Effects of Micro-Channel Geometry and Surface Modification on Heat Transfer within an Evaporator

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Abstract

A micro capillary pumped loop (MCPL) system is a highly efficient heat transfer device that uses capillary force in the evaporator region as the driving force to pump working fluid in a loop. In this study, the effects of micro-channel geometry and surface modification within an MCPL evaporator of MCPLs will be studied for improving the heat transfer performance. Techniques of surface modification are applied in this study to selectively define the surface as a hydrophilic or hydrophobic area. Results show that the higher the heating power provided by the micro heater, the faster the growing rate of the thermal bubble will be. Generally speaking, the larger the amount of injected working fluids applied, the faster the thermo bubble motion will be. When the size of the channel is scaled down, nucleation of the thermal bubble would occur easily and heat transfer enhancement would be expected. It is also found that bubbles generated by heater h2 (initial location of diffuser) will have a self-driven force to move the bubbles downward because of using a hydrophilic diffuser area. These findings will be useful to the further the optimal design of MCPLs in the future.

Key Words: Micro Capillary Pumped Loop (MCPL), Thermo Bubble, Micro-Channel, Heat Transfer, Surface Modification

1. Introduction

Nucleate boiling is a highly efficient heat transfer process favored in many industrial applications. Recently, the boiling experiments undertaken by Kenning et al. generated on the heat transfer surface were performed to examine the phenomenon of bubbles [1]. It was proven that the growth and departure of the bubbles could cause an effect on the temperature fluctuation of the heat transfer surface. Therefore, the wall could be cooled by a liquid micro layer during the process of bubble growth. Here, the liquid micro layer could further be controlled by the profile of a superheating wall. An interaction between the cavity spacing of the heat transfer surface and the nucleation sites of the bubbles would exist [2–7]. In addition, the relationship between the bubbles coalescence and the cavity spacing, the temperature interaction between the nucleation sites, and the role of bubble movement would also be examined [8,9]. The standard approach which relates heat transfer in nucleate boiling to heat transfer to the superheated layer, averaged over the time between two successive departures of a bubble from a given site, is extended in order to relate the heat flux to the wall superheated through the heating surface characteristic [10]. The evaporation of the superheated liquid layer within the region of the bubbles would oc-
cupy the main space of the heat transfer surface [11]. Kiger et al. (2006) indicated that the ratio of the evaporation of the micro layer to the total heat transfer surface heat flux was about 14.7% [12]. When combined heat transfer of the evaporating heat transfer in the thin film region and the boiling heat transfer in the intrinsic meniscus region occurs, open capillary microgrooves can hold higher cooling capacity [13,14]. The hypothesis of a superheat layer adhering to the whole bubble surface was denied by Labuntsov [15]. A force balance of an individual bubble in the boiling region [16] and a bubble detachment diameter based on a correlation of bubble growth rate [17] has been addressed in this study.

Considering simultaneous energy transfer among vapor bubbles, a liquid micro layer and heater, a numerical analysis was carried out to realize the bubble growth in the heterogeneous boiling state [18]. A dynamic micro layer model adopting Cooper’s correlation of micro layer thickness was addressed and utilized to investigate the bubble growing process and predicted the critical heat flux of a fully developed nucleate boiling [19]. Thome et al. (2004) studied an elongated bubble flow in micro-channels and confirmed that the instantaneous evaporation of the thin film around the bubbles would drive up the bubble growth [20]. Upon the bubble growth in a capillary tube, bubbles in a spherical shape at the initial stage, and then a confined shape with a column in the middle and a hemispherical shape at two ends, would be found. These reports show that many studies related to boiling mechanisms were executed, but fewer studies of bubble motion control including modifications of diffuser/nozzles [21,22] and surface gradients [23–25] are found. This study would focus on knowing the effects of micro-channel geometry and surface modification within an evaporator because realizing their impact on heat transfer performance is important in MFCs. Therefore, a series of studies related to (1) heating location and constant heating power (2) flow rates and constant heating power (3) scaling effect of a micro-channel upon the heat transfer of thermal bubble motion would be executed in this study.

2. Chip Design of Thermal Bubble Channel

In this study the prototype of a thermal bubble micro-channel chip, shown in Figure 1, would be utilized, the duct channels whose dimensions are 7980 μm × 500 μm and 5280 μm × 500 μm respectively were designed on the right and left side of the diffuser/contractor within the evaporator. Three blocks with a dimension of 1500 μm × 100 μm imbedded in the micro-channel would be used to act as a check valve for the vapor bubbles producing a different pressure drop between the right and left sides of the channel in order to force them to move downstream.

