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Forced Convective Boiling Heat Transfer of Acetone in Parallel Silicon Microchannels

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Abstract:-An experiment was carried out to investigate the forced convective boiling heat transfer with acetone in parallel silicon microchannels having hydraulic diameter of 155.4μm. Tests were performed over a saturated pressure range of 1.16-1.33bar, inlet liquid temperature of 22.8-38.3 ^{o}C, mass flux of 63.3-250.3kg/ (m^2s), heat flux of 153.9-481.1kW/m^2. The effects of mass flux, vapor quality and heat flux on the measured flow boiling heat transfer coefficient were examined and it is found that flow boiling heat transfer coefficient of acetone is a strong function of mass flux and vapor quality, and only a weak function of heat flux, in the present data range. Seven previous empirical correlations are assessed and deemed unable to predict the flow boiling heat transfer coefficient well because of the unique nature of bubble explosive induced forced convective boiling heat transfer in microchannels. Based on the present data, an empirical correlation was proposed for the flow boiling heat transfer coefficient.

Key-words:- Microscale heat transfer, Silicon Microchannels, Flow boiling, Explosive bubble, MEMS

1 Introduction

There are a growing number of experimental studies on two-phase flow and boiling heat transfer in microchannels. Compared with microscale single-phase flow and heat transfer, microscale boiling heat transfer may have many advantages of low thermal resistance, compact dimensions, small coolant inventory, and low flow rate requirements. Therefore, microscale boiling heat transfer can be applied in many technical applications and has attracted great attentions.

Hetsroni et al [1] performed tests to visualize the flow pattern and to measure heat transfer coefficient during explosive boiling of water in parallel triangular microchannels. They concluded that the boiling process of water was explosive boiling with periodic wetting and dryout, and that heat transfer coefficient was strongly dependent on the vapor quality.

Wu and Cheng [2] carried out a series of experiments to study different boiling instability modes of water flowing in microchannels at various heat flux and mass flux. They found three periodic boiling modes with long period and large amplitude in their experiments.

Kandlikar [3] considered that in low Reynolds number flows, nucleate boiling systematically emerges as the dominant mode of heat transfer, and that the high degree of wall superheat required to initiate nucleation in microchannels leads to rapid evaporation and flow instabilities, often resulting in flow reversal in multiple parallel channel configuration.

Qu [4] conducted tests on saturated flow boiling heat transfer in a water-cooled microchannel heat sink and results show that the saturated flow boiling heat transfer coefficient is a strong function of mass velocity, and only a weak function of heat flux. So they convinced that the dominant heat transfer mechanism is forced convective boiling and not nucleate boiling.

In our previous studies, Xu et al. [5] found that all microchannels repeat the transient flow patterns in a timescale of milliseconds while the fluid pressures/temperatures are stable. A full cycle can be subdivided into three substages, and four flow patterns are identified. Based on the above four transient flow patterns, Xu et al [6] performed 102 runs with acetone using as work fluid and proposed five heat transfer mechanisms, provided a link between the transient flow patterns and the heat transfer process, and divided the microscale boiling heat transfer into three regions with the boiling number.

The microscale boiling heat transfer boiling heat transfer can display the nucleated boiling behavior (defined as the region 2 mode in [6]), and the forced convective boiling heat transfer behavior (defined as region 3 in [6]). Bubble explosive induced forced convective mechanism may domain the region 3 in microscale.

In the present paper we analyze the microscale boiling heat transfer coefficients with effects of the mass fluxes, vapor mass qualities and heat fluxes in region 3. We present the comparisons between our experimental data with the available correlations both for micro and macro scales, and present new correlations for our experimental data.

