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International Journal of Heat and Mass Transfer 50 (2007) 5017–5030
International Journal of HEAT and MASS TRANSFER
www.elsevier.com/locate/ijhmt

Flow boiling of liquid nitrogen in micro-tubes: Part II – Heat transfer characteristics and critical heat flux

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Received 29 January 2007; received in revised form 27 June 2007
Available online 23 October 2007

Abstract

This paper is the second portion of a two-part study concerning the flow boiling of liquid nitrogen in the micro-tubes with the diameters of 0.531, 0.834, 1.042 and 1.931 mm. The contents include the heat transfer characteristics and critical heat flux (CHF). The local wall temperatures are measured, from which the local heat transfer coefficients are determined. The influences of heat flux, mass flux, pressure and tube diameter on the flow boiling heat transfer coefficients are investigated systematically. Two regions with different heat transfer mechanism can be classified: the nucleate boiling dominated region for low mass quality and the convection evaporation dominated region for high mass quality. For none of the existed correlations can predict the experimental data, a new correlation expressed by *Co*, *Bo*, *We*, K_p and *X* is proposed. The new correlation yields good fitting for 455 experimental data of 0.531, 0.834 and 1.042 mm micro-tubes with a mean absolute error (MAE) of 13.7%. For 1.931 mm tube, the flow boiling heat transfer characteristics are similar to those of macro-channels, and the heat transfer coefficient can be estimated by Chen correlation. Critical heat flux (CHF) is also measured for the four tubes. Both the CHF and the critical mass quality (CMQ) are higher than those for conventional channels. According to the relationship that CMQ decreases with the mass flux, the mechanism of CHF in micro-tubes is postulated to be the dryout or tear of the thin liquid film near the inner wall. It is found that CHF increases gradually with the decrease of tube diameter.

Keywords: Micro-tube; Flow boiling; Heat transfer; Critical heat flux; Liquid nitrogen

1. Introduction

For the wide applications in high heat flux electronic chip cooling, microelectromechanical system (MEMS), ink-printer design, optical multiplexers, high efficiency and compact air-cooled heat exchangers, there are many studies on the flow boiling in micro-channels. Table 1 summarizes the related flow boiling heat transfer studies in a single micro-channel [1–10,14] and multi-channel micro-channels [11–13]. As mentioned in the reviews by Kandlikar [15], Watel [16] and Thome [17], there are two major heat transfer mechanisms for flow boiling in micro-channels: nucleate boiling, forced convective heat transfer or combined mechanism. Nucleate boiling is characterized by continuous bubble nucleation, growth and detachment. Convective boiling is characterized by heat transferred by conduction and convection through the liquid film and vaporization at the vapor/liquid interface. Most studies listed in Table 1 belong to the combined mechanism, for example, Refs. [3,6,8–14]. According to the classification of wall superheat [3], heat flux [6], mass quality [12] or *Bo* (boiling number) [13], the flow boiling heat transfer is divided into nucleate boiling dominated region and convective boiling dominated region. Some studies [1,2,4,5] show the heat transfer is governed by the nucleate boiling. Only Lee and Lee [7] reported that the heat transfer is dominated by convective boiling. Actually, recent studies [11–14] demonstrated that it seems reasonable to consider the

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doi:10.1016/j.ijheatmasstransfer.2007.08.017

Nomenclature

A	cross section area of tube (m^2)
b	Laplace constant
B_o	Bond number
Bo	Boiling number
Bo^*	modified Boiling number
Co	confinement number
c_p	specific heat (J/kg K)
D	hydraulic diameter (m)
E	enhancement factor
$E\ddot{o}$	Eötvös number
f	friction factor
Fr	Friedel number
g	gravitational acceleration (m/s^2)
G	mass flux (kg/m^2 s)
h	heat transfer coefficient (W/m^2 K)
h_{fg}	latent heat of vaporization (J/kg)
k	thermal conductivity (W/m K)
K_S	surface dimensionless parameter
K_p	pressure dimensionless parameter
L	tube length (mm)
M	number of experimental data
N	parameter in Chen correlation
Nu	Nusselt number
p	pressure (Pa)
Pe^*	modified Peclet number
Pr	Prandtl number
Δp	pressure drop (Pa)
q	average heat flux (W/m^2)
Re	Reynolds number
S	suppression factor
S_a	inner surface area of tube (m^2)
T	temperature (K)
ΔT	wall superheat (K)
We	Weber number
x	mass quality
X	Lockhart–Martinelli parameter
z	longitudinal abscissa (m)

Greek symbols

μ	viscosity (kg/m s)
ρ	density (kg/m^3)
σ	surface tension (N/m)
ξ	constant

Subscripts

CHF	critical heat flux
eq	equilibrium
exp	experimental
F	fluid
G	gas
i	inner surface of tube
in	inlet of tube
L	liquid
nb	nucleate boiling
o	outer surface of tube
out	outlet of tube
pred	predicted
sat	saturation
sc	subcooled
Tp	two-phase
w	wall of tube
z	longitudinal location

dominated heat transfer mechanism according to different magnitude of x or Bo.