This study would intend to control the bubble motion within the channel of the diffuser/contractor effectively. A modified surface would be applied using a hydrophilic and hydrophobic technique. A diffuser with an angle and maximum width of 60° and 2665 μm, shown in Figure 1, would be fabricated into the hydrophilic area. Conversely, the contractor shown in Figure 1 would be surface modified as a hydrophobic area by coating with teflon and have a cooling plate attached on the surface of the right side of the outlet channel acting as a condenser.

![Figure 1. Prototype of thermal bubble micro-channel chip and positions of heaters h1–h4.](image)
This chip device with four heaters would be fabricated by using MEMS technology. The fabrication process including the cleaning wafer, spin photoresist (PR) of AZ4620, exposure, development, buffered oxide etching (BOE) and PR removal all utilized is shown in Figure 2. Here, an s-type heater plate shown as h1 and h2 whose width line, with a heating region and spacing between h1 and h2 is 30 μm, 190 μm × 500 μm and 650 μm respectively is used. Similarly, other heaters shown as h3 and h4, with a width line and spacing between h3 and h4 50 μm and 730 μm respectively were designed. In addition, the heating region was 50 μm × 2665 μm for h3 and 50 μm × 2290 μm for h4. All heaters are silicon wafer and fabricated with patterned TaAl thin film heaters to enhance the value of electrical resistance and further generate the bubbles easily.

In this study, the heating resistance would be set as h1 = 1574 Ω, h2 = 1076 Ω, h3 = 1060 Ω, h4 = 933 Ω for h1-h4 respectively for providing different heating power within the chip. A series of studies related to (1) selection of suitable heating locations in the case of constant heating power W = 93 mW (2) flow rates and constant heating power (3) scaling effect of the micro-channel upon the heat transfer of thermal bubble motion would be executed by using the CCD & microscope for capturing the flow image of bubble motion in this study.

3. Experimental Results and Discussion

In this study the nucleation phenomena of thermal bubbles would be analyzed by the flow visualization under different heating power. To show the image clearly, pink colored pure water would be utilized.

3.1 Selection of Suitable Heating Location at Case of Constant Heating Power W = 93 mW

Four heaters with different heating locations in the case of constant heating power W = 93 mW would be investigated to find a suitable heating location utilized to effectively control the motion of thermal bubbles within the evaporator. Comparing the four micro heaters at the same heating power, results shown in Figure 3 can be analyzed as follows. The thermal bubble at the h1 heating position could not move toward the diffuser region because it faced less heating power and the appearance of a larger pressure drop originating from the check valve. When applying a greater heating power, the moving resistance would be overcome and the thermal bubble could then pass through the check valve. These statements indicate that the position of h1 seems not to be a suitable location to effectively control the motion of the thermal bubble heat transfer.

Similarly, the heating positions of h3 and h4 would also not be suitable to control because the thermal bubble could not touch the two side walls of the channel under heating positions h3 and h4, respectively.

From the video imaging of the charge coupled device (CCD) & microscope, the thermal bubble shown in Figure 3 would grow fast and move downstream under a heating power 93 mW (h2). When heating time was

Figure 2. The fabrication process of a micro-channel chip.
set at $t = 4$ sec, the thermal bubble shown in Figure 3(a) could move to the diffuser and the separation of the thermal bubble shown in Figure 3(b) would occur at a heating time of $t = 8$ sec. Figure 3(c) shows that the thermal bubble resulting from the accumulation of heating power keeps growing and moving at $t = 31$ sec. The front velocity of the elongated bubble slug would accelerate and the adjacent two bubbles shown in Figure 3(d) would then merge at a heating time of $t = 33$ sec [26]. This result indicated that the details of the trailing bubble acceleration and merging process could be observed. Here, related parameters of the trailing bubble including the shape, velocity and acceleration [26] would greatly affect the dynamics of the bubble. Figure 3(e) shows that the motion of the bubble in the hydrophobic area possesses the ability to enhance the hydrophobic effect and reducing the shear viscous force of the wall surface [27] would be kept after $t = 33$ sec. To sum up, the position of heater h2 at the intersection of the duct channel and diffuser would seem to be a suitable heating location and is used in this study and the following series of studies.

