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Bubble Dynamics and Flow Boiling Characteristics in a Chemically Patterned Microchannel

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***Abstract* -** Flow boiling heat transfer in microchannels is of significant interest for thermal management applications, where the latent heat of phase change offers an efficient method to dissipate large heat fluxes in a compact device, such as a mciro heat spreader or a heat pipe. However, a significant challenge for the implementation of microscale phase change heat spreaders is associated with micro/nano flow instabilities due to insufficient micro/nano bubble removal, leading to local liquid dry-out that severely limits the heat removal efficiency. Furthermore, for the various heat transfer mechanisms involved, it is difficult to predict the location of nucleation sites at which the onset of nucleate boiling (ONB) occurs. In this paper, a chemcially patterned surface has been developed to manipulate nucleation boiling in a micro fluid flow channel. Bubble dynamics and heat transfer with shear force conditions in a heterogeneous wettability microchannel were studied experimentally and compared with a homogeneous hydrophilic microchannel. The bubble nucleation site and coalescence are studied experimentally. The effects of chemically patterned surfaces on bubble nucleation and bubble pinning and depinning in a microchannel will be investigated utilizing high speed visualization techniques and analytical modelling. Effects of mass flux on flow boiling in a wettability patterned microchannel are studied. Chemically patterned surfaces are manufactured on glass/silicon wafers. It is found that the heat transfer coefficient can be significantly enhanced by chemical patterns in comparison to a hydrophilic surface. The surface temperature with chemically patterned surfaces is lower than hydrophilic surfaces.

***Keywords*:** Flow Boiling, Chemically Patterned Surface, Bubble Dynamics, Nucleation Site Density, Triple Contact Line.

1. Introduction

Flow boiling heat transfer in microchannels has recently emerged as a highly efficient cooling technique to address the current and future high heat flux dissipation issues in many cutting-edge areas, such as microelectronic devices, high power laser diode arrays, chemical reactors and so on. It has been known that the surface characteristics have significant impact on the heat transfer performance in flow boiling. Previous researchers [1-2] studied the wetting effect on nucleate boiling heat transfer. It has been found that a hydrophilic surface can significantly enhance the heat transfer coefficient (HTC). On the other hand, when a hydrophilic surface is used, the liquid wetting on the surface will result in high critical heat flux CHF [1]. Phan et al. [3] found that although HTC can be improved when the surface is hydrophobic. However, a general problem for all hydrophobic surfaces is that, with the increasing of the surface hydrophobicity, the bubble emission frequency decreases while the bubble departure diameter increases. As a result, CHF will be reduced. To resolve this dilemma, a mixed hydrophobic and hydrophilic surface has been proposed by Betz et al. (2010) [4], utilizing hydrophobic islands on hydrophilic networks for simultaneous HTC and CHF enhancement in pool boiling.

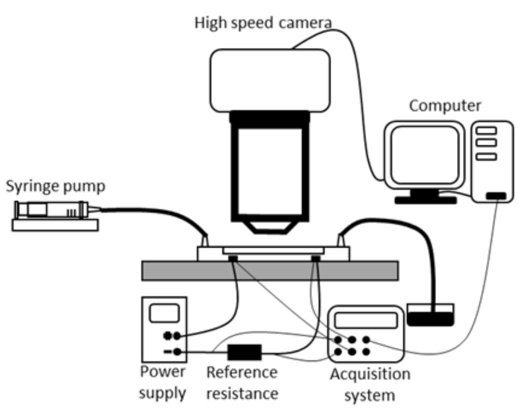
In thermal management, boiling heat transfer in microspaces under flow conditions is of significant interest for many applications, where the phase change heat transfer offers an efficient tool for high heat flux dissipation in a compact device. However, a main challenge for microscale flow boiling cooler is associated with difficulty in micro/nano bubble removal from the heating surface, leading to local liquid dry-out which severely limits the heat removal efficiency. Due to various heat transfer mechanisms involved, it is difficult to active nucleation sites at which the onset of nucleate boiling (ONB) occurs. The effects of surface wettability on flow boiling heat transfer in microchannels were studied by several researchers [5-6]. However, the channel surfaces they used were with homogenous hydrophobicity [5-6]. Therefore, the flow boiling heat transfer performance on chemically patterned surface, i.e., a substrate surface mixed with hydrophilic network and hydrophobic dots in a microchannel has not yet been reported. Inspired by our previous study (Amy et al. [4] and Chen and Qiu [7]), we try to extend this technique to from pool boiling to flow boiling in a microchannel. The question is whether a wettability patterned surface (a mixed hydrophobic/hydrophilic surface) can have a higher heat transfer coefficient and high critical heat flux than a hydrophilic surface under flow boiling conditions. Due to the complexity of flow effects on the boiling heater transfer in a microchannel including nucleation site density, heat transfer coefficient and bubble departure, the mechanisms that enhance the heat transfer performance has not been well understood. Therefore, it is crucial to understand the transport phenomena occurring at a wettability patterned surface which is of great interest in thermal management of power electronics.

