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STUDY OF THERMAL BUBBLE MOTION IN MICROCHANNEL

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ABSTRACT

The micro capillary pumped loop system (MCPL) is a highly efficient device for heat transfer because the main driving force is a result of thermo-bubbles in micro-channel. In this study, the scaling effect with respect to the dimensional geometry of MCPL was studied for improving the heat transfer performance. The results showed that when a larger heating power was provided by microheater, the growing rate of thermal bubble was faster. Generally speaking, injecting a larger amount of working fluids resulted in faster thermo bubble motion. When the size of channel was scaled down, the nucleation of thermal bubble occurred easily and a positive performance of heat transfer was expected. These findings will be useful to the further optimal design of MCPL.

Keywords: MCPL, Micro-channel, Thermal bubble

INTRODUCTION

Nucleate boiling is a highly efficient heat transfer process favored in many industrial applications. Compared to pooling boiling, combined phase change triggered in open capillary microgrooves can achieve higher heat transfer coefficients and heat fluxes. Heat sinks with open capillary microgrooves have emerged with a strong potential in applications for spacecraft thermal control, high-power laser thermal management and microelectronic device cooling. Recently, it has become possible to produce artificial cavities using the Micro Electro Mechanical Systems (MEMS) technology. This technology allows boiling points, i.e. cavities, to be arranged freely. It is easy to create the cavities of various shape, size, and depth using this technology. The MEMS methods provide a way to examine boiling phenomena mechanistically, for example, with respect to the effect of the cavity size, the cavity shape and the cavity arrangement. Kenning et al. [1] performed pool boiling experiments and examined the behavior of bubbles that were generated on the heat transfer surface. The heat transfer surfaces used in their experiments were thin stainless-steel sheets. They measured the instantaneous temperature distribution on the back side of the heat transfer surface using a liquid crystal thermometry together with high-speed video recording. It was proven that the heat transfer surface temperature fluctuation was caused by the effect of the bubble growth and departure. The wall was cooled by the evaporation of a liquid micro layer present during the growth of bubble. The evaporation of the liquid micro layer was affected by the profile of the wall superheat. They pointed out that the effect of micro-layer evaporation on the heat transfer surface temperature was limited within the range of the maximum radius of the bubble generated on the cavity. Judd and Chopra [2] conducted boiling experiments using a glass plate as a heat transfer surface. The glass plate was coated with the thin layer of stannic oxide for heating. They observed the bubble behavior through the glass plate and examined the relation between the cavity spacing and the bubble interaction phenomena occurring between the neighboring nucleation sites. Dhir [3] and Shoji et al. [4–7] performed pool boiling experiments using a silicon wafer as the heat transfer surface. They created cavities on the silicon wafer surface using the MEMS technology. Dhir reported that the analytically predicted bubble shape agreed well with the measured bubble shape. Shoji et al. [reference?] reported that the interaction between the nucleation sites was composed of the bubble coalescence, thermal interaction, and the hydraulic interaction. Authors [8-9] examined the nucleate boiling following Shoji et al.'s procedure. Cylindrical-artificial cavities of 10 μm in diameter and 40 μm in depth were formed on a mirror-finished silicon wafer surface. The arithmetical mean roughness of the silicon wafer measured with an AFM (Atomic Force Microscope) was 2.2 nm. Pool nucleate boiling experiments using water were performed with the silicon wafer heat transfer surfaces. The relationship between the bubble coalescence and the cavity spacing, the temperature interaction between the nucleation sites, and the role of bubble movement were examined. The extent of the influence that a boiling bubble exerted in the pool nucleate boiling has been investigated by many researchers. Mikic-Rohsenow [10] proposed that the boiling bubble pushed up the superheated liquid layer to bulk liquid to the double extent of the size. Saha et al. [11] reported the evaporation of the superheated liquid of the micro and the macro layer within the extent of the bubble diameter occupied the main part of the heat transfer from the surface. Their analytical model, which was based on their proposal, provided good agreement with experimental data for a plane horizontal surface. Kiger et al. [12] measured the heat transfer surface temperature below the boiling bubble with a spatial resolution of 22 ~ 40 μm by using elaborated micro sensors in the pool boiling of FC-72. The result was that the ratio of the evaporation of the micro layer to the total heat transfer surface heat flux was 14.7 %. It is believed that to examine the evaporation of the micro layer around the boiling bubble, it is important to consider the nucleate boiling. In addition, under the condition of pure evaporating heat transfer, open capillary microgrooves can bear heat loads of up to a magnitude of 108W/m^2 [13] as shown by the intensive evaporation of the thin liquid film adjacent to the triple phase contact line [14]. When combined heat transfer of evaporating heat transfer in the thin film region and boiling heat transfer in the intrinsic meniscus region occurs, open capillary microgrooves can hold a higher cooling capacity. Labuntsov [15] denied the concept of a superheat layer adhering to whole bubble surface, and developed a correlation of bubble growth rate without knowledge of a detailed pattern of the bubble base. Zeng et al [16] analyzed force balance of an individual bubble in boiling pool and predicted bubble detachment diameter referring to Zuber's correlation of bubble growth rate [17]. R. Mei et al [18] carried out a numerical analysis to study bubble growth in heterogeneous boiling, considering simultaneous energy transfers among vapor bubble, liquid microlayer and heater. Zhao et al [19] proposed a dynamic microlayer model to analyze the bubble growing process and predicted the critical heat flux in fully developed nucleate boiling. The model adopted Cooper's correlation of microlayer thickness. Research results of boiling mechanism in microchannels are also numerous. For example, Thome et al [20] studied elongated bubble flow in micro channels and confirmed that instantaneous evaporation of the thin film around bubble drives bubble growth. Kenning et al [21] analyzed bubble growth in a capillary tube, considered bubble in a spherical shape at initial stage and then a confined shape with a column in the middle and a hemispherical shape at two ends. A number of experimental and theoretical investigations on pool boiling and flow boiling in micro channels have been conducted, but as of now few have been done on nucleate boiling in open capillary microgrooves. To explain the boiling mechanism in open capillary microgrooves, particular theoretical and experimental studies have to be done based on the special geometric structure of open micro grooves. The aim of the work described here is to shed light upon the boiling mechanism by analyzing individual bubble's growing process, and determining the bubble growth rate.