2 Experiment system

2.1 Test section

Fig. 1 shows the configuration and dimensions of the test section, and which was fabricated using standard MEMS (Micro Electro Mechanical System) fabrication techniques. The test section mainly consists of three parts, the silicon substrate, the Pyrex glass, and the Platinum thin film heater. Ten parallel triangular microchannels were etched in the silicon base using KOH solution, each 300μm wide, 212μm deep, forming a hydraulic diameter of 155.4μm. A pyrex glass cover with the thickness of 410μm was bonded with the silicon substrate using anodically bonding technique, in order to perform high speed flow visualization. A Platinum thin film with thickness of 1000Å was deposited on the back of the silicon substrate using Chemical Vapor Deposition method. Connected with alternating current, the Platinum thin film can be used as a heater to supply heat to the fluid flowing through the microchannels. And the heating power can be adjusted by a transformer with precision of ±0.1W. The effective heating area is 16mm×4.2mm.

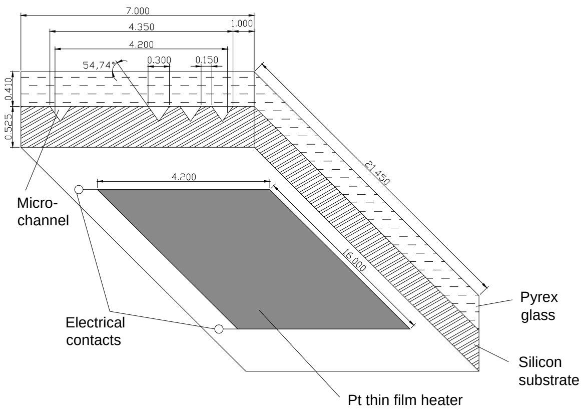

Fig. 1 Silicon microchannel test section (all dimensions are in mm)

2.2 Experimental setup

The experimental system is shown by Fig. 2. Acetone was used as working fluid. Pushed by high pressure Nitrogen, acetone with desired temperature flows through 2μm filter, microchannels, heat exchanger and container in turn. The inlet and outlet temperatures were measured by thermocouples with the errors within ±0.3 ^{o}C. The inlet pressure was measured by a Setra pressure transducer (Model 206) with precision of ±1%, and the pressure drop across the test section was measured by a Senex pressure differential transducer with an uncertainty of ±0.1%. An infrared radiator imaging system (FLIR ThermaCAM SC3000) was used to measure the wall temperatures of the thin film heater. After being calibrated, its accuracy is ±0.4 ^{o}C. The combined optical system comprises a Leica M stereo-microscope and a HG-100K high speed camera, which was used to obtain the transient periodic flow pattern of acetone boiling process. The steady acetone mass flow rate was determined by weighing the mass increment over a longer given period of time using a high precision electronic balance, which has the accuracy of ±0.02g.

3 Data reduction and error analysis

The working fluid used in the present study is pure liquid acetone, and the physical properties of acetone are taken from [7]. Based on experimental system, the measured parameters, inlet temperature T_{in}, mass flow rate m and heating power Q, all can be got. The length of the subcooled liquid area can be calculated as

$$L_{sp} = mc_{pf} L_h (T_{sat} - T_{in}) / Q \qquad (1)$$

Where c_{pf}, L_h, T_{sat}, T_{in} are Specific heat, heating length, saturated temperature, and inlet liquid temperature respectively. The local vapor mass quality and boiling heat transfer coefficient may be computed as

$$x(z) = \frac{c_{pf}(T_{in} - T_{sat}) + \frac{z}{L_h}\frac{Q}{m}}{h_{fg}} \qquad (2)$$

$$h(z) = \frac{q}{T_w(z) - T_{sat}} \qquad (3)$$

Where z, h_{fg}, q, $T_w(z)$ are flow direction coordinate, latent heat of evaporation, effective heat flux based on the total area of the side walls, and wall temperature in z coordinate respectively.