This paper aims at understanding the effects of chemically patterned surface on flow boiling heat transfer. A microchannel with hydrophilic/hydrophobic patterns on the channel wall has been fabricated. The flow boiling heat transfer in a chemically patterned microchannel was studied. Bubble dynamics, heat transfer and fluid flow manipulated by the wettability patterns are reported and discussed. Fluid flow, bubble generation, breakup and departure are visualized and measured. It is an attempt to develop a technique for improving the heat transfer coefficient to further reduce the surface temperature with liquid cooling utilizing surface micro modification techniques.

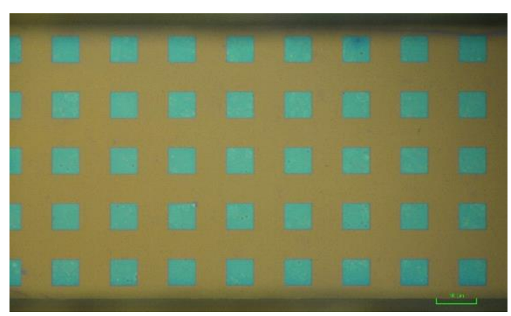
2. Methodology

2.1. Experimental Setup

Figure 1 (a) shows the experimental apparatus and the flow circuit. It consisted of four major components: a working fluid loop, a test section integrated with a heating unit, a data acquisition system and a visualization system. A syringe pump pushed the deionized water to the test section. After the test section, water was collected in a container. Power for the heater was supplied by the DC power supply. A precise 2Ω resistor (MP2060) was connected in series with the heater and voltage across the resistor, Vr, was measured. The current of the heater was calculated from I = Vr/R and the resistance of the heater could be calculated. The average temperature of the heater was determined from the heater resistor, which was calibrated before the experiment. Two t-type temperature sensors were applied to measure the inlet and outlet water temperature. All voltage and temperature signals were collected by a Data Acquisition Switch Unit (Agilent 34970A). A microscope with a high-speed camera (Motion Xtra HG-100K, Redlake Co.) was used to capture bubble behavior and flow patterns in the microchannel. To quantitatively measure bubble dynamics and heat transfer under flow boiling in a chemically patterned microchannel, chemically patterned surfaces are manufactured on glass/silicon wafers (Figure 1 (b)). The hydrophobic patterns are used to control the nucleation sites in flow boiling in a microchannel. Microfabrication techniques were used for developing chemically patterned surface [8] and high-speed visualization technique was employed to visualize the bubble dynamics in flow boiling conditions.



(a)



(b)

Fig. 1: (a) Experimental Setup (b) Microscopy image of patterned surface with square Teflon patterns (green) of side 50μm×50μm and pattern-to-pattern spacing 100μm.

