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Flow boiling of binary mixtures in microchanneled plates

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Abstract—Experiments were conducted to investigate the subcooled flow boiling heat transfer characteristics of binary mixtures in microchannel plates. Generally, mixtures with small more volatile component concentrations augmented the flow boiling heat transfer, while those with large concentrations decreased the heat transfer as compared with the pure more volatile liquid. There existed an optimum concentration at which the flow boiling heat transfer reached a maximum value. These characteristics were found to be affected by both liquid flow velocity and amount of subcooling. The heat transfer coefficient at the onset of flow boiling and in the partial nucleate boiling region was greatly influenced by liquid concentration, microchannel and plate configuration, flow velocity and amount of subcooling. However, microchannel size, flow velocity, subcooling of the mixture, and liquid concentration had no significant effect on the heat transfer coefficient in the fully nucleate boiling regime. The level of augmentation induced by increasing the number of channels diminished as size decreased.

INTRODUCTION

Micro-manufactured structures/components with extremely small channels in which fluids are contained or through which fluids flow, have been employed in the thermal control of electronic equipment and devices as an effective cooling method. However, experimental data have indicated that the fluid flow and heat transfer in microchannels are more strongly dependent upon the selection of the working fluid which can be a significant factor in the cooling performance. This is especially true for the flow boiling of mixtures in microchannels and as a result, additional investigations are needed to identify the heat transfer characteristics, the effect of liquid species and mixing concentrations so as to increase the effectiveness of mixtures in existing applications and enhance the design of new systems.

Very few investigations have been conducted on the flow boiling of liquid through microchannels, and no research dealing with the flow boiling of mixtures in microchannels is available in the open literature [1]. Peng and Wang [2, 3] and Peng *et al.* [4] conducted a sequence of experiments to observe the flow boiling phenomena and investigate the heat transfer of water and methanol flowing in microchannels or microchanneled structures. The flow boiling was initiated at lower wall superheats and an apparent partial boiling regime was observed, even for liquids with significantly high inlet subcooling. It was noted that the microchannel size had a significant influence on the onset of flow boiling [1]. Bowers and Mudawar [5] experimentally investigated the flow boiling of liquid R-113 through mini- and microchannels. This work indicated that the inlet subcooling had little effect on CHF and the superheated outlet conditions. These investigations also provided the first indication that the flow boiling in microchannels exhibited features that differed from those normally encountered in conventional-sized flow passages.

Although many previous experimental and analytical investigations have been done for pool boiling of binary and multi-component mixtures, the flow boiling of mixtures has not received much attention. Rammohan *et al.* [6], Sivagnanam *et al.* [7–9] and Wenzel *et al.* [10, 11] studied subcooled flow boiling of binary and multicomponent mixture systems and investigated the effect of liquid velocity, subcooling and concentration. Models were proposed to predict the heat transfer and describe the physical processes. General information, however, for flow boiling of mixtures through microchannels or circular tubes is currently not available [12].

Experiments were conducted to investigate the flow boiling of subcooled binary mixtures of methanol and water flowing through a variety of microchannels. The measured heat transfer results are presented and compared to identify the flow boiling characteristics and the effect of parameters such as liquid flow velocity, concentration, applied heat flux, wall superheat, liquid temperature, and microchannel geometric configuration. Particular emphasis is placed on the effect of mixture concentration.

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NOMENCLATURE

D_h	hydraulic diameter of microchannel
M	mass flowrate
H	height of microchannel
h	heat transfer coefficient
L	length of microchannel
Q	total power input
q''	heat flux
T	temperature
W	width of microchannel
W_c	center-to-center distance of microchannel
W_t	width of microchannel structure/plate
X	mole fraction of more volatile component.

Subscripts

f	liquid
in	inlet
w	wall.

TEST SETUP

The test facility illustrated in Fig. 1 was constructed for the current investigation. It consists of a liquid reservoir, liquid pump, filter, heat exchanger for liquid temperature control, cooling heat exchanger, flow meter, test article and adjusting valves. The working liquid coolant consisting of a binary mixture of water and methanol was pumped from the bottom of the reservoir and circulated through the test loop. Exiting the pump, the working fluid passed through a heat exchanger where it was heated or cooled depending upon the test subcooling conditions. The appropriately metered volume flow rate entered the test loop and flowed through a filter, flow meter, test article and cooling heat exchanger, finally returning to the reservoir, while the remaining flow was routed to the reservoir through the by-pass loop.

The test module shown in Fig. 2 was fabricated from a stainless steel substrate and utilized a fiberglass plastic cover, which served as both insulator and sealant. Eight rectangular cross-sectional microchannel configurations, 50 mm long each, were manufactured and evaluated. The geometric and characteristic parameters are summarized in Table 1. Two plenums were machined on a stainless steel plate and connected by the microchannel to form the test section. A pressure tap was located in each to measure the inlet and outlet pressure. Two thermocouples were also installed in the entrance and exit plenums, to measure the liquid temperature. In addition, three thermocouples were distributed longitudinally and moun-

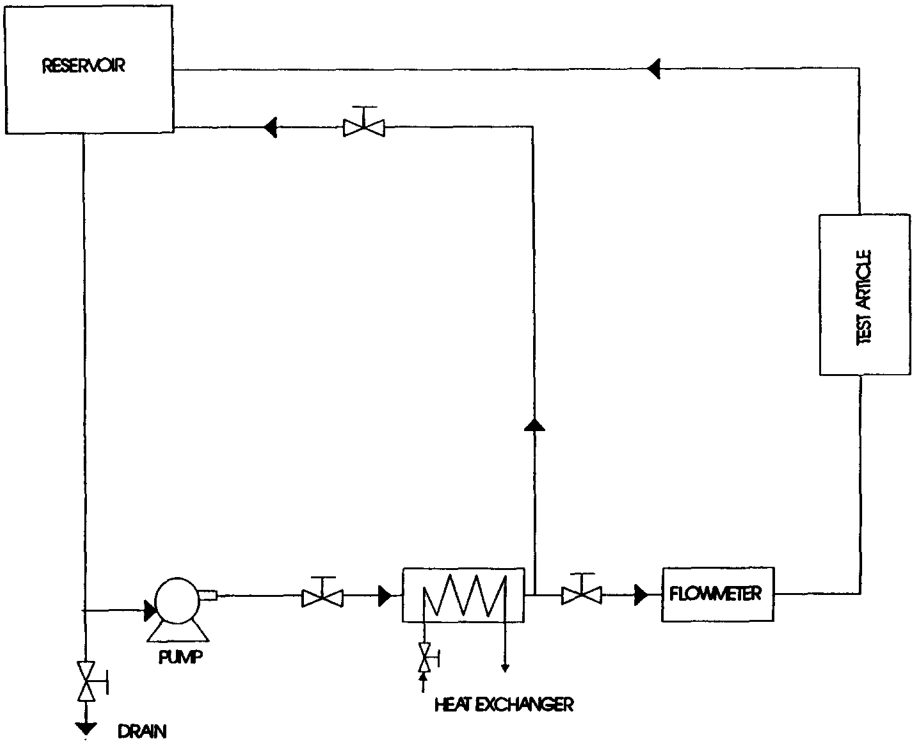

Fig. 1. Test setup.

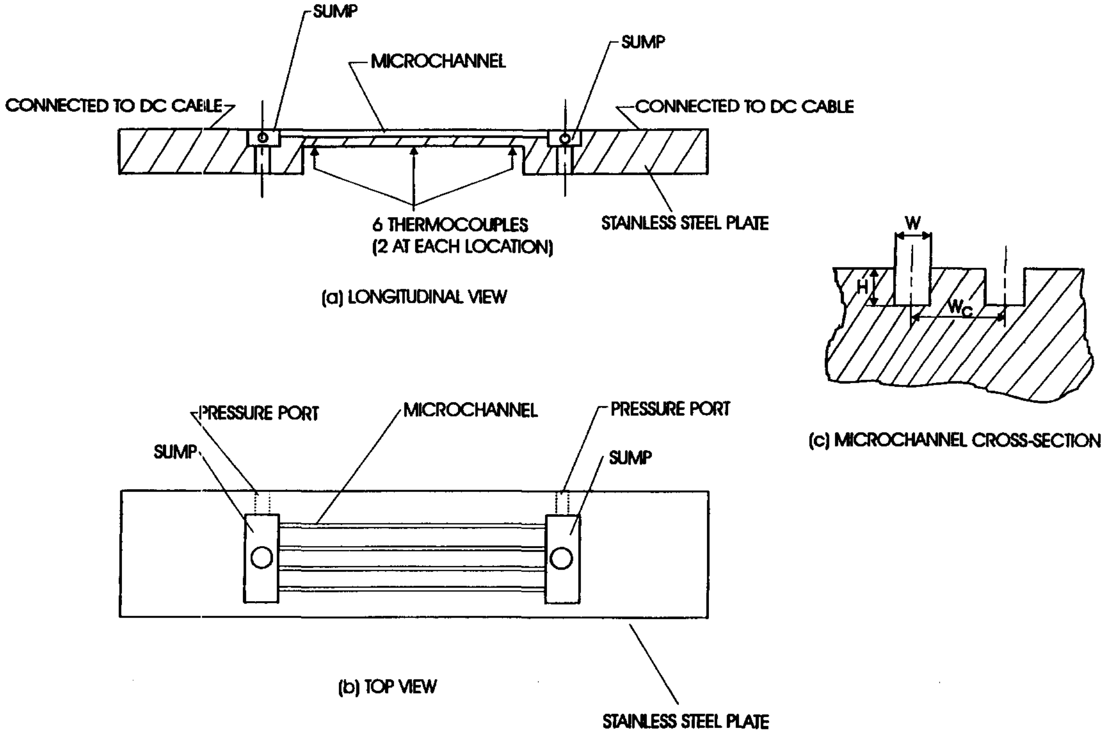

Fig. 2. Test article.

Table 1. Geometric parameters of the test sections

Plate	W [mm]	W_c [mm]	W_t [mm]	L [mm]	H [mm]	D_h [mm]
1	0.4	4.5	18	45	0.2	0.267
2	0.4	2.8	18	45	0.3	0.343
3	0.4	2.0	18	45	0.3	0.343
4	0.3	4.6	18	45	0.2	0.24
5	0.3	2.8	18	45	0.3	0.30
6	0.3	2.0	18	45	0.3	0.30
7	0.2	4.5	18	45	0.2	0.20
8	0.2	2.8	18	45	0.3	0.24
9	0.2	2.0	18	45	0.3	0.24
10	0.1	4.5	18	45	0.2	0.133
11	0.1	2.8	18	45	0.3	0.15
12	0.1	2.0	18	45	0.3	0.15

ted on the back of the test section to measure the wall temperature of the microchannel as a function of axial position. During the test, the test article was placed in an insulated housing to minimize the heat loss due to convection and radiation.

EXPERIMENTAL DESCRIPTION

Binary mixtures of methanol and water were evaluated. Nine variant combinations or binary mixtures with mole fractions of the more volatile component of $X = 0$, 5.88, 12.3, 23.2, 36.0, 51.1, 69.2, 83.5 and 100 were tested. Experiments were conducted at inlet liquid temperatures ranging from 18°C to 27.5°C, corresponding to a liquid subcooling range of approximately 38–82°C. Liquid velocities ranged from 0.1 to 4.0 m s^{-1}. In all of the tests, the flow rate of the working fluid entering the test article was measured using a rotameter, and its magnitude was controlled by the adjusting valves installed in the test loop and by-pass line. The inlet liquid temperature was maintained at a constant value using the heat exchanger placed in the test loop by heating or cooling.

The stainless steel plate substrate was electrically heated by directly connecting the test sections to a d.c. transformer that provided low voltage and high electric current. In this way, heat generated in the substrate or plate was transferred to the liquid flow from the two sides and bottom of the microchannel, as illustrated in Fig. 2(c). As a result of the Joule heating, the heat flux was assumed to be uniform and constant along the longitudinal length and the wetted periphery, except for the top surface, which was insulated. The input voltage and current could be adjusted to control the input power, and were used to determine the applied heat flux, defined as

$$q'' = \frac{Q}{W_t L} \tag{1}$$

where Q is total power input. In the calculations, Q was modified by accounting for the heat loss due to convection and conduction.

Experiments were conducted under steady-state conditions. For each different configuration, the liquid flow rate, liquid temperatures, inlet and outlet pressures, wall surface temperatures, input voltage and currents were all measured and recorded. The measurements and resulting uncertainties were analyzed and are listed in Table 2.

Table 2. Experimental uncertainties

Variables	Uncertainty [%]
Flow rate	1.5
Velocity	3.5
Voltage	0.5
Current	0.5
Heat flux	8
Length scale	1–2
Pressure	1
Liquid temperature	1.5
Wall temperature	1
Heat transfer coefficient	10

Because of the extremely small flow channel size, the local bulk liquid temperature increased rapidly along the longitudinal length and greatly depended upon the applied heat flux, flow rate, inlet temperature, etc. For convenience, the local heat transfer coefficient is defined as:

$$h = \frac{q''}{T_w - T_{in}}. \tag{2}$$

The uncertainty associated with the computed local heat transfer coefficient was lower than ±10%.

FLOW BOILING CURVES

Effect of liquid concentration

The measured results for the flow boiling of binary mixtures with different mole fractions through plate 11 are presented in Figs. 3(a) and 3(b) for liquid velocities, $U = 1.04\ \mathrm{m\ s^{-1}}$ and $U = 0.54\ \mathrm{m\ s^{-1}}$, respectively. In these graphs there are two areas included, the convective heat transfer regime and the subcooled flow boiling regime. Here the discussions will focus on the former, flow boiling. The flow boiling curve for pure water is highest in these graphs, and the flow boiling heat transfer is larger than for either pure methanol or mixture flow under the same wall superheat. For binary mixtures the boiling heat transfer is augmented when the mole fraction of methanol is lower than $X = 36.0$, as compared with the pure methanol flow boiling shown in Fig. 3. For cases of mixtures with $X \geqslant 51.1$, the boiling curves are lower than that of pure methanol flow, indicating that the flow boiling heat transfer is restrained by increasing liquid concentrations. These results indicate that small mole fractions of the more volatile component (about $X \leqslant 36.0$) increases the flow boiling heat transfer, and higher concentrations ($X \geqslant 51.1$) diminish the heat transfer when compared to the pure more volatile liquid, methanol. Comparing Fig. 3(a) with Fig. 3(b), it is apparent that the concentration at which the highest flow boiling augmentation occurs relative to the pure more volatile liquid is also strongly affected by liquid velocity. For a liquid velocity of $U = 1.04\ \mathrm{m\ s^{-1}}$, this concentration is $X = 5.88$, as shown in Fig. 3(a). Figure 3(b), the results for a liquid velocity of $U = 0.54\ \mathrm{m\ s^{-1}}$, indicates the optimum concentration is $X = 12.3$. This implies that the optimum concentration of the more volatile component could be changed by the liquid velocity, and the effect of the mole fraction on the flow boiling heat transfer would depend upon the liquid velocity. It is clear from the experimental results that the flow velocity tends to decrease the optimum concentration and the range of concentrations in which the boiling heat transfer is enhanced. These discussions also imply that the selection of the appropriate binary mixture and fluid composition is critically important in practical applications. For example, if the binary mixture of methanol and water with $X = 5.88$ is chosen as the working fluid, the flow boiling heat transfer rate is about 1.8–2.0 times higher than that of pure methanol at a liquid velocity of $U = 1.04\ \mathrm{m\ s^{-1}}$. Alternatively, if the mixture of $X = 83.5$ or $X = 69.2$ were chosen, the heat transfer rate would be as much as 1.5 times lower.

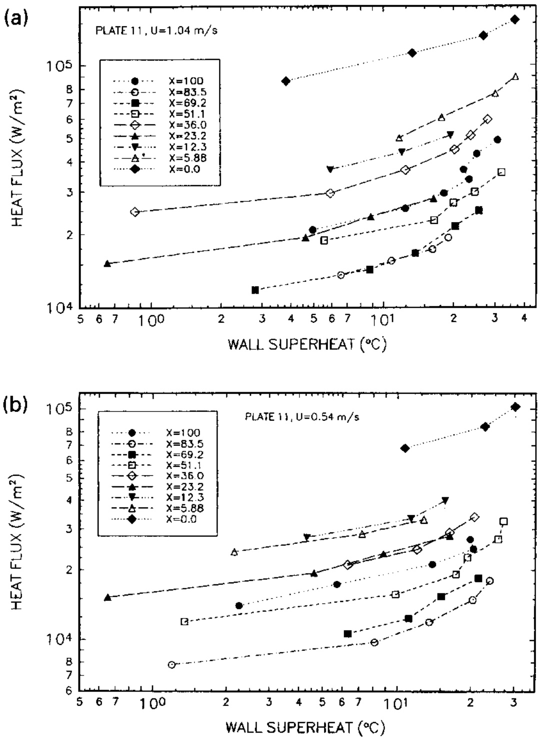

Fig. 3. Effect of liquid concentration on flow boiling curve.

Effect of microchannel configuration and number

Figure 4 illustrates typical flow boiling curves for different test plates with the same liquid flow velocity and $X = 36.0$. For test plates with identical numbers of microchannels and different configurations, four channels on each plates in Fig. 4(a) and six channels on each plate in Fig. 4(b), the heat transfer is quite different, even though the flow velocity through each microchannel is identical. From the results presented in these graphs, it is apparent that the boiling heat transfer rate is lower for the plate with the smaller microchannels than for the plate with larger micro-

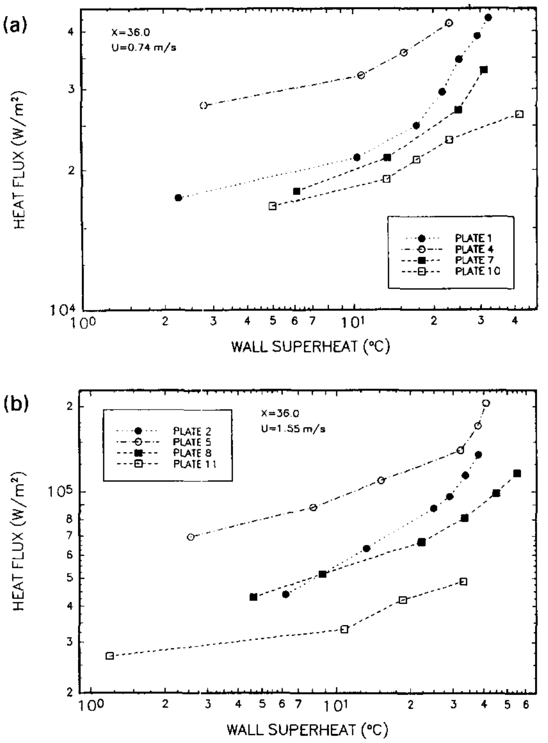

Fig. 4. Effect of microchannel size on flow boiling curve.

channels. However, there is an exception for plates 4 and 5 which have smaller microchannels than plate 1 and 2, respectively. For all of the plates tested, plates 4–6 have the highest flow boiling performance. This implies that the microchannels of these plates are already in the optimum configuration. Comparing the experimental results shown in Fig. 4(a) and those in Fig. 4(b), it is clear that the flow boiling heat transfer was significantly enhanced by increasing the number of microchannels in the test plate.

Effect of flow velocity and subcooling

As is the case for most situations, increasing the mass flux or flow velocity resulted in higher boiling onset wall superheat and tended to enhance the onset of the partial flow boiling regime. The results also indicated that the mass flux or liquid flow velocity did not significantly influence fully nucleate boiling, as illustrated in Fig. 5. The influence of liquid subcooling on flow boiling is comparable to that of the mass flux. Increasing the liquid subcooling induced the same consequence as increasing the mass flow rate. These experimental results are consistent with the previous experimental observations made by Peng *et al.* [1–4].