Moreover, an important problem is about the criterion of macro- and micro-channels. Kandlikar [15] classified the channels by the diameter as conventional channels for $D > 3.0$ mm, minichannels from 0.2 to 3.0 mm, and micro-channels below 0.2 mm. However, many researchers think the criterion should be based on the combination of channel size and thermo-hydraulic properties rather than only on the channel dimension. For example, Kew and Cornwell [4] proposed the confinement number, $Co = (\sigma/(\rho_L - \rho_G)gD^2)^{1/2}$, as the criterion, and found that heat transfer exhibited different characteristics while $Co < 0.5$. Chen et al. [18] summarized the existing diameter criteria, and found that the two-phase flow patterns in the 2.88 mm tube are different from those in 1.10 and 2.01 mm micro-tubes, whereas similar to those in normal-sized tubes. For comparison, all the criteria and the deduced critical diameter for water/air, R-134a and liquid nitrogen are shown in Table 2. Eötvös number and Bond number are defined as $E\ddot{o} = (2\pi)^2\sigma/(\rho_L - \rho_G)gD^2$ and $B_o = ((\rho_L - \rho_G)gD^2/\sigma)^{1/2}$, respectively. It can be seen that the critical diameter decreases with increasing pressure, and large discrepancy exists for the different criteria. For example, the critical diameter determined by $E\ddot{o} = 1$ is even more than 20 times that by $B_o = 0.3$. Hence, further research is still required to establish reasonable classification of micro- and macro-channels based on heat transfer characteristics.

In the design of micro-channels flow boiling system, the critical heat flux (CHF) is also an important design parameter because it determines maximum feasible heat dissipation rate. A sudden decrease of heat transfer coefficient will occur at CHF. For the heat-flux-controlled system, such a decrease of heat transfer coefficient may cause a soar of the wall temperature, and lead to catastrophic system failure. Though there have been many researches and correlations [19] of CHF for the conventional channels, only