2.2. Analytical Modeling

To study bubble detachment which is an important characteristic of bubble dynamics related to heat transfer performance, the detachment frequency and the heat transfer coefficient is investigated. According to previous study, hydrophobic surface can trigger and promote bubble nucleation, but it makes bubbles difficult to departure. Here, we develop a local forces model of three-phase line to quantitatively evaluate and compare the requirement for bubble movement on different surfaces. For a moving bubble in a homogenous channel, two external forces from back (F_b) and front (F_f) acting on three-phase lines of bubble must larger than the maximum pinning forces, which leads to:

$$F_b \geq s_b \delta_{lg}(\cos\theta_{equ} - \cos\theta_{ao}) \tag{1}$$

$$F_f \geq s_f \delta_{lg}(\cos\theta_{ro} - \cos\theta_{equ}) \tag{2}$$

where s_b and s_f is the back and front three-phase line lengths and $s_b = s_f$ as flow is slow and stead, δ_{lg} is the surface tension, θ_{equ}, θ_{ro} and $\theta_{ao}$are equilibrium, receding and advancing contact angle. Therefore, the minimum requirement of total forces needed to move a bubble in a homogenous channel is

$$F_{t,homo} = F_b + F_f = s\delta_{lg}(\cos\theta_{ro} - \cos\theta_{ao}) \tag{3}$$

For a patterned surface, the maximum pinning forces should be adjusted and the minimum external forces requirement comes to:

$$F_{t,patten} = s\delta_{lg}\left(\left(\cos\theta_{ro,philic} - \cos\theta_{ao,philic}\right)\emptyset + \left(\cos\theta_{ro,phobic} - \cos\theta_{ao,phobic}\right)(1-\emptyset) + H_r\right) \tag{4}$$

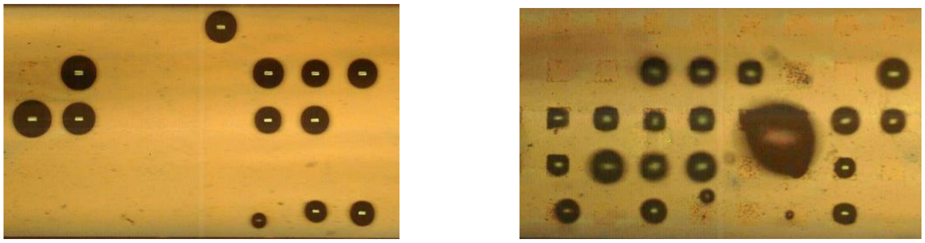
where subscripts $philic$ and $phobic$ represent hydrophilic and hydrophobic surfaces, $\emptyset$ is area fraction of hydrophilic area and H_r is surface roughness factor. For the bubbles with same base diameter, the ratio of minimum external forces to bubble detachment on patterned and hydrophobic surface can be expressed as:

$$\frac{F_{t,patten}}{F_{t,phobic}} = \frac{\left(\cos\theta_{ro,philic} - \cos\theta_{ao,philic}\right)\emptyset + \left(\cos\theta_{ro,phobic} - \cos\theta_{ao,phobic}\right)(1-\emptyset) + H_r}{\cos\theta_{ro,phobic} - \cos\theta_{ao,phobic}}. \tag{5}$$

In our case, the hydrophilic and hydrophobic material are silicon oxide and Teflon with receding and advancing contact angle $\theta_{ro,philic} = 18.7°$,$\theta_{ao,philic} = 36.6°$, $\theta_{ro,phobic} = 134.1°$ and $\theta_{ao,phobic} = 87.4°$, $H_r = \frac{(b)^2}{l^2}$=0.25 and $\emptyset = 0.8$. Therefore, the ratio of total forces is $\frac{F_{t,patten}}{F_{t,phobic}} = \frac{0.45}{0.74} = 0.6 < 1$, which means bubble detachment on patterned surface is much easier than hydrophobic surface. This quantitatively analysis also indicated that, on patterned surface, we can take advantages from both hydrophilic (easy bubble detachment) and hydrophobic (easy bubble nucleation) properties to enhance heat transfer performance. Therefore, on chemically patterned surface, the bubbles can detach and move fast, improving the heat transfer in flow boiling.

3. Results and Discussion

Figure 3, shows that the bubble behaviours on chemically patterned surface under follow boiling. When heat flux increased, more bubbles appeared in the confined hydrophobic island, which confirms that the hydrophobic island can effectively trigger bubble nucleation during flow boiling. Bubbles then grow and depart from the patterned surface quickly.