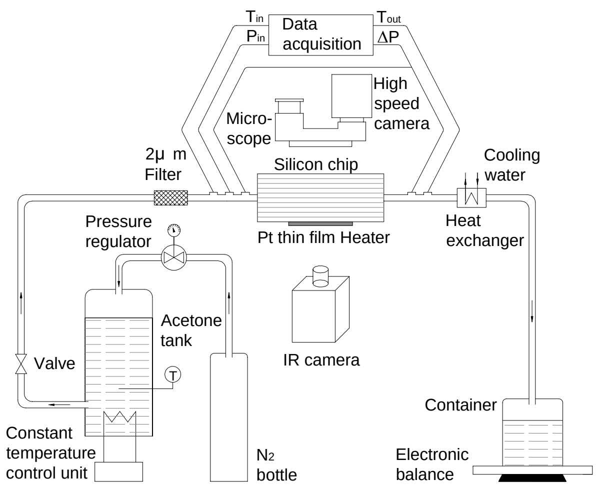

Fig. 2 Schematic diagram of the experimental setup

The present paper use 37 runs with the following data ranges: saturated pressures of 1.16-1.33bar, inlet liquid temperatures of 22.8-38.3 ^{o}C, mass fluxes of 63.3-250.3kg/(m^{2}s), heat fluxes of 153.9-481.1 kW/m^2, exit vapor qualities of 0.78-1.15, and boiling numbers $Bo=q/(Gh_{fg})$ of 3.566×10^{-3}- 5.046×10^{-3}.

Performing the standard error analysis, the maximum errors due to the measurements within the mentioned above data ranges are less than 1.62%, 4.96% for local vapor mass quality and boiling heat transfer coefficient respectively.

4 Experimental results and discussions

Under present experimental conditions, microscale boiling heat transfer mainly displays the forced convective boiling heat transfer behavior.

4.1 Boiling heat transfer coefficient

It can be seen from Fig. 3 that boiling heat transfer coefficients decrease with the increasing of local vapor mass qualities. Curve 1 and curve 2 are one set, and curve 3 and curve 4 are another set. Comparing curve 1 and curve 2, it can be found that boiling heat transfer coefficients increase with the increasing of mass fluxes, while keeping the other parameters very close. And comparing curve 3 and Curve 4, we can get the same conclusion.

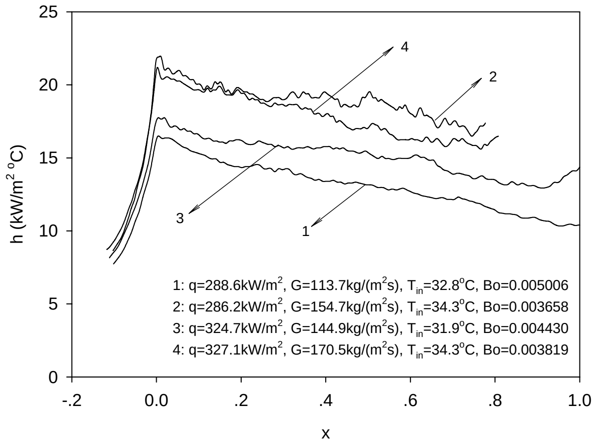

Fig. 3 Effect of mass flux on heat transfer coefficients

In order to study the effect of heat fluxes on the boiling heat transfer coefficients, some test runs were done with nearly constant mass flux. As shown in Fig. 4, the boiling heat transfer coefficients are less dependent on the heat fluxes.

Commonly for all these runs, boiling heat transfer coefficients decrease with the increasing of local vapor qualities, increase with the increasing of mass fluxes, and less dependent on the heat fluxes. This particular characteristic can be explained by the high bubble explosive induced forced convective heat transfer mechanism under the high boiling numbers, which has been described at length in section 3.4 of Xu et al. [6].