Table 1
Summary of heat transfer characteristics studies in micro-channels

Author	Channel dimension	Test fluid and parameter range	Remarks
Lazarek and Black [1]	Single tube, $D = 3.15$ mm, heated length 123 mm and 246 mm	R-113; $G = 125$–750 kg/m^2 s; $p = 1.3 \times 10^5$–4.1×10^5 Pa; $q = 1.4$–38 W/cm^2	The dependence of flow boiling heat transfer on heat flux and its independence of quality suggest the control mechanism is nucleate boiling. The correlation with simple form: $Nu = 30Re^{0.857}Bo^{0.714}$ is presented
Wambsganss et al. [2]	Single tube, $D = 2.92$ mm, heated length 368 mm	R-113; $G = 50$–300 kg/m^2 s; $q = 0.88$–9.075 W/cm^2	Ten heat transfer correlations are evaluated. The effects of high boiling number and slug flow pattern lead to the domination of the nucleation boiling. Lazarek correlation agrees the data well
Tran et al. [3]	Single tube, $D = 2.46$ mm, heated length 870 mm	R-12 and R-113; $G = 50$–1800 kg/m^2 s; $p = 2 \times 10^5$–5×10^5 Pa; $q = 0.5$–20 W/cm^2	As the wall superheat is above 2.75 °C, it is nucleate boiling regime. For the wall superheat below 2.75 °C, it is convective boiling regime. The heat transfer coefficient is correlated by *Bo*, *We*, and the liquid to vapor density ratio
Kew and Cornwell [4]	Single tube, $D = 1.39$–3.69 mm, heated length 500 mm	R-141b; $G = 188$–1840 kg/m^2 s; $q = 0.97$–9.0 W/cm^2;	Intermittent dry-out occurs at very low quality. The processes in flow boiling in the minichannels are similar to those occurring during nucleate boiling, hence the nucleate pool boiling correlation give reasonable results
Bao et al. [5]	Single tube, $D = 1.95$ mm, heated length 250 mm	R-11 and HCFC-123; $G = 50$–1800 kg/m^2 s; $p = 2 \times 10^5$–5×10^5 Pa; $q = 0.5$–20 W/cm^2	The heat transfer coefficients are independent of mass flux and vapor quality, but strong influence of the heat flux and system pressure. Therefore, the nucleate boiling are the dominant mechanism, and the Cooper pool-boiling correlation describes the flow boiling with reasonable accuracy
Lin et al. [6]	Single tube, $D = 1.0$ mm	R-141 b; $G = 300$–2000 kg/m^2 s; $p = 1.35$–2.20 bar; $q = 1.0$–115 W/cm^2; $T_{in} = 29$–32.5 °C;	For $q < 6$ W/cm^2, at low quality the heat transfer coefficient is dominated by nucleate boiling, increases with heat flux; at high quality the convective boiling is independent of heat flux. For $q > 6$ W/cm^2, the convective boiling is dominant
Lee and Lee [7]	Rectangular channels with width 20 mm and different height 0.4–2 mm	R-113; $G = 50$–200 kg/m^2 s; $q = 1.5$ W/cm^2	For $x = 0.15$ –0.75, the flow pattern appeared to be annular. The heat transfer coefficients increase with the mass flux and the local quality, the effect of heat flux is minor. The Kandlikar's correlation agrees with the data with 10.7% mean deviation
Yu et al. [8]	Single tube, $D = 2.98$ mm, heated length 910 mm	Water; $G = 50$–200 kg/m^2 s; $p = 2.0 \times 10^5$ Pa	Tran correlation can predict the experimental data of the present study with a diversity of ±30%
Sumith et al. [9]	Single tube, $D = 1.45$ mm, heated length 100 mm	Water; $G = 23.5$–152.7 kg/m^2 s; $q = 1.0$–70.5 W/cm^2	Large heat transfer enhancement is observed. The dominant flow pattern in the tube is a slug-annular or an annular flow, and then liquid film evaporation is found to dominate the heat transfer. An equation based on the Chen's correlation is proposed, and it can predict the heat transfer coefficients within an error of ±30%
Yun et al. [10]	Single tube, $D = 0.98$ mm, heated length 1200 and 400 mm, respectively	CO_2; $G = 500$–3570 kg/m^2 s; $q = 0.7$–4.8 W/cm^2	The heat transfer coefficients are strongly affected by heat flux. The effect of mass flux is only significant when the superficial liquid Weber number is less than 100
Pettersen [11]	25 flow channels of $D = 0.8$ mm and 0.5 m in length	CO_2; $G = 190$–570 kg/m^2 s; $q = 5$–20 W/cm^2	Heat transfer data can be correlated well with a combination models for nucleate boiling, convective evaporation, dryout incipience and post-dryout heat transfer
Lee and Mudawar [12]	0.231×0.713 mm^2; heated length 25.30 mm	R-134a; $q = 15.9$–93.8 W/cm^2;	Nucleate boiling occurs only at low qualities ($x < 0.05$) at low heat fluxes, and medium ($0.05 < x < 0.55$) and high ($x > 0.55$) quality regions are dominated by annular film evaporation
Xu et al. [13]	10 triangular micro-channel with $D = 0.155$ mm, heated length 21.45 mm	Acetone; $G = 64$–600 kg/m^2 s; $p = 1$–2 bar; $q = 15$–48 W/cm^2	Three heat transfer regions are identified: At low boiling number, heat transfer coefficient increases with mass quality; At medium boiling number, it is dependent on the heat flux, independent of mass flux and vapor qualities (nucleate boiling heat transfer model); At high boiling number, it decreases with increasing local vapor quality (bubble explosive induced forced convective heat transfer mechanism)
Diaz and Schmidt [14]	Single 0.3×12.7 mm^2 rectangular channel, heated length 200 mm	Water and ethanol; $G = 50$–500 kg/m^2 s; $q = 40$ W/cm^2	The heat transfer coefficients decrease with increasing quality for water. For ethanol, the heat transfer coefficients increase with quality at low heat flux. With increasing heat flux, the heat transfer coefficients decrease with quality

limited attention is paid for the micro-channels. Qu and Mudawar [20] reported that vapor backflow induced by flow instability was the mechanism of CHF in micro-channel, and proposed a new CHF correlation using the data of R-113 and water. Zhang et al. [21] and Sarma et al. [22] developed their own new correlations for flow boiling in small-diameter tubes, respectively. However, Wojtan et al. [23] investigated CHF of R-134a and R-245fa in 0.5

Table 2
Critical diameter for different criteria

Criteria		Critical diameter (mm)				
		Air/water 0.10 MPa	Air/water 0.60 MPa	R-134a 1.0 MPa	LN_2 0.1 MPa	LN_2 0.9 MPa
1	$Co = 0.5$	5.43	1.70	1.51	2.13	1.52
2	$E\ddot{o} = 1$	17.07	5.33	4.74	6.67	4.78
3	$E\ddot{o} = 100$	1.71	0.53	0.47	0.67	0.48
4	$B_o = 0.3$	0.82	0.26	0.23	0.32	0.23

and 0.8 mm micro-channels, and found the correlation of Qu and Mudawar [20] significantly over-predicted the experimental data. They proposed a microscale version of the Katto correlation [24] to correlate the data.