CHIP DESIGN OF THERMAL BUBBLE CHANNEL

According to the theory of thermal bubble motion, the prototype design of thermal bubble microchannel chip is shown in Figure 1. The right and left side of duct microchannel have dimensions are 7980μm×500 μm and 5280μm×500 μm respectively. Three blocks, whose dimensions are 1500μm ×100μm, were imbedded in the microchannel and acted as vapor bubble checked valves for producing different pressure drops with respect to right and left sides of channel and forces the generation of vapor bubble toward to right downstream. In addition, a diffuser with an angle and maximum width of 60º and 2665μm was fabricated into a hydrophilic area which was used to connect the two sides of the duct channel. Here, the right side of duct channel was set as a hydrophobic area and a cooling plate attached on the surface of the right side of outlet channel acted as a condenser. A fabrication process, shown in Figure 2, was done using the MEMS technology.

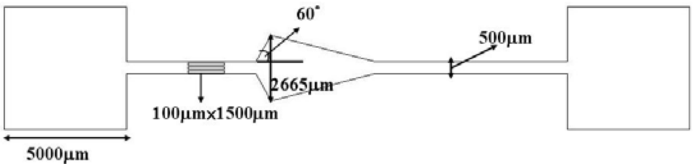

Fig. 1 The prototype of thermal bubble microchannel chip

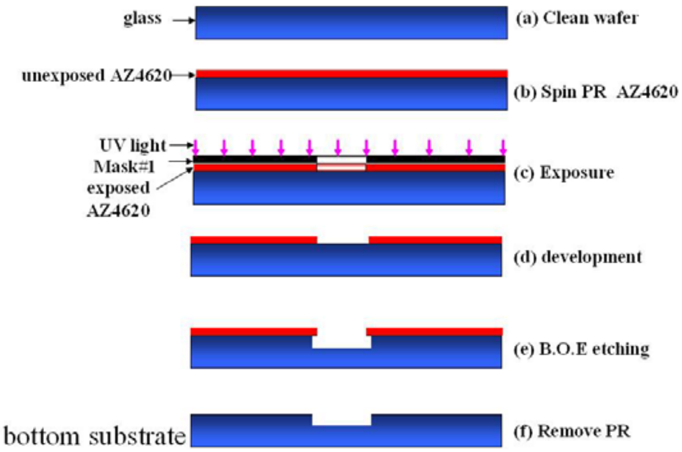

Fig. 2 The fabrication process of microchannel chip

EXPERIMENTAL RESULTS AND DISCUSSION

In this study, the generation phenomenon of thermal bubble was analyzed by flow visualization under different heating powers. To show the image clearly, pure water in pink color was utilized, and four micro-heaters shown in Figure 3 were fabricated by MEMS technology and imbedded in different locations of chip system. Here, the heating resistance for h1-h4 were set as 1574Ω, h2=1076Ω、h3=1060Ω、h4=933Ω respectively. Two cases with respect to different heating locations and constant heating power W=93mW and different flow rates and constant heating power were studied and are addressed below.

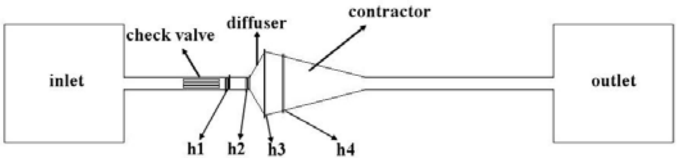

Fig. 3 Positions of four different of heaters, h1-h4, imbedded in the chip system

Case 1: different heating location and constant heating power W=93mW

Concerning the different thermal resistances for the four heaters, a constant heating power with 93 mW for the four heaters was selected and applied to realize the dynamic behavior of thermal bubble in the microchip. Comparison with the four microheaters operating at the same heating power yielded the following results: the thermal bubble at the heating position of h1 could not move to the diffuser region because it faced a lesser heating power. The thermal bubble would pass through the check valve at a larger heating power. Therefore, the position of h1 seems unsuitable for controlling the thermal bubble. In addition, the positions of h3 and h4 were also unsuitable for control because the thermal bubble cannot touch the side wall of channel under the heating positions of h3 and h4. However, the position of heater h2 was at the intersection of duct channel and diffuser. The thermal bubble shown in the Figure 4 grew fast and moved downstream under a heating power of 93mW at h2. Figure 4(a) shows that the thermal bubble moved to the diffuser at the heating time t=4 sec, Figure 4(b) shows that the separation appearance of thermal bubble at the heating time t=8 sec, Figure 4(c) shows that the thermal bubble keeps moving at t=31 sec, Figure 4(d) shows the merging appearance of thermal bubbles at heating time t=33 sec, and Figure 4(e) shows that the motion of bubble in the hydrophobic area remained after t=33sec . Hence, the position of h2 was suggested.

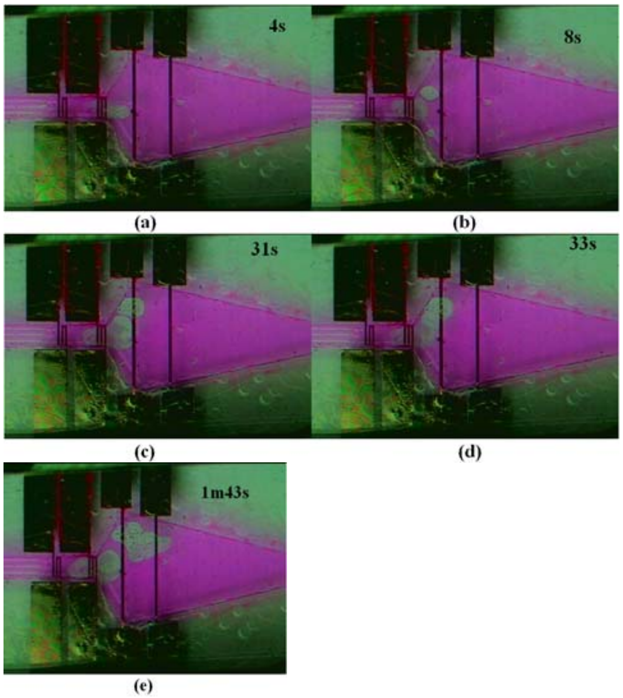

Fig. 4 The images of thermal bubble motion at the heating position h2 with 93mW at different heating time (a) t=4 sec (b) t=8 sec (c)t=31 sec (d)t=33 sec (e) after t=33sec .

Case 2: different flow rate and constant heating power

In this study, the effect of different pouring flow rates and constant heating power of 93mW at h2 on the motion of a thermal bubble was investigated and is shown in Figure 5. Figure 5(a) shows an experimental control at the case of pouring zero flow for realizing the effect of varying flow rate but constant heating power on the thermal bubble. Figure 5(b) shows that at a pouring flow rate of 20 l/min steady production of thermal bubbles occurred and moved downstream. Figure 5(c) shows that a separation of thermal bubble occured because the thermal bubble was affected by the pressure drags resulting from the dimension of heater h2 and the pouring flow rate. The thermal bubble merged together and grew continuously until it touched the wall of the diffuser channel. At this time, the thermal bubble in diffuser as shown in Figure 5 (d) was easily moved to outlet of channel. Similarly, increasing the pouring flow rate at same heating power produced more of the thermal bubbles.

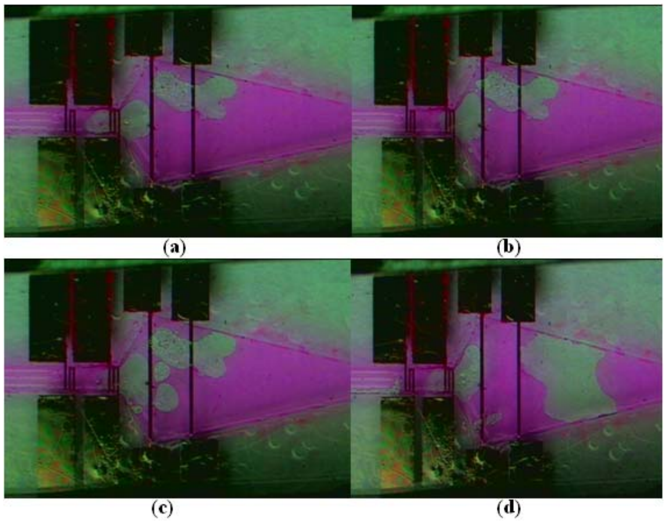

Fig. 5 The images of thermal bubble motion at case (a) without flow rate and case of a constant pouring flow rate 20 l/min (b)thermal bubbles were pushed forward(c) the thermal bubbles were separated (d)the thermal bubbles in the diffuser moved downstream to outlet of channel.

Scaling effect upon the thermal bubble motion

Tsai and Lin [25] indicated that the driving force of thermal bubble for bubble motion was easily produced and increased the ability of heat transfer when the channel was scaled down. A channel width of 500μm was selected and a heating power 93mW of heater h2 was provided to investigate the scaling effect upon the thermal bubble in this study. Results are addressed as follows: at the beginning of heating, the thermal bubble oscillated at about 5 Hz between the duct channel and diffuser. This phenomenon showed that a steady state of thermal equipment had been achieved. The growth of thermal bubble occurred continuously and stopped at 1000μm under a continuous heating condition. The thermal bubble moved forward because of the surface tension of the diffuser. When the thermal bubble moved away the heater, the thermal gradient on the front side and backward side of thermal bubble was different. The surface tension of the front side of the thermal bubble was larger than on the backward side of the thermal bubble. The original state of thermal equipment of the chip ceased and the motion of thermal bubble was pushed forward. Figure 6 shows the image of thermal bubble with a heating power 76mW at different conditions with a microchannel width of 100 μm. Results of Figure 6 show that the thermal bubble was filled easily with the channel. The variation of geometrical dimensions for the channel easily caused an imbalance between the front side and backward side of the thermal bubble and increased the bubble motion. This result showed that scaling down the channel would provided a positive effect on the thermal bubble motion and improved the ability of heat transfer.

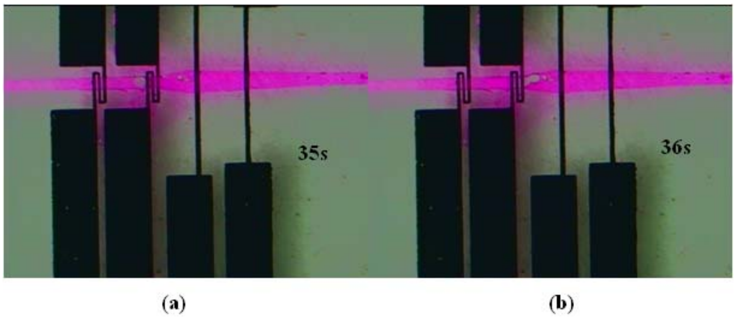

Fig. 6 The image of thermal bubble at heating power 76mW at the condition of the width with 100 μm of microchannel (a)t=35 sec (b)t=36 sec

CONCLUSIONS

The micro capillary pumped loop system (MCPL) is a highly efficient device for heat transfer because the main driving force is a result of thermo-bubbles in micro-channel. In this study the scaling effect of dimensional geometry was investigated and the results were as follows:

Concerning the convenience of controlling the thermal bubble, the location of h2 at the intersection point between the duct channel and diffuser was suggested. Generally speaking, a larger heating power prompted the occurrence of more thermal bubbles. In addition, increasing the pouring flow rate produced more thermal bubbles and improved the ability of heat transfer. When the dimensions of channel were scaled down, it provided a positive effect on the thermal bubble motion and improved the ability of heat transfer. These observations would be useful for the MCPL design.

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