**3.2 Case of Flow Rate with 20 $\mu$l/min and Heating Power 93 mW**

Ho et al. (2010) indicated that the characteristic bubbles are dependent on the flow rate. They also demonstrated that the prong pressure of the nasal bubble depended on the interaction of the submersion depth and flow amplitude [28]. This evidence showed that the flow rate is an important factor for realizing the dynamics of bubbles under the case of a constant heating power. In this study an inlet flow rate of 20 $\mu$l/min and a heating power 93 mW of h2 would be used to observe the motion of thermal bubble. Here, an experimental control at the case of pouring zero flow, but with constant heating power shown in Figure 4(a), would be used for comparison with other cases. When a pouring flow rate of 20 $\mu$l/min was provided a steady state of thermal bubble, shown in Figure 4(b), would be kept and held while moving downstream. Figure 4(c) shows that thermal bubble separation would occur because of the effect of the pressure drag resulting from the dimension of the h2 heater and the pouring flow rate [28].

At this moment in time, the thermal bubbles would be merged together and continuously get bigger until touching the wall of the diffuser channel. Then the thermal bubble, shown in Figure 4(d), in the diffuser could be easily moved to the outlet of the channel within the evaporator. Therefore, increasing the pouring flow rate at the same heating power would produce more thermal bubbles.
3.3 Scaling Effect of Microchannel Upon the Thermal Bubble Motion

Tsai and Lin (2002) indicated that the driving force of thermal bubbles for bubble motion could easily control and increase the ability of heat transfer when the channel was scaled down [22]. Pan and Chen (2014) also indicated that changing the dimensionless parameters of rising bubbles and channel width would affect the bubble shape [21], rising trajectory and the wake behind the bubbles and further affect the performance of heat transfer. Here, a channel width of 500 μm was selected and heating power 93 mW (h2) would be provided for realizing the scaling effect upon the dynamics of the thermal bubbles.

It was observed that at the start of heating, the thermal bubble would oscillate at about 5 Hz, a frequency that is less than the resonant frequency originating from the viscous effects between the region of the duct channel and diffuser. This phenomenon shows that a thermal bubble in a steady state has been achieved, but the growth of the thermal bubble would occur and stop at 1000 μm under a continuous heating condition. Based on these observations, the possible reason should be the nonlinear interaction of bubble oscillations [29]. Here, the viscous effects are more complex because the viscosity would tend to slow down the motion and the viscous force would cause a decrease in the oscillation frequency and amplitude of bubbles [29].

Now, the thermal bubble would move away the heater and downstream because of the surface tension of the diffuser occurring in the case of a thermal gradient on its front and backward side. Therefore, the original thermal equilibrium within the evaporator channel would be broken and the thermal bubble would be pushed forward. Figure 5 shows that the thermal bubble could reach the side walls and occupy the whole channel easily at the condition of a micro-channel width of 100 μm and heating power 76 mW within the evaporator. Therefore, the geometrical effect of the microchannel within the evaporator could more easily cause an imbalance of forces between the front and backward side of the thermal bubble and more easy of bubble motion. The evaporation momentum force arises due to the difference in liquid and vapor densities at an evaporating interface [30]. This resulting rapid interface motion would increase the convection heat transfer because of possessing a higher heat transfer coefficient within the bubbles [30]. This result shows that the channel scaled down would provide a positive effect on the thermal bubble motion and improve the ability of heat transfer in the micro capillary pumped loop (MCPL) system [31].

4. Conclusions

The micro capillary pumped loop (MCPL) system is a highly efficient device for heat transfer because the main
driving force is resulting from thermo-bubbles in the micro-channel structures of an evaporator. In this study the effects of micro-channel geometry scaling with hydrophilic/hydrophobic surface design would be investigated.

Concerning the control of thermal bubbles, the heater location of h2 at the intersection point between the duct channel and diffuser would be suggested. Results show that a larger heating power provided would produce a larger thermal bubble. Increasing the pouring flow rate will produce more thermal bubbles and enhance the heat transfer performance of the bubbles. When the dimension of the channel within evaporator was scaled down, it would provide a positive effect on the heat transfer performance of the bubbles. Results also show that bubble generated by heater h2 will have a self-driven force to move the bubbles downward because of using a hydrophilic diffuser area. These findings will be useful to the further optimal design of MCPLs in the future.

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