HEAT TRANSFER COEFFICIENT BEHAVIOR

Effect of liquid concentration

The effect of liquid concentration on the flow boiling heat transfer coefficient is illustrated in Fig. 6. For typical situations, the heat transfer coefficient of single-phase convection is nearly independent of the applied heat flux, and for subcooled flow boiling is proportional to q'' on a log–log graph. The experimental results illustrated in Fig. 6 are consistent with this conclusion. The results in both Figs. 6(a) and (b) indicate that pure liquid (water or methanol) flow boiling has the greatest heat transfer coefficient. For binary mixtures, the concentration did not result in large variations in the coefficient; however, these plots clearly indicate the strong influence of liquid mole concentration on the onset of boiling. As shown in Fig. 6, there does not appear to be a strong enhancement or decrease on the heat transfer as a result of varying the mixture composition. Actually, the mixture composition resulted in a pivotal augmentation or reduction in heat transfer. For flow boiling, the heat transfer for the coefficient, h, cannot be used to

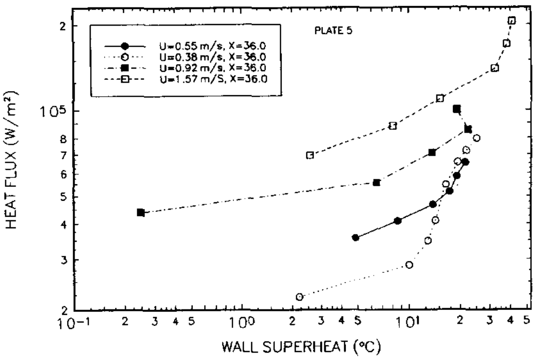

Fig. 5. Effect of flow velocity on flow boiling curve.

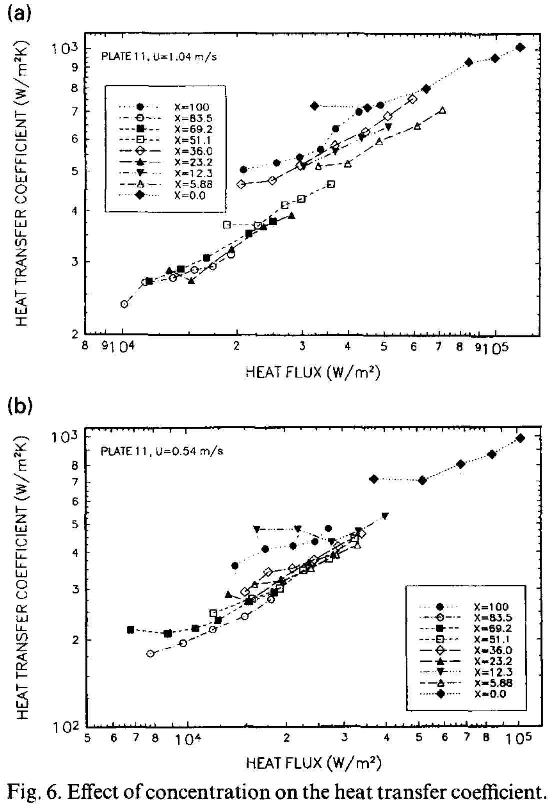

Fig. 6. Effect of concentration on the heat transfer coefficient.

describe the performance perfectly, due to the contribution of the change in latent heat, saturation temperature, etc. caused by the mixture concentration.

Effect of microchannel and plate configuration

Figures 7(a) and (b) present the measured heat transfer coefficient as a function of the applied heat flux for constant liquid velocity and constant mole concentrations through different microchanneled plates consisting of both four and eight channels. The variation in the heat transfer coefficient with wall surface heat flux reveals that the microchannel geometric scale and configuration resulted in an apparent impact on single-phase convection, flow boiling initiation and partial flow boiling as would be expected for subcooled flow. For the plate with identical channel numbers the microchannel size also influenced the heat transfer coefficient in the fully developed flow, nucleate boiling regime. The effect for different plates is clearly evident in Figs. 7(a) and (b). Figure 8 compares the heat transfer coefficients of plates 4, 8 and 9. These plates have the same microchannel hydraulic diameter and number of channels (four, six and eight channels, respectively). Plates 8 and 9 have the same microchannel size and configuration (see Table 1). As expected, there is a significant difference in the single-phase convective heat transfer coefficient. For fully nucleate boiling, plate 9 has the highest coefficient, due to the largest number of channels. However, the boiling heat transfer coefficients of plate 4, which has four channels and plate 8, with six channels, are identical. This might be caused by the similarity in the channel cross-configuration, or might be associated with the relative ratios of W/H and W/W_c. As a result, either the microchannel size and shape or the plate configuration resulted in a significant variation in the flow boiling heat transfer.

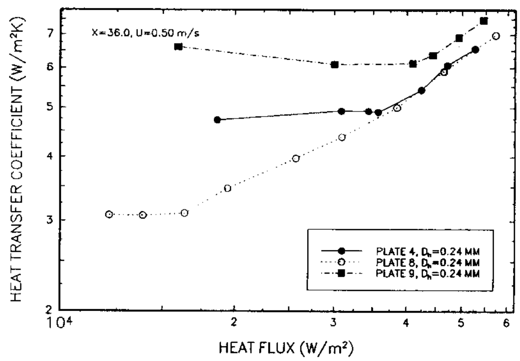

Fig. 8. Effect of channel number and configuration on heat transfer coefficient.

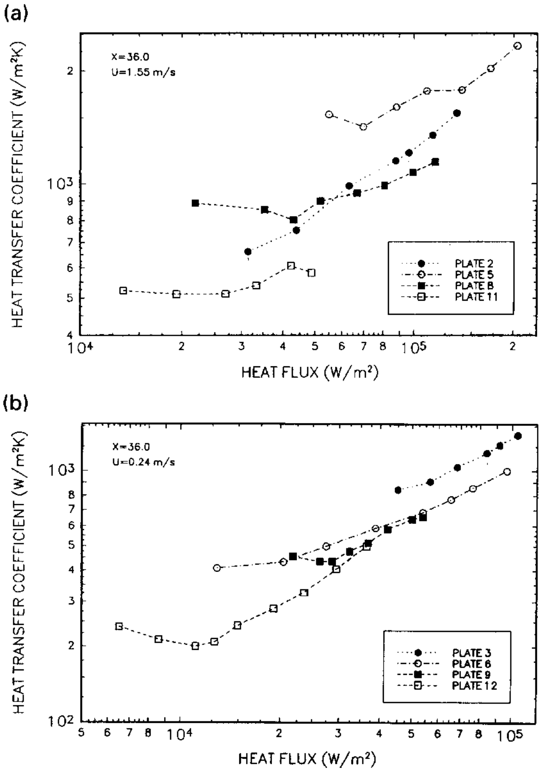

Fig. 7. Effect of microchannel size on the heat transfer coefficient.

Figure 9 illustrates the experimental results for the plates with identical microchannel configurations and a different number of channels. Apparently, increasing the size of the microchannel enhanced the flow boiling heat transfer of the plates. The difference between the different plates or the heat transfer enhancement was diminished as the microchannels became smaller. The difference between plates 2 and 3, which have a microchannel cross-section of 0.4×0.3 mm^2, is greatest, as illustrated in Fig. 9(a). The difference between plates 11 and 12, which have microchannel cross-sections 0.1×0.3 mm^2, is smallest and tends to vanish, as shown in Fig. 9(c).

Effect of flow velocity and subcooling

As noted above, the flow boiling curves indicate that increasing the flow velocity and subcooling resulted in a higher boiling onset wall superheat and tended to enhance the onset of the partial flow boiling regime, but had no evident influence on fully nucleate boiling. The results illustrated in Fig. 10, which presents the variation of heat transfer coefficient with heat flux at different flow velocities, also supports these conclusions.

CONCLUSIONS

A sequence of experiments were conducted to investigate the subcooled flow boiling of a binary mixture flowing through 12 kinds of microchanneled plates/structures having four to eight channels and microchannel hydraulic diameters of 0.133–0.343 mm. The impact of microchannel scale, geometric configuration, liquid velocity, liquid subcooling and liquid concentration on the flow boiling were investigated experimentally. Liquid composition or concentration was shown to have a critical influence on the flow boiling. Generally, mixtures with small, more volatile

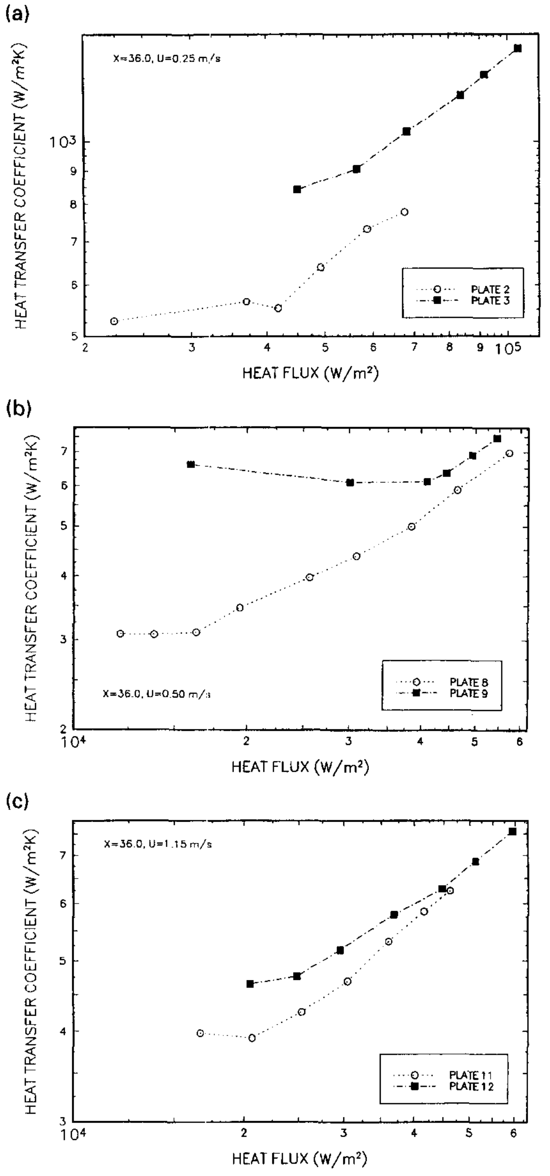

Fig. 9. Effect of the plate configuration on the heat transfer coefficient.

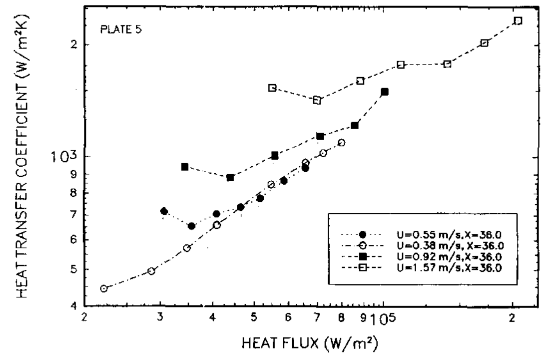

Fig. 10. Effect of flow velocity on the heat transfer coefficient.

component concentrations augmented the heat transfer, while those with large, more volatile component concentrations decreased the heat transfer, when compared with the pure more volatile liquid. There existed an optimum concentration at which the flow boiling heat transfer reached a maximum value. These characteristics were found to be affected by liquid flow velocity and subcooling. Increasing the number of microchannels and utilizing an appropriate microchannel configuration was shown to significantly improve the flow boiling heat transfer. However, this augmentation diminished as the microchannels became smaller.

If the heat transfer coefficient, defined in equation (2), is used to describe the heat transfer characteristics, some very interesting conclusions can be drawn. The heat transfer coefficient at the onset of flow boiling and in the partial nucleate boiling region was greatly influenced by liquid concentration, microchannel size and plate configuration, flow velocity and subcooling. However, microchannel size, flow velocity, subcooling of the mixture and liquid concentration had no significant effect on the heat transfer coefficient in the fully nucleate boiling regime. Microchannel cross-sectional configuration and the number of channels, resulted in variations of the coefficient, and the augmentation induced by increasing the number of channels diminished as the microchannels became smaller.

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