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CRITICAL HEAT FLUX ON FLOW BOILING OF ETHANOL–WATER MIXTURES IN A DIVERGING MICROCHANNEL WITH ARTIFICIAL CAVITIES

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ABSTRACT

This study investigates experimentally the convective boiling heat transfer and the critical heat flux (CHF) of ethanol–water mixtures in a diverging microchannel with artificial cavities. Experimental results show that the boiling heat transfer and the CHF are significantly influenced by the molar fraction (x_m) as well as the mass flux. The CHF increases from x_m=0 to 0.1, and then decreases rapidly from x_m=0.1 to 1 at a given mass flux of 175 kg/m^{2}s. The maximum CHF is reached at x_m=0.1 due to the Marangoni effect, indicating that small additions of ethanol into water could significantly increase the CHF. On the other hand, the CHF increases with increasing the mass flux at a given molar fraction of 0.1. None of existing correlations for the CHF on flow boiling of pure component in a microchannel could present the correct trend as the CHF data on flow boiling of ethanol–water mixtures, and none of those correlations could predict the CHF precisely. However, the experimental results of the CHF show an excellent agreement with an empirical correlation for the CHF prediction of flow boiling of the mixtures, proposed by Lin et al. [1]. That, the overall mean absolute error of this correlation is 8.49% and more than 80% of the experimental data are predicted within a ±15% error band, confirms the correlation may accurately catch the Marangoni effect on the CHF of ethanol–water mixtures (present study) as well as methanol–water mixtures (our previous study [1]), and it is expected that this correlation may be applied for other convective boiling of binary mixtures.

INTRODUCTION

Critical heat flux on boiling of multi-component mixture

Two-phase flow and boiling of multi-component mixture is of fundamental importance and significant interest for many applications such as chemical engineering, process industries, and refrigeration systems. An example of applications is the design of microchannel evaporator of alcohol solutions in the micro-reformer, producing hydrogen. As ethanol can be regarded as a renewable raw material and easily obtained from the biological, it is a better candidate than methanol for environmental point of view. Therefore, mechanism of the two-phase flow, boiling heat transfer, and the critical heat flux (CHF) of ethanol–water mixtures are of critical interest.

McGillis et al. [2] explored the experiments using binary mixtures of water with methanol or 2-propanol to determine the CHF in saturated pool boiling. They found that the CHF of the mixture is increased above that of pure water significantly under the conditions of small additions of alcohol, but it is decreased to that of pure alcohol at higher concentrations of the alcohol. Moreover, they pointed out that the CHF of the mixture could not be predicted by the basic model, such as the Zuber's model. McGillis and Carey [3] demonstrated that in the alcohol–water mixtures with large surface tension differences strongly affect the CHF for pool boiling. Surface tension differences would induce the additional liquid restoring force. Such a mechanism is known as the Marangoni effect. They proposed a modified model, accounting for the Marangoni effect on the CHF, to predict the CHF accurately for the mixture and operating conditions employed in their study.

Fujita and Bai [4] carried out the experiments of the CHF in nucleate pool boiling of binary mixtures. They found that aqueous mixtures of methanol and ethanol revealed the increase of the CHF significantly at a particular molar fraction of more volatile components, i.e., methanol or ethanol. The maximum CHF for methanol–water and ethanol–water mixtures is reached at the molar fraction (x_m) of about 0.3 and 0.1, respectively. They further proposed the Marangoni number, *Ma*, as a controlling factor to influence the CHF. The Marangoni number, defined by Fujita and Bai [4], is expressed as follows:

$$Ma = \frac{\Delta\sigma}{\rho_l v_l^2}\left[\frac{\sigma}{g(\rho_l - \rho_v)}\right]^{1/2} \cdot Pr \quad (1)$$

NOMENCLATURE

Co	[-]	confinement number
D_h	[m]	mean hydraulic diameter
d_e	[m]	heated equivalent diameter
G	[kg/m^{2}s]	mass flux
g	[m/s^2]	gravitational acceleration
h_{lv}	[kJ/kg]	latent heat of vaporization
L	[m]	channel heated length
MAE	[-]	mean absolute error
Ma	[-]	Marangoni number
Ma_{max}	[-]	maximum Marangoni number of the binary mixture under consideration
P	[Pa]	pressure
Pr	[-]	Prandtl number
q''	[kW/m^2]	heat flux
q''_{CHF}	[kW/m^2]	critical heat flux, CHF
T_b	[℃]	bubble point temperature
T_d	[℃]	dew point temperature
T_{sat}	[℃]	saturated temperature
T_w	[℃]	wall temperature
v_l	[m^2/s]	liquid kinematic viscosity
We_D	[-]	Weber number based on the hydraulic diameter
We_L	[-]	Weber number based on the channel heated length
W_{in}	[m]	inlet width of a channel
W_{out}	[m]	outlet width of a channel
x_m	[-]	ethanol molar fraction

Special characters

ρ_l	[kg/m^3]	liquid density
ρ_v	[kg/m^3]	vapor density
β	[degree]	divergence angle of a channel
σ	[N/m]	surface tension
$\Delta\sigma$	[N/m]	difference in the surface tension of the fluid at the dew point and the bubble point
ΔT_{sat}	[℃]	wall superheat

Studies on pool boiling of binary mixtures are widely available in the literature; however, there are few researches on flow boiling of mixtures in a channel, especially in a micro-scale channel. For example, Peng et al. [5] conducted a pioneering study on the subcooled flow boiling heat transfer characteristics of methanol–water mixtures in microchannels experimentally. They found that liquid compositions of more volatile component, i.e., methanol, have a great effect on the boiling heat transfer characteristics. They reported that the flow boiling heat transfer increases at small concentrations ($\leq$ 36.0%), but decreases at higher concentrations ($\geq$ 51.1%).

Recently, Lin et al. [1] explored experimentally the convective boiling heat transfer and the CHF of methanol–water mixtures in a diverging microchannel with artificial cavities. They found that the CHF increases slightly from x_m=0 to 0.3, and then decreases rapidly from x_m=0.3 to 1 at the same mass flux. The maximum CHF is reached at x_m=0.3, especially for the mass flux of 175 kg/m^{2}s due to the Marangoni effect. Flow visualization demonstrates that the flow pattern of the liquid film breakup persists to a higher heat flux at x_m=0.3 than other molar fractions. The Marangoni effect drives liquid flow toward the contact line and, therefore, a higher heat flux.

Existing correlations for the critical heat flux on flow boiling in a microchannel

Qu and Mudawar [6] explored the experiments to measure the CHF for flow boiling of water in a rectangular microchannel heat sink, and proposed an empirical correlation for the CHF (q''_{CHF}) as follows:

$$q''_{CHF} = 33.43 G h_{lv} \left(\frac{\rho_v}{\rho_l}\right)^{1.11} We_L^{-0.21} \left(\frac{L}{d_e}\right)^{-0.36} \quad (2)$$

Koşar et al. [7] investigated the flow boiling of water in microchannels with 7.5 μm wide reentrant cavities on the sidewalls, and proposed a correlation for the CHF as the following expression:

$$q''_{CHF} = 0.0035 G h_{lv} We_D^{-0.12} \quad (3)$$

Wojtan et al. [8] performed the experiments to determine the CHF for flow boiling of refrigerants (R-134a and R-245fa) in a microchannel, and proposed a following correlation to predict the CHF:

$$q''_{CHF} = 0.437 G h_{lv} \left(\frac{\rho_v}{\rho_l}\right)^{0.073} We_L^{-0.24} \left(\frac{L}{D_h}\right)^{-0.72} \quad (4)$$

Qi et al. [9] presented a study concerning the flow boiling of liquid nitrogen in microtubes, and proposed a CHF correlation as:

$$q''_{CHF} = (0.214 + 0.140 Co) G h_{lv} \cdot \left(\frac{\rho_v}{\rho_l}\right)^{0.133} We_D^{-0.333} \frac{1}{1 + 0.03 L / D_h} \quad (5)$$

where $Co = \{[\sigma / ((\rho_l - \rho_v) g)]^{1/2} / D_h\}$ is the confinement number, proposed by Kew and Cornwell [10].

Kuan [11] proposed a correlation for the CHF of flow boiling of water and R123 in multi-microchannels as follows:

$$q''_{CHF} = 0.2305 G h_{lv} \left(\frac{L}{d_e}\right)^{-0.9056} \quad (6)$$

These above correlations indicate that the CHF is usually proportional to Gh_{lv} and some negative power of Weber number at a given pressure, i.e., density ratio, and a given length diameter ratio. However, it should be noted that the above correlations are for the CHF of pure component boiling. Notably, since the Marangoni effect is of important effect on both boiling heat transfer and CHF of mixtures, the empirical correlation should involve such an effect. In the literature, however, there are very few studies on the flow boiling and evaporation of binary mixtures in microchannels, especially on the CHF prediction.

In our previous study [1], we proposed an empirical correlation, involving the Marangoni effect, for the CHF prediction of flow boiling of the binary mixture (methanol–water mixtures). The empirical correlation is expressed as follows:

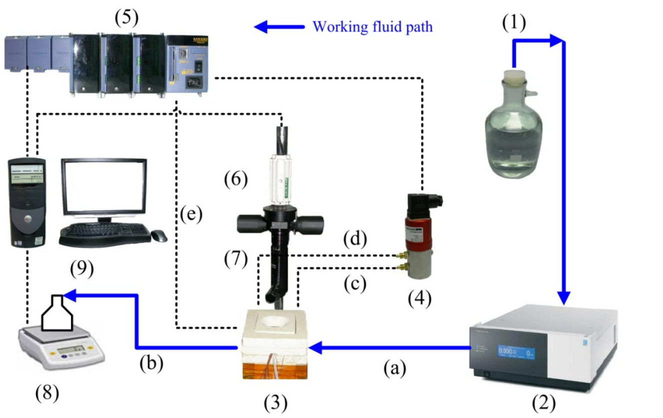
$$q''_{CHF} = 0.00216 G h_{lv} We_D^{-0.078} \left(1 - 0.44 \frac{Ma}{|Ma_{\max}|}\right)^{-1} \quad (7)$$

All the properties should be taken at the outlet of the channel.

Flow boiling in a diverging microchannel

Flow boiling in a microchannel is usually subject to the two-phase flow instability with the flow reversal and the local dry-out condition [12]. Such the two-phase flow instability is undesirable as it will reduce the CHF and may break down the heat transfer devices [13]. Consequently, it is of significant interest to develop a microchannel with both stable two-phase flow and high boiling heat transfer capability. Lu and Pan [14] demonstrated that the two-phase flow instability for flow boiling in a diverging microchannel can be significantly suppressed. This is because such a steep pressure gradient near the inlet in the diverging microchannel may help to resist the reversed flow of bubbles and significantly stabilizes the two-phase flow [15]. Recently, Lu and Pan [16, 17] found that flow boiling of water in a diverging microchannel with laser-drilled artificial nucleation sites can further enhance the two-phase flow stability as well as the boiling heat transfer.

The present study, following the previous work [1], investigates experimentally the convective boiling heat transfer and the CHF of ethanol–water mixtures in a diverging microchannel with artificial cavities. The effects of the mass flux and the ethanol molar fraction on the boiling heat transfer and the CHF are explored. Moreover, the experimental results are compared with existing correlations for the CHF on flow boiling of pure component as well as the empirical correlation for the CHF on flow boiling of the mixtures (involving the Marangoni effect on the CHF for the convective boiling heat transfer of binary mixtures), proposed in our previous study.



(1) Filtering flask	(6) High Speed CCD Camera	(a) Working Fluid inlet
(2) HPLC pump	(7) Optical zoom system	(b) Working Fluid outlet
(3) Test module	(8) Balance	(c) Pressure inlet
(4) Differential pressure transmitter	(9) PC	(d) Pressure outlet
(5) Data acquisition system		(e) Thermocouple

Figure 1 Experimental setup.

EXPERIMENTAL DETAILS

Experimental setup

The experimental setup, as shown in figure 1, consists of a high-performance liquid chromatography (HPLC) pump (Dionex, model: P680), a pressure transducer (Huba Control UK, model: 692), a flow visualization system, a data acquisition system (YOKOGAWA, model: MX100), a test section, and a heating module. The HPLC pump provides forced flow of the working fluids in the microchannel with accurate and stable mass flow rates. The entrance of the HPLC pump was installed with a filter of a net size of 0.1 μm to prevent impurities from entering the test section. Moreover, the exhausted fluids from the test section were drained to a container on an electronic balance, which provided calibration of the flow rate. The differential pressure transducer used in the present study is with a short response time of 0.005 s and the sampling rate for pressure measurement was set at 100 Hz. Flow visualization was conducted by using a high-speed digital camera (IDT, model: MotionPro X4 Plus) with a microlens (OPTEM, model: Zoom 125C), a 250 W fiber optic illuminator (TECHNIQUIP, model: FOI-250), a monitor, and a personal computer. To capture the fast-changing flow pattern, the typical frame rate and exposure time were 5000 frame/s and 50 μs, respectively. The signals from thermocouples and pressure transducers were recorded by the data acquisition system. The pressure at the outlet chamber is approximately 1 atm. The present study employed ethanol–water mixtures as the working fluid. Seven molar fractions (x_m=0, 0.1, 0.2, 0.5, 0.7, 0.89, and 1) of ethanol–water mixtures at a given mass flux of 175 kg/m^{2}s and seven mass fluxes (G=175, 265, 350, 438, 525, 613, and 700 kg/m^{2}s) at a given molar fraction of 0.1 were tested. Here, molar fractions of 0 and 1 are referred to as pure water and ethanol, respectively.

Test section and heating module

Figure 2 illustrates the test module, including the test section and the heating module. Figure 2(a) displays a schematic of the single channel with a divergence angle of β, i.e., a half of the included angle. Figure 2(a) also illustrates 24 artificial cavities (serving as nucleation sites) distributed in the whole channel on the bottom wall of microchannel, with uniform spacing of 1 mm. Artificial cavities are a laser-drilled pit with a mouth diameter of about 20 μm. The test section with a single diverging microchannel is a silicon strip with a dimension of 40 mm × 10 mm, as shown in figure 2(b). The length and depth of the channel are 25 mm and 85 μm, respectively. The width of the diverging microchannel varies linearly from 215 (W_{in}) to 1085 μm (W_{out}), resulting in a divergence angle of 1 degree and a mean hydraulic diameter of 147 μm.

The dimension of the heating module is 16 mm × 10 mm × 30 mm, and the heating surface area is 16 mm × 10 mm. The heating module is a copper block heated by a cartridge heater with the controllable power. To minimize heat loss, the whole test module is covered with a thick ceramic fiber except the top surface of the test section for the flow visualization. Figure 2(c) shows that the test section is adhered to the heating module with a silver adhesive (DuPont Electronics, 4817N). The contact thermal resistance between the test section and the heating module was determined to be 0.24×10^{-4} Km^2/W [18]. Figure 2(c) also illustrates that two thermocouples were placed at the inlet chamber and outlet, respectively, and the three thermocouples were embedded 2 mm under the heating surface to measure the wall temperature distribution along the microchannel. The interval between the two neighboring thermocouples was 5 mm. The wall temperature of the microchannels can be obtained by evaluating the total thermal resistance from the location of the thermocouple to the bottom wall of the microchannel. The channel wall heat flux was determined by considering energy balance with various heat losses, including natural convection, thermal radiation from the top surface, and conduction to the inlet and outlet chambers. The detailed procedure for the evaluation of various heat losses was presented in the previous study [18].

Measurement uncertainty

The measurement uncertainty for volume flow rate in the microchannels after calibration was estimated to be ±3%. The uncertainties in temperature measurements were ±0.2 ℃ for the T-type thermocouples. The uncertainty in pressure transducer measurements was ±1%. The overall uncertainty of wall heat flux under flow boiling was ±4.5%. The uncertainty of heat flux generally decreases with increasing heat flux and/or mass flux.

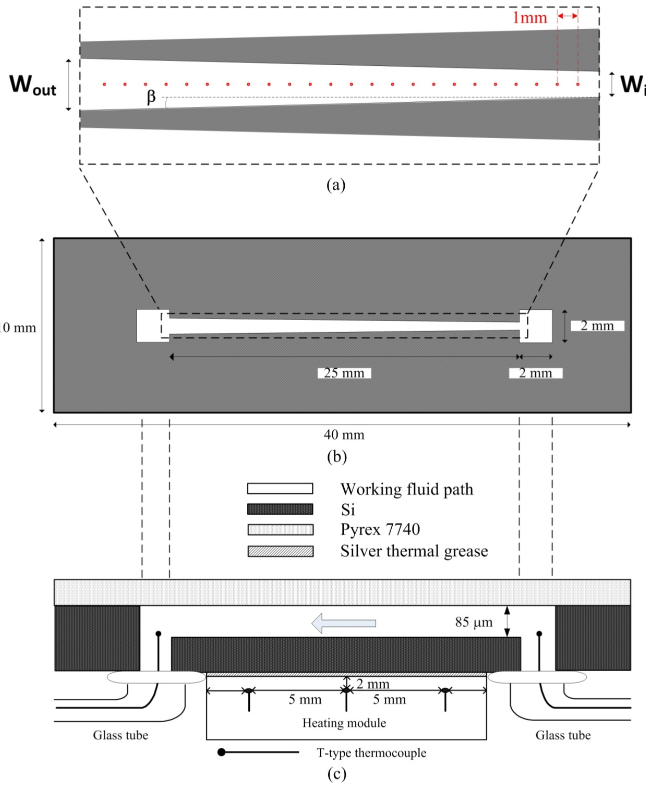


Figure 2 Schematic of the test module (not to scale).

PHASE DIAGRAM, MARANGONI PARAMETER, AND SURFACE TENSION OF ETHANOL–WATER MIXTURES

Figure 3 presents the vapor–liquid equilibrium phase diagram of ethanol–water mixtures as a function of different ethanol molar fractions based on the Wilson's equation [19] at atmospheric pressure (P=101 kPa). This figure clearly shows that the maximum temperature difference between the dew point (T_d) and bubble point (T_b) is located at x_m=0.1 to 0.2, presenting the widest range of the liquid–vapor coexistent region, which may postpone the CHF happening and increase the CHF. The ethanol–water mixture is a positive mixture [20], of which the surface tension decreases with increasing concentration of the more volatile component (figure 4), i.e., ethanol. Moreover, there is an azeotropic point for the ethanol–water mixtures at x_m=0.89, as shown in figure 3. Under boiling conditions, due to the preferential evaporation of the more volatile component of the mixture near the heated surface, a concentration gradient, as well as temperature gradient, along the liquid–vapor interface may be induced therein, and the Marangoni force induced may pull the bulk liquid toward the contact line [21].

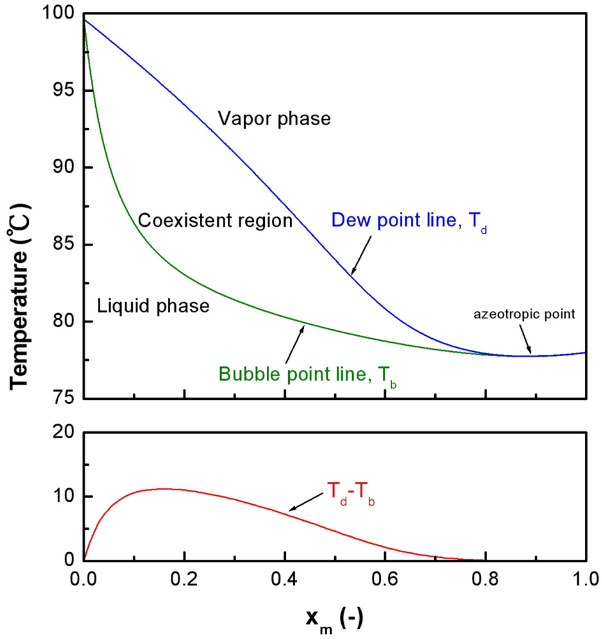


Figure 3 Phase equilibrium diagram of ethanol–water mixtures at P=101 kPa.

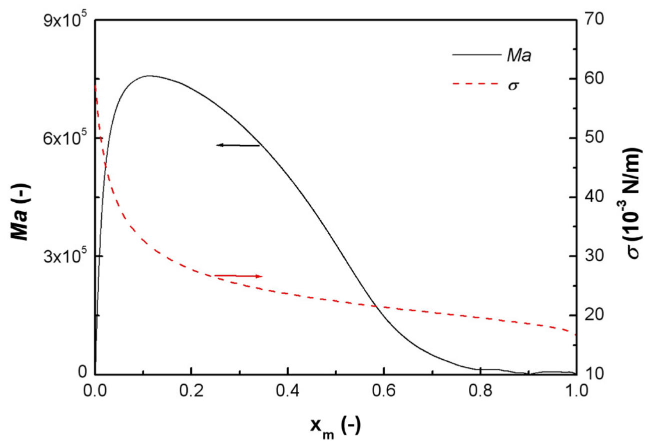


Figure 4 Marangoni parameter and surface tension of ethanol–water mixtures at P=101 kPa and the bubble point temperature as a function of ethanol molar fraction.

Figure 4 illustrates the surface tension of ethanol–water mixtures at the saturation temperature (bubble point temperature) and the corresponding Marangoni numbers. Since the surface tension decreases sharply with increasing the molar fraction in the low molar fraction region, the existence of strong Marangoni force would be expected therein. The figure shows that *Ma* reaches its maximum at about x_m=0.1. It is generally believed that the Marangoni convection supplying the liquid toward the contact line would directly delay the dry-out of the liquid film. It would, therefore, enhance the heat transfer rate and improve the CHF.

RESULTS AND DISCUSSION

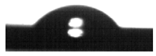
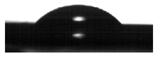
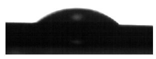
Boiling curve

Figure 5 illustrates the heat flux (q'') as a function of the wall superheat ($\Delta T_{sat} = T_w - T_{sat}$) at different molar fractions of ethanol for G=175 kg/m^{2}s. In the present study, the heat flux is based on the area of the bottom and side walls of the channel, the wall temperature (T_w) is the arithmetic mean of three wall temperatures measured, and the saturated temperature (T_{sat}), i.e., the bubble point temperature, is that corresponding to the system pressure, i.e., the mean of inlet and outlet pressures. It should be noted that the bubble point is different for different ethanol molar fractions as illustrated earlier in the previous section.

Figure 5 clearly illustrates the significant effect of the molar fraction on boiling curve. For the single-phase convection region, the heat flux increases with decreasing the molar fraction, i.e., the heat flux is the highest for pure water whereas it is lowest for pure ethanol at a given wall superheat. This is due to the differences in thermal–physical properties of fluids among mixtures with different molar fractions. After boiling incipience (two-phase flow region), the heat flux increases rapidly with increasing the wall superheat until approaching the CHF condition. The figure indicates that the wall superheat for the onset of nucleate boiling is different for mixtures with different molar fractions. There is significant temperature overshoot for ethanol solutions of molar fraction between 0.2 and 0.89 because ethanol solution is more hydrophilic than water. As shown in table 1, the contact angle on the surface of the silicon wafer decreases with increasing the molar fraction. However, there is no temperature overshoot for pure ethanol although its contact angle is the smallest. Moreover, there seems to be no uniform trend for the effect of molar fraction on boiling curve. The boiling curve for pure water is definitely on top of that of pure ethanol.

The boiling curve for all molar fractions demonstrates an asymptotical plateau before the appearance of dry-out heat flux. Such plateau region is characterized by the liquid film breakup. Intermittently dry-out and re-wetting take place; consequently, the heat flux increases slightly only while the wall superheat is increased. In such particular region, the boiling curve of small molar fraction (x_m=0.1) is on top of that of pure water. Indeed, the maximum CHF is reached at x_m=0.1, indicating that small additions of ethanol into water could significantly increase the CHF. It may result from the Marangoni effect, as discussed earlier.

Table 1 Contact angle of ethanol–water mixtures at different molar fractions on the surface of the silicon wafer.

Molar fraction (x_m)	Contact angle (degree)	Image
0 (water)	47	
0.1	45	
0.2	38	
0.5	32	
0.7	24	
0.89	10	
1 (ethanol)	7	

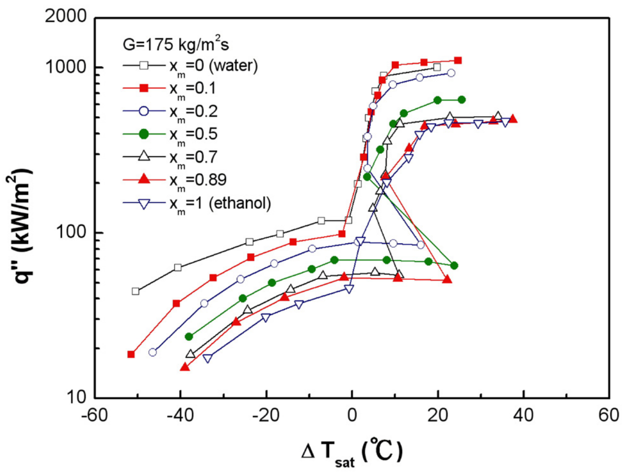


Figure 5 Boiling curves for ethanol–water mixtures as a function of ethanol molar fraction at G=175 kg/m^{2}s.

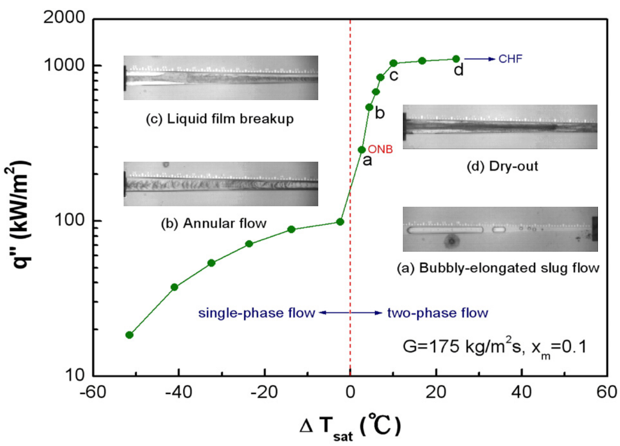


Figure 6 Typical two-phase flow patterns at x_m=0.1 and G=175 kg/m^{2}s.

Figure 6 shows typical two-phase flow patterns at x_m=0.1 and G=175 kg/m^{2}s corresponding to certain part of the boiling curve. Similar to the previous study [1], four boiling regimes are indentified, namely: (a) bubbly-elongated slug flow, (b) annular flow, (c) liquid film breakup, and (d) dry-out. Under the conditions of relatively low heat flux, bubbles nucleated and grow rapidly becoming an elongated slug bubble, named bubbly-elongated slug flow; for medium to high heat fluxes, the bubbly-elongated slug flow evolves to the annular flow, especially in the region near the exit; further increasing the heat flux, breakup in the liquid film appears and the flow pattern is referred to as liquid film breakup. Accordingly, the evaporation of a thin liquid film either in the bubbly-elongated slug flow, annular flow, or liquid film breakup region, is the major mechanism of the heat transfer for convective boiling in the microchannel. For even higher heat fluxes, liquid film are evaporated immediately and completely, regarded as the dry-out, while entering the channel. Such the heat flux is regarded as the CHF.

Critical heat flux

Figure 7 shows experimental results of the CHF as a function of the molar fraction at G=175 kg/m^{2}s. The figure indicates that, for small molar fraction (x_m=0.1), the CHF increases with increasing the molar fraction and reaches a maximum at x_m=0.1. For molar fractions greater than 0.1, the CHF decreases rapidly with increasing the molar fraction until the molar fraction reaches 0.7, after which the CHF remains unchanged. The CHF at x_m=0.1 is about 110% and 234% of that at x_m=0 and 1, respectively. Similarly, Fujita and Bai [4] reported that the maximum CHF is obtained at about x_m=0.1 for the pool boiling of ethanol–water mixtures. Such an increase of the CHF with small additions of ethanol in the water is clearly due to the Marangoni effect as pointed out in the literature [3, 4]. Indeed, the Marangoni number, defined by equation (1), demonstrates the maximum at x_m=0.1 (see figure 4). The Marangoni effect drives liquid flow toward the contact line and helps the surface being wetted at a higher heat flux.

The predictions of existing correlations in the literature, i.e., equations (2) to (7), for the CHF of pure component or mixture boiling based on mixture properties are also plotted in figure 7. The predictions of equations (3) to (6) show that the CHF decreases rapidly with increasing the molar fraction from x_m=0 to 0.1, and then decreases slowly. This is mainly due to the latent heat of vaporization decreases rapidly from x_m=0 to 0.1, i.e., the latent heat of vaporization of water is much higher than that of ethanol–water mixtures, even for a small fraction of ethanol. On the other hand, the prediction of equation (2) illustrates that the CHF increases slowly from x_m=0 to 1 because the Weber number and the density ratio are more dominant than the latent heat of vaporization. Notably, none of existing correlations for the CHF on flow boiling of pure component in a microchannel, i.e., equations (2) to (6), could present the correct trend as the CHF data on flow boiling of ethanol–water mixtures, and none of those correlations could predict the CHF precisely. Those correlations are unable to predict the concentration effect at all. This is because that the Marangoni effect, which plays an important role on flow boiling of binary mixtures, is not considered in those correlations. Significantly, experimental results of the CHF show an excellent agreement and demonstrate a consistent trend with an empirical correlation for the CHF prediction of flow boiling of the mixtures, i.e., equation (7), proposed in our previous study [1].

Figure 8 presents experimental results of the CHF as a function of the mass flux at x_m=0.1 and the predictions of equation (7) are also plotted in the figure for comparison. Due to the power limitation of the heating module, the CHF were not reached at G=525, 613, and 700 kg/m^{2}s. Figure 8 demonstrates that the CHF significantly increases with the mass flux, which is accordant with reports and correlations for the CHF on flow boiling in microchannels [1, 6–9, 11]. The CHF is about 2200 kW/m^2 at the mass flux of 438 kg/m^{2}s. Moreover, the figure indicates that the correlation of Lin et al. [1] can predicted the experimental data very well.

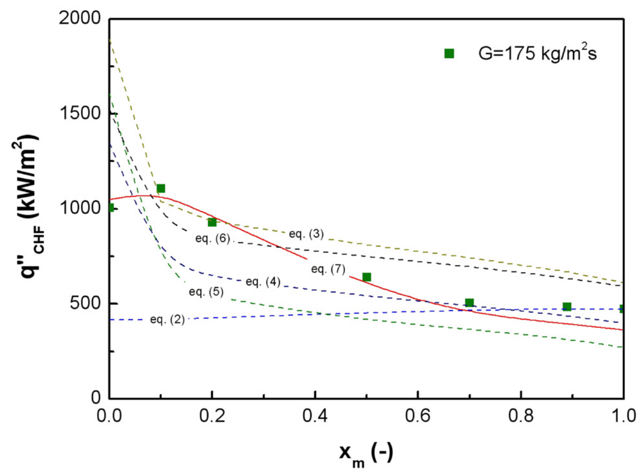


Figure 7 Critical heat flux as a function of the molar fraction at G=175 kg/m^{2}s.

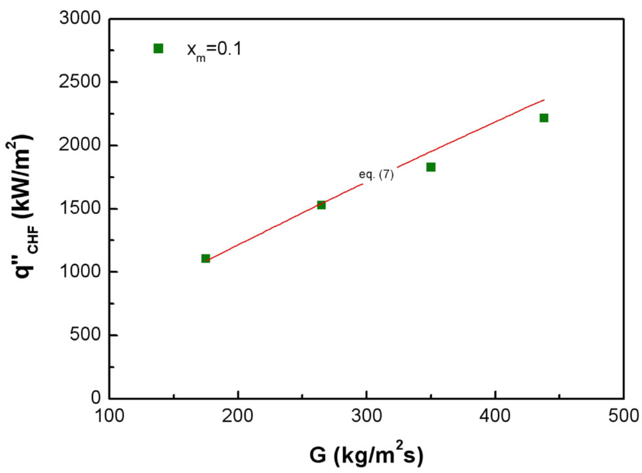


Figure 8 Critical heat flux as a function of the mass flux at x_m=0.1.

Comparison with existing correlations

Figure 9 depicts the comparison of experimental CHF data with the predictions of existing correlations. Figures 9(a) to 9(e) show that most of the correlations other than Lin et al. [1] in the literature underpredict the experimental data except for that of Koşar et al. [7] and Kuan [11], a mean absolute error (MAE) is between 20.6% and 45.5%, and less than 50% of the experimental data are predicted within a ±15% error band. For example, a MAE of the correlation of Qu and Mudawar [6] and Kuan [11] is 41.4% and 20.6%, respectively. And only about 30% and 40% of the experiment data are predicted within a ±15% error band by the correlation of Qu and Mudawar [6] and Kuan [11], respectively.

On the other hand, the predictions of the correlation proposed by Lin et al. [1] show an excellent agreement with the experimental data. The overall mean absolute error of this correlation is only 8.49% and more than 80% of the experimental data are predicted within a ±15% error band, as shown in figure 9(f). The present experimental results confirm that the correlation of Lin et al. [1] may accurately catch the Marangoni effect on the CHF of ethanol–water mixtures. Such an excellent agreement demonstrates that the correct of Lin et al. [1]. This correlation may be recommended for the CHF prediction of convective boiling of other binary mixtures.

SUMMARY AND CONCLUSIONS

This study investigates experimentally the convective boiling heat transfer and the critical heat flux of ethanol–water mixtures in a diverging microchannel with artificial cavities. Experimental results show that the boiling heat transfer and the CHF are significantly influenced by the molar fraction as well as the mass flux. Moreover, the experimental results are compared with existing correlations for the CHF on flow boiling of pure component in a microchannel as well as the empirical correlation for the CHF on flow boiling of the mixtures (involving the Marangoni effect on the CHF for the convective boiling heat transfer of binary mixtures), proposed in our previous study [1]. The following conclusions may be drawn from the results of the present study.

1. There is significant temperature overshoot for ethanol solutions of molar fraction between 0.2 and 0.89 because ethanol solution is more hydrophilic than water. However, there is no temperature overshoot for pure ethanol, although its contact angle is the smallest.
2. The CHF increases from x_m=0 to 0.1, and then decreases rapidly from x_m=0.1 to 1 at a given mass flux of 175 kg/m^{2}s. The maximum CHF is reached at x_m=0.1 due to the Marangoni effect and the widest range of the liquid–vapor coexistent region. The CHF at x_m=0.1 is about 110% and 234% of that at x_m=0 (pure water) and 1 (pure ethanol), respectively, indicating that small additions of ethanol into water could significantly increase the CHF.
3. On the other hand, the CHF increases with increasing the mass flux at a given molar fraction of 0.1, for example, the CHF at G=265 and 350 kg/m^{2}s is about 138% and 166%, respectively, of that at G=175 kg/m^{2}s.

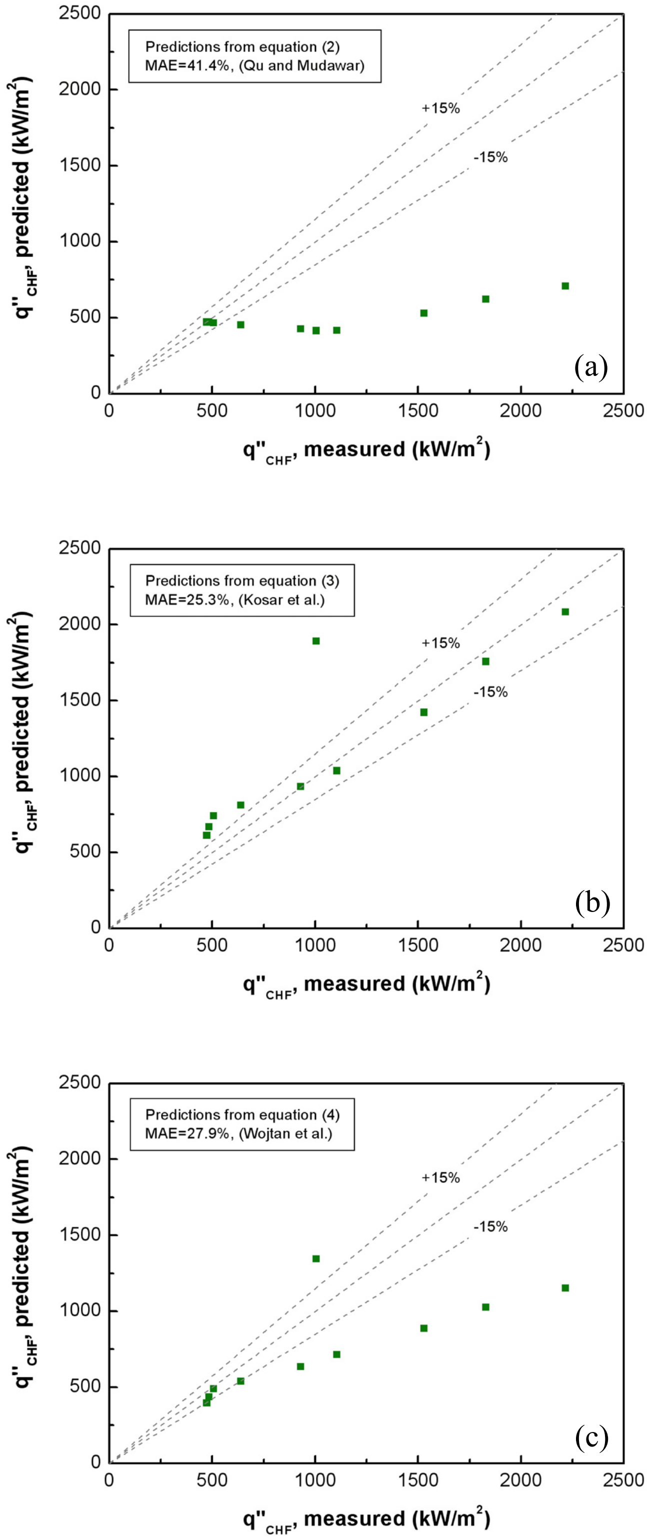


Figure 9 Comparison of the experimental CHF data with existing correlations, (a) Qu and Mudawar [6], (b) Koşar et al. [7], (c) Wojtan et al. [8], (d) Qi et al. [9], (e) Kuan [11], and (f) Lin et al. [1].

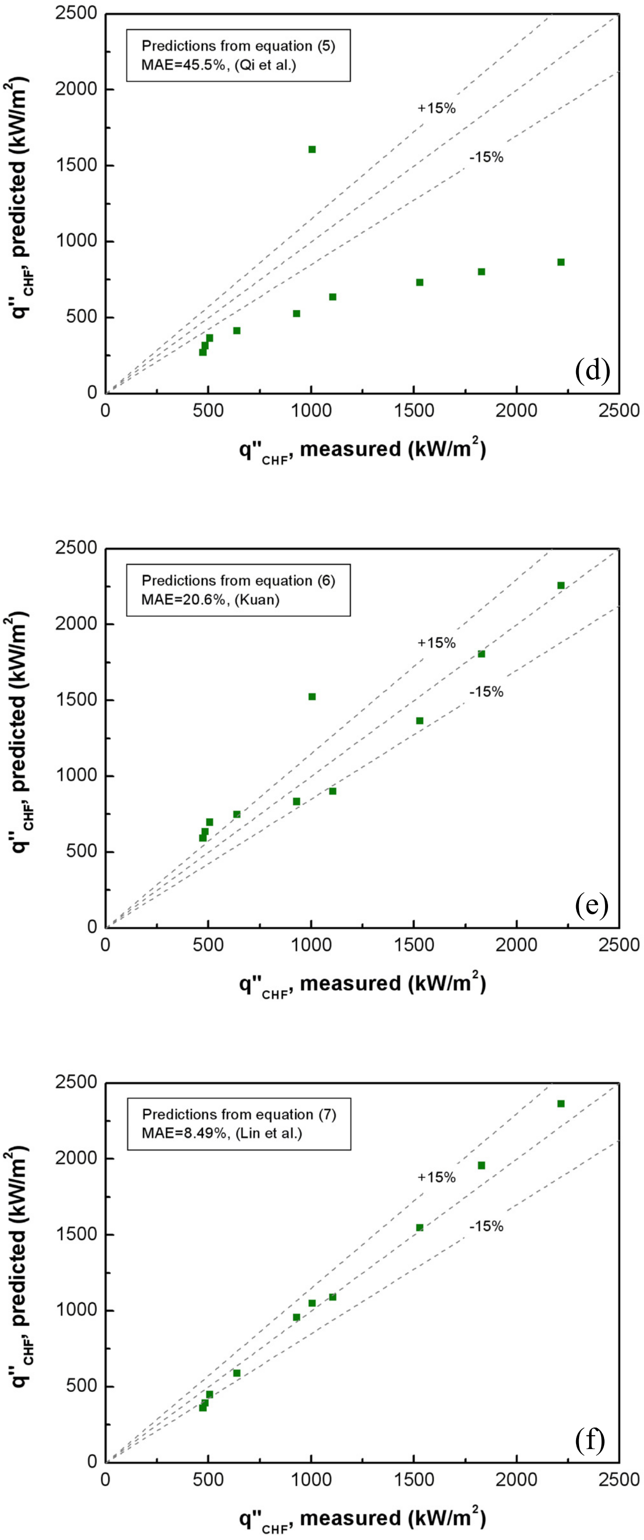


Figure 9 (continued)

4. Existing correlations for the CHF on flow boiling of pure component in a microchannel, such as the correlation of Qu and Mudawar [6], Koşar et al. [7], Wojtan et al. [8], Qi et al. [9], and Kuan [11], can not predict the correct trend as the CHF data on flow boiling of ethanol–water mixtures, and most of those correlations predict the CHF poorly.
5. On the other hand, the CHF show an excellent agreement with the empirical correlation for the CHF prediction, proposed by Lin et al. [1], which considers the Marangoni effect on the CHF for the convective boiling heat transfer of binary mixtures. The overall mean absolute error of this correlation is 8.49% and more than 80% of the experimental data are predicted within a ±15% error band.
6. The present experimental results confirm that the correlation of Lin et al. [1] may accurately catch the Marangoni effect on the CHF of ethanol–water mixtures. Such an excellent agreement demonstrates that the correct of Lin et al. [1]. This correlation may be recommended for the CHF prediction of convective boiling of other binary mixtures.

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