(a) (b)

Fig. 2: Bubble dynamics on the wettability surface (Mass flux 203 kg/m^{2}s, flow direction from right to left) (a) Heat flux=60.23 W/cm^2 and (b) Heat flux=80.02 W/cm^2.

The enhancement of heat transfer performance can be reflected in Figure 3 which shows HTC against effective heat flux. This enhancement can be attributed to the nucleation promotion of patterned surface, which lower energy barrier of nucleate boiling, fast detachment of bubble, which prevent dry out and enhance HTC, and recirculation flow which improve heat transfer of two phase flow. Figure 3 also shows the error bars and the maximum relative uncertainty of HTC is 2.92%.

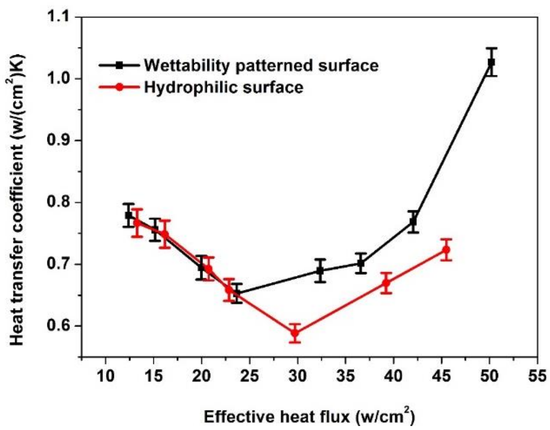


Fig. 3: Measured HTC curve of a wettability patterned surface and hydrophilic surface (mass flux 103 kg/m^{2}s).

4. Conclusion

In this paper, we describe a technique of chemically patterned surfaces on flow boiling heat transfer. On a chemically patterned surface, the number of bubble nucleation sites is significantly larger than a plain surface. In flow boiling on a chemically patterned surface, early bubble growth and departure will help to enhance heat transfer and prevent the dry-out at high critical heat flux. The HTC can be significantly enhanced using chemically patterned surfaces.

Acknowledgements

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References

[1] H. S. Ahn, C. Lee, H. Kim, H.J. Jo, S.H. Kang, J. Kim, J. Shin, M. H. Kim, "Pool Boiling CHF Enhancement by Micro/Nanoscale Modification of Zircaloy-4 Surface," *Nuclear Eng. Design*, vol. 240, no. 10, pp. 3350-3360, 2010.

[2] Y. Takata, S. Hidaka, M. Masuda, T. Ito, "Pool boiling on a superhydrophilic surface," *International Journal of Energy Research*, vol. 27, no. 2, pp. 111–119, 2003.

[3] H. T. Phan, N. Caney, P. Marty, S. Colasson, J. Gavillet, "Surface wettability control by nanocoating: the effects on pool boiling heat transfer and nucleation mechanism," *International Journal of Heat and Mass Transfer*, pp. 5459–5471, 2009.

[4] A. R. Betz, J. Xu, H. Qiu, D. Attinger, “Do surface with mixed hydrophilic and hydrophobic areas enhance pool boiling?,” *Applied Physics Letter*, vol. 97, 2010.

[5] S. G. Kandlikar, “Scale effects on flow boiling heat transfer in microchannels: A fundamental perspective,” *International Journal of Thermal Sciences*, vol. 49, pp. 1073-1085, 2010.

[6] H. T. Phan, N. Caney, P. Marty, S. Colasson, & J. Gavillet, “Flow boiling of water in a minichannel: The effects of surface wettability on two-phase pressure drop,” *Applied Thermal Engineering*, vol. 31, pp. 1894-1905, 2011.

[7] X. Chen, H. Qiu, "Bubble dynamics and heat transfer on a wettability patterned surface," *International Journal of Heat and Mass Transfer*, vol. 88, pp. 544-551, 2015.

[8] M. He, D. Liao, & H. Qiu, “Multicomponent Droplet Evaporation on Chemical Micro-Patterned Surfaces,” *Scientific Reports*, vol. 7, p. 41897, 2017.