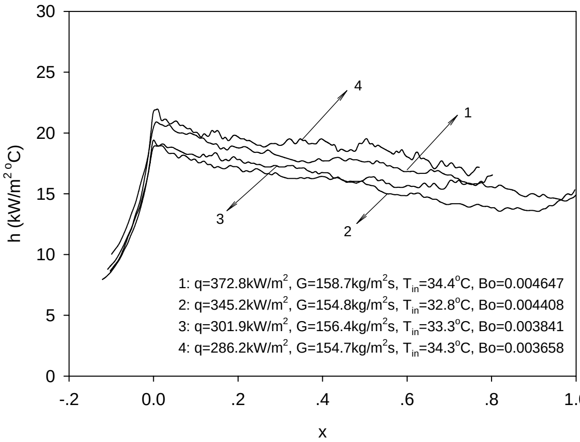

Fig. 4 Effect of heat flux on heat transfer coefficients

4.2 Comparison with Macro correlations

Two cases were selected randomly to compare with six widely used correlations for flow boiling heat transfer in macrochannels. The six correlations (No.1 - No.6) are summarized in Table 1. Only the references are given in Table 1, the detailed correlations are not given here. They could be classified as three types: the Chen summation correlations, the asymptotic correlations and the correlations developed only based on single-phase convective heat transfer coefficient h_{sp}.

The variation of predicted-to-measured heat transfer coefficient ratio h_{pred}/h_{exp} with vapor quality x was presented in Fig.5. The predictive accuracy of these correlations can be overall evaluated by the mean relative error (MRE) defined as

$$MRE = \frac{1}{M}\sum\frac{|h_{pred} - h_{exp}|}{h_{exp}} \times 100\% \qquad (4)$$

Where M is the number of data points. The MRE of each correlation is listed in Table 1, ranging from 36.4% to 467.5 %.

Obviously, these correlations are weak to illustrate the mechanism. Most notably, some correlations predict an increasing h_{tp} with increasing x, while the experimental data show the opposite trend.

Table 1 Flow boiling heat transfer coefficient correlations

No.	Reference	MAE (%)
1	Chen [8]	53.5
2	Shah [9]	121.7
3	Gungor and Winterton [10]	304.8
4	Kandlikar [11]	72.8
5	Liu and Winterton [12]	36.4
6	Steiner and Taborek [13]	467.5
7	Warrier et al. [14]	310.8
8	Present study	6.2

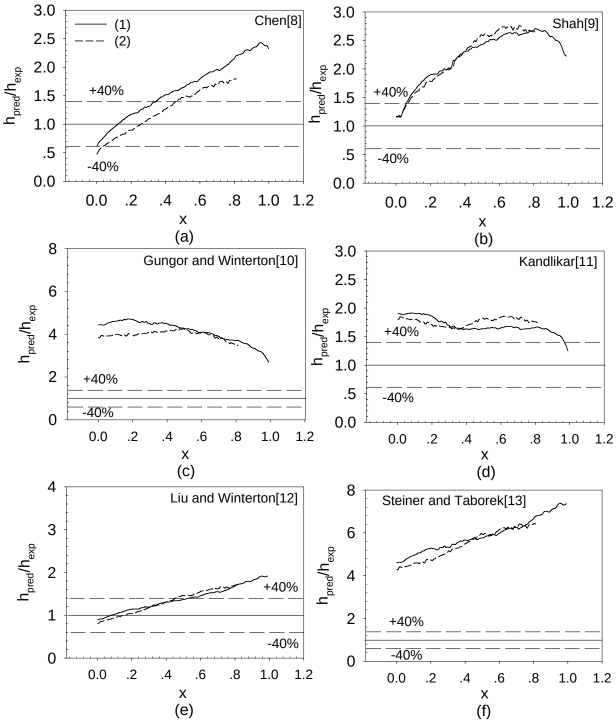

Fig. 5 Comparison of two cases with predictions of macro-channel correlations:
(1) q=288.6kW/m^2, G=113.7kg/(m^{2}s), T_{in}=32.8 °C, Bo=0.005006;
(2) q=359.6kW/m^2, G=178.8kg/(m^{2}s), T_{in}=34.2 °C, Bo=0.004003

4.3 Comparison with Mini/Micro correlation

Warrier et al. [14] correlated the heat transfer as a function as the Boiling number and vapor quality. They did not specifically illustrate which heat transfer mechanism was dominant in their study. But they found that the heat transfer coefficient decreased monotonically with increasing vapor quality. According to the decreasing trend, their correlation should have a reasonable prediction for the present data. On the contrary, the significant deviation between prediction and measurement is observed, as shown in Fig. 6. The deviation is due to the high Bo number range in the present work, which causes the correlation to predict an increasing trend of the heat transfer coefficient with vapor quality. At high Bo numbers, the bubble explosion results in high evaporation momentum force, suppressing the inertia force.

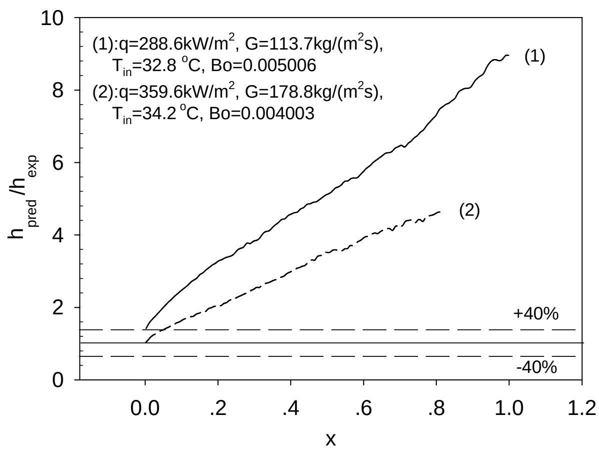

Fig. 6 Comparison of two cases with predictions of micro-channel correlation

4.4 New correlation

The above assessment of the previous correlations suggests that developing a new correlation is needed to accurately predict the flow boiling heat transfer coefficient in microchannels.

In present study, bubble explosive induced forced convective boiling heat transfer is the dominant heat transfer mechanism. The boiling heat transfer is dependent on mass velocity and vapor quality, but not sensitive to heat flux. In terms of the commonly used correlation method for convective boiling, the measured heat transfer coefficients can be correlated in the form of

$$h_{tp} = Eh_{sp} \quad (5)$$

Where E is the correction factor, h_{sp} is the all fluid, laminar fully developed convective heat transfer coefficient and is assumed to be equal to $4.364k_l/d_h$. Where k_l is thermal conductivity of acetone, and d_h is hydraulic diameter of microchannel. The factor E should include the effects of mass velocity, vapor quality and heat flux. Therefore, in the present work, E is correlated as a function of the all-liquid Reynolds number Re_{lo}, the boiling number Bo and vapor quality. For simplification, a linear relationship between the heat transfer coefficient and vapor quality is assumed during the correlation. The expression of the new correlation is as following:

$$\begin{aligned} & h_{tp} = Eh_{sp}\,,\ h_{sp} = 4.364\frac{k_l}{d_h} \\ & E = 0.2946\,Re_{lo}^{0.5876} + f\left(Re_{lo}\right)Bo^{0.4514}x \qquad (6) \\ & Re_{lo} < 100,\ f\left(Re_{lo}\right) = -1.0560\,Re_{lo}^{0.6507} \\ & Re_{lo} > 100,\ f\left(Re_{lo}\right) = -0.0481\,Re_{lo}^{1.241} \end{aligned}$$

Four cases are selected randomly to compare with the prediction from this new correlation in Fig. 7. The correlation shows excellent predictive capability, and most of the data falls within a ± 10% error range.

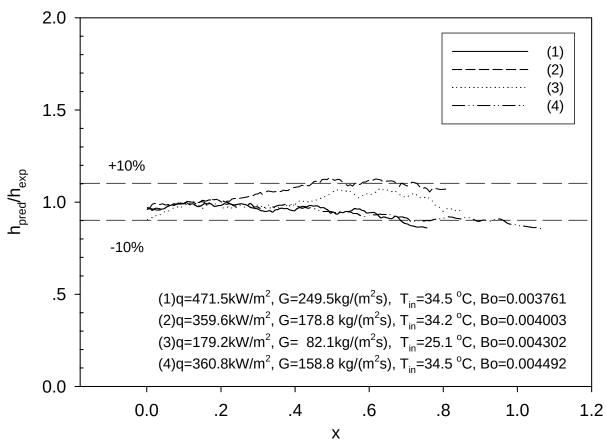

Fig. 7 Comparison of four cases with predictions of new correlation

5 Conclusions

This study is devoted to the effects of heat flux, mass flux and vapor mass quality on the flow boiling heat transfer coefficient in the forced convective microscale boiling heat transfer region. Assessment of the suitability of previous empirical heat transfer correlations was accomplished. The important findings can be summarized as follows.

(1) In forced convective dominant region the mircroscale boiling heat transfer coefficients are a strong function of mass flux and vapor

quality, and only a weak function of heat flux.

(2) Comparisons between our present experimental data with the available heat transfer correlations were performed and assessed.

(3) A new correlation was developed and more accurate prediction was obtained.

Acknowledgements

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References:

[1] G. Hetsroni, A. Mosyak, E. Pogrebnyak, et al, Explosive boiling of water in parallel microchannels, *International Journal of Multiphase Flow*, 31, 2005, 371-392.

[2] H.Y. Wu, P. Cheng, Boiling instability in parallel silicon microchannels at different heat flux, *International Journal of Heat and Mass Transfer*, 47, 2004, 3631-3641.

[3] S.G. Kandlikar, Heat transfer mechanisms during flow boiling in microchannels, *ASME Journal of Heat Transfer*, 126, 2004, 8-16.

[4] W.L. Qu, I. Mudawar, Flow boiling heat transfer in two-phase micro-channel heat sinks-1. Experimental investigation and assessment of correlation methods, *International Journal of Heat and Mass Transfer*, 46, 2003, 2755-2771.

[5] J.L. Xu, Y.H. Gan, D.C. Zhang, et al, Microscale boiling heat transfer in a micro-timescale at high heat fluxes, *Journal of Micromechanics and Microengineering*, 15, 2005, 362-376.

[6] J.L. Xu, S. Shen, Y.H. Gan, et al, Transient flow pattern based microscale boiling heat transfer mechanisms, *Journal of Micromechanics and Microengineering*, 15, 2005, 1344-1361.

[7] C.L. Yaws, *Chemical Properties Handbook*, McGraw-Hill Book Co., 1999.

[8] J.C. Chen, Correlation for boiling heat transfer to saturated fluids in convective flow, *I&EC Process Design Development*, 5, 1966, 322-329.

[9] M.M. Shah, Chart correlation for saturated boiling heat transfer: equations and further study, *ASHRAE Transaction*, 88, 1982, 185-196.

[10] K.E. Gungor, R.H.S. Winterton, A general correlation for flow boiling in tubes and annuli, *International Journal of Heat and Mass Transfer*, 29, 1986, 351-358.

[11] S.G. Kandlikar, A general correlation for saturated two-phase flow boiling heat transfer inside horizontal and vertical tubes, *ASME Journal of Heat Transfer*, 112, 1990, 219-228.

[12] Z. Liu, R. H. S. Winterton, A general correlation for saturated and subcooled flow boiling in tubes and annuli, based on a nucleate pool boiling equation, *International Journal of Heat Mass Transfer*, 34, 1991, 2759-2766.

[13] D. Steiner, J. Taborek, Flow boiling heat transfer in vertical tubes correlated by an asymptotic model, *Heat Transfer Engineering*, 13, 1992, 43-69.

[14] G. R. Warrier, V.K. Dhir, L.A. Momoda, Heat transfer and pressure drop in narrow rectangular channels, *Experimental Thermal and Fluid Science*, 26, 2002, 53-64.