From the above reviews of flow boiling heat transfer studies in micro-channels, it is found that the experimental fluids are mainly related to the conventional fluids, such as water and refrigerants, but no works have been done for liquid nitrogen. As a typical cryogenic fluid, liquid nitrogen is widely used in the fields of biological and medical engineering, space technology, and the cooling of high temperature superconductivity (HTS) devices. Many micropassages are usually formed in these applications, and liquid nitrogen flows through the micro-channels, absorbs the heat and evaporates. Liquid nitrogen owns many distinct properties, such as small contact angle and surface tension, which may make its flow boiling characteristics quite different from those of conventional fluids, for example, water and refrigerants.

As a consequence, a systematic study is carried out to obtain a comprehensive understanding of flow boiling of liquid nitrogen in micro-tubes. Four micro-tubes with the diameters of 0.531, 0.834, 1.042 and 1.931 mm are tested. Some contents including the onset of flow boiling (ONB), two-phase flow instability, and two-phase flow pressure drop have been reported at the first part of the study [25]. This paper is the second part, and emphasizes on the heat transfer characteristics and critical heat flux (CHF). The effects of tube diameter, mass flux, heat flux, pressure and mass flux on heat transfer characteristics will be investigated. Some distinct features and related mechanism for CHF in micro-tubes are also presented.

2. Experimental apparatus and procedures

The experimental apparatus and procedures have been depicted in detail in Part I of this study [25]. Main measured parameters are the pressures and temperatures at inlet and outlet of along the micro-tubes, mass flux, seven wall temperatures at different location along the micro-tubes, the input electric voltage and current to the heater.

3. Data reduction and uncertainty analysis

The local heat transfer coefficient is calculated by

$$h = q/(T_{w,z} - T_{F,z}), \tag{1}$$

where q and $T_{w,z}$ are calculated by the methods expressed in Ref. [25], and $T_{F,z}$ is the bulk mean temperature. In the single-phase flow region, $T_{F,z}$ is determined by the heat balance calculation

$$T_{F,z} = T_{F,in} + \int_0^z \frac{qS}{GAc_{p,L}(z)L}\mathrm{d}x. \tag{2}$$

In the two-phase flow region, $T_{F,z}$ is the saturated temperature corresponding to the saturated pressure determined by the pressure drop model [25].

According to the measurement uncertainties of the tube diameter, tube length, temperature, pressure difference and mass flux, the uncertainties of x and h are determined to be less than 3.2% and 8.5%, respectively.

4. Results and discussion

4.1. Flow boiling heat transfer

4.1.1. The wall temperature and local heat transfer coefficients

Fig. 1 shows the local flow boiling heat transfer characteristics for 0.531 mm micro-tube at low, medium and high heat flux, respectively. The local heat transfer characteristics include the variations of wall and fluid temperature (I), mass quality (II) and flow boiling heat transfer coefficient (III) along the micro-tube. As shown in Fig. 1(a, I) and (b, I), the wall temperature presents a type of fold line at low and medium heat flux, i.e., the wall temperature increases in the initial single-phase convection region, and then decreases gradually once the ONB occurs. The trend accords with the observations of infrared thermography by Diaz and Schmidt [14] and Hetsroni et al. [26], and Yen et al. [27] also gives similar variations of wall temperature. In Fig. 1(c, I), the wall temperature increases abruptly at T6 and T7 due to the dryout caused by high heat flux.

The main flow temperature calculated according to the method in Section 3 is also given in Fig. 1. The decrease of wall temperature at the flow boiling section is mainly because of the drop of fluid saturated temperature corresponding to pressure decrease. Compared with the traditional channel, the variation of the fluid temperature is very large due to the large pressure drop; for example, it is as large as 8.7 K in Fig. 1(a, I). Moreover, the variation of the saturated temperature is not linear, and it may not be felicitous to simply set the saturated temperature constant [3] or linearize the temperature [5] if the saturated temperature varies obviously.

Fig. 1(a, II), (b, II) and (c, II) demonstrates the variation of mass quality. Due to the flashing evaporation, the mass quality does not change linearly along the micro-tube, instead increases rapidly near the outlet.

The parts (III) of Fig. 1(a)–(c) show the heat transfer coefficients versus the channel length. The heat transfer

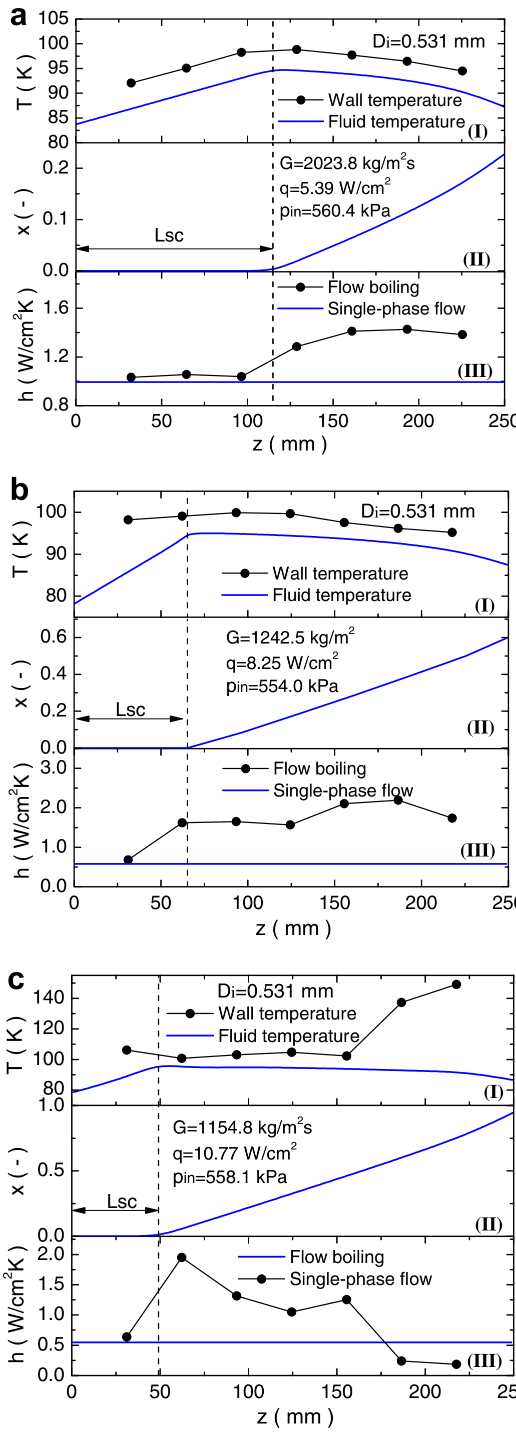

Fig. 1. Local flow boiling heat transfer characteristics for 0.531 mm micro-tube at different heat fluxes: (a) low heat flux; (b) medium heat flux; (c) high heat flux.

coefficients for the single-phase convection can be predicted well by the Gnielinski correlation [25]

$$Nu = \frac{(f/8)\cdot(Re-1000)Pr}{1+12.7\sqrt{f/8}(Pr^{2/3}-1)} \tag{3}$$

and are also given in the figures for comparison. It is found that the heat transfer coefficients for the flow boiling are 2–3 times of those for the single-phase convection. While dryout occurs, the heat transfer coefficient drops accidentally, even turns lower than that for the single-phase convection. At low heat flux, heat transfer coefficient increases with the mass quality for $x < 0.1$, and then does not change apparently. At medium heat flux, heat transfer coefficient owns the peak at the ONB, and then basically keeps constant with the mass quality. For high heat flux, the heat transfer coefficient decreases rapidly with the mass quality for the partial dryout. Similar trends are found that the heat transfer coefficient may increase, keep constant and decrease with mass quality by increasing heat flux [6,12,28]. The main reason is considered to be that different heat flux or mass quality regions are governed by different heat transfer mechanisms. For the low quality region, heat transfer is dominated by nucleate boiling, but is governed by convective evaporation for high quality region. With the increase of mass quality, partial dryout may occur and heat transfer coefficient decreases. Recently, Xu et al. [13] proposed the boiling number, *Bo*, as the key for classifying the regions with different dominant mechanism.

The local heat transfer characteristics in 0.834 and 1.042 mm micro-tubes are similar to those in 0.531 mm micro-tube. But for 1.931 mm tube, obvious differences are found in Fig. 2. It can be seen that the results in 1.931 mm tube show similar trends to those observed in the conventional-sized channel, i.e., the heat transfer coefficient increases with mass quality at low and medium heat flux. Hence, the critical diameter of micro-tubes seems to 1.931 mm for liquid nitrogen and present experimental conditions, which accords the result determined by the criterion of $Co = