, the vertical orientation has lower thermal resistance than the horizontal orientation. The case of the reverse orientation shows the highest thermal resistance in the charged cases, the vacuum for normal operation inside the MPHE is kept up to heating power of 12W.

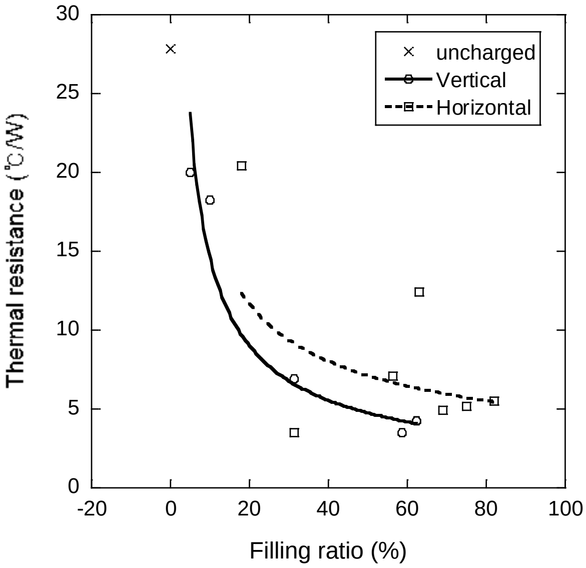

Fig. 5 Variations of thermal resistance according to the filling ratios of working fluid

Fig. 5 shows the variations of thermal resistance according to the filling ratios of working fluid at heating power of 14W. The data are compared at various inclination angles. Even though the filling ratio changes, the thermal resistances of the vertical orientation are always lower than that of the horizontal orientation. The lowest thermal resistances of the vertical and the horizontal orientations are 3.4(℃/W) and 4.9(℃/W), respectively. The filling ratio is optimum at the lowest thermal resistances. In this figure, the optimum filling ratio happens at 60% and 70% in the case of the vertical and the horizontal orientations, respectively. The difference of optimum filling ratios is caused by thermo-syphon effect through gravitational force. It is natural that the fast return of working fluid from condenser to evaporator is favorable to the increase of thermal performance in heat pipes. The vertical orientation has the highest thermal performance even at low filling ratio due to the strongest gravitational force compared with other orientations.

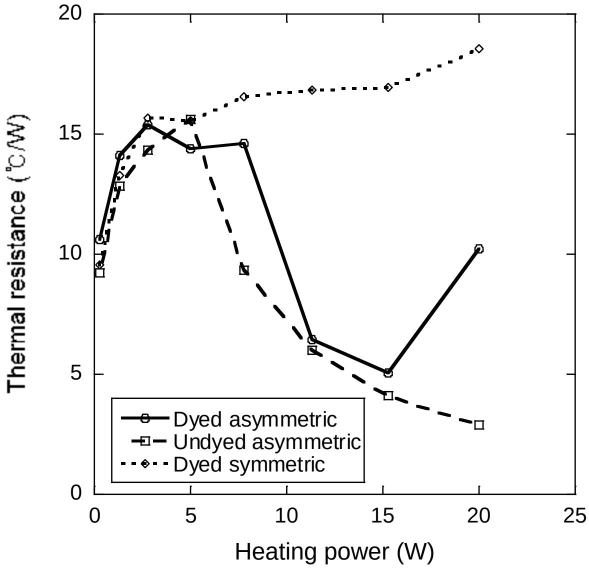

Fig. 6 Variations of the thermal resistance according to heating power in the case of dyed or undyed working fluid

Fig. 6 shows the variations of thermal resistance according to heating power in the case of dyed or undyed working fluid. In addition, the asymmetric and symmetric shapes of channel are tested. The dyed working fluid denotes that a very small amount of fluorescent dye (rhodamine B) is added to the working fluid. For the asymmetric channel, the thermal resistance of the undyed working fluid (pure ethanol) is lower than the dyed working fluid. The rhodamine B is worked as impurity in working fluid, so that the thermal performance decreased significantly at the heating power of 20W. For the symmetric channel, the thermal resistance becomes lower compared with that for the asymmetric channel. In both the symmetric and asymmetric channels, the operation of MPHE starts at the heating powers of 5W. However, the flow in the symmetric channel is quickly stabilized at the increased heating power, which results in the increase of thermal resistance. On the other hand, in the case of the asymmetric channel, the working fluid circulates more actively at the increased heating power, which results in the drastic decrease of thermal resistance.

3.1 Thermal flow visualization using LIF technique

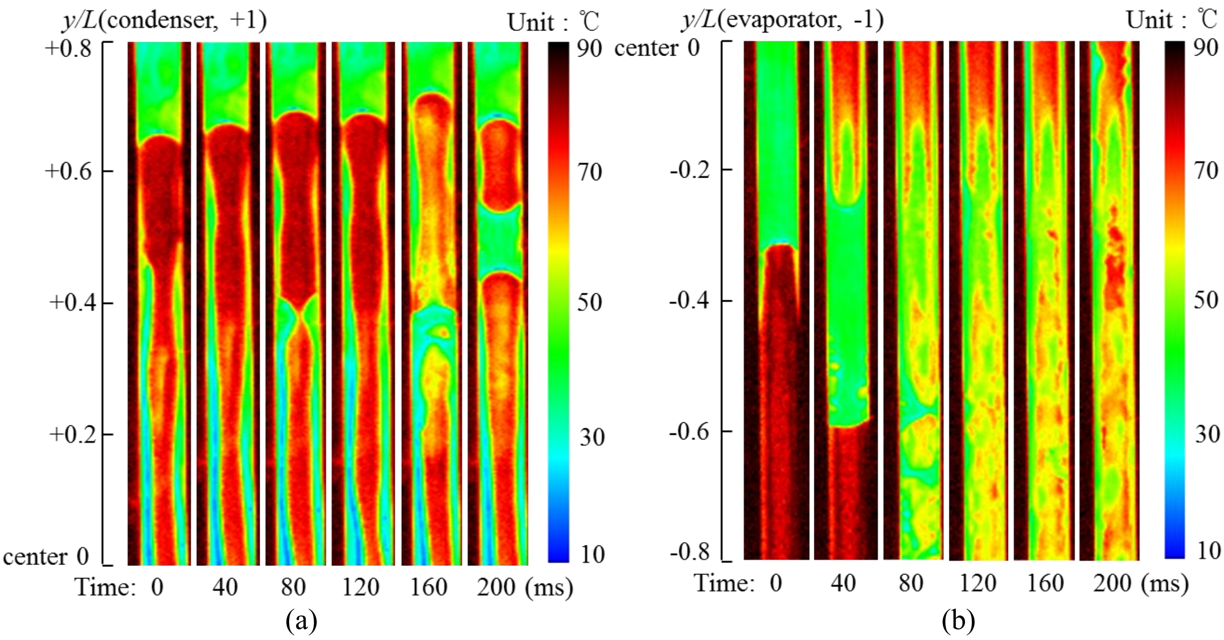

Fig. 7 Visualization of thermal flow using LIF at the channel with a diameter of 1.0 mm; (a) generation of slug flow, (b) dispersion of slug flow

Fig. 7 shows the thermal flow visualization for the asymmetric MPHE under the vertical orientation. The temperature fields are measured inside the channel with a diameter of 1.0 mm. Temporal variations of the thermal flow are considered. The length from the evaporator section (+direction) to the condenser section (-direction) is nondimensionalized by the whole channel length.
The flow behaviors inside the channels are classified into two processes such as generation and dispersion of slugs. In the generation of slug flow ((Fig. 7(a)), annular flow in a form of thin film occurs on the side wall of channel. The liquid phase of the annular flow moves to the evaporator and the gas phase moves to the condenser. Finally, the liquid phase gathers in the middle of the channel, which gives rise to the formation of a new slug flow. In the dispersion slug ((Fig. 7(b)), the slug approaches evaporator section accompanying with the increase of liquid temperature. At the instance that the temperature of slug exceeds 70℃, the slug gets dispersed into a new annular flow by the boiling phenomenon. The repetitive process of the generation and dispersion of slug is the main mechanism of heat transfer in MPHE.

4 Conclusions

In this study, the evaluation of thermal performance for the asymmetric and symmetric MPHEs has been conducted by measuring the temperature fields using a LIF technique. The MPHEs with looped micro channels were fabricated by MEMS process. Ethanol mixed with rhodamine B was used as a working fluid and the thermal flows inside the channels were visualized. With regard to the inclination angle, the vertical orientation has the highest thermal performance even at low filling ratio due to the strongest gravitational force compared with other orientations. The asymmetric MPHE gives the better performance of heat transfer than the symmetric MPHE due to the active repetitive circulation between the generation and dispersion of slug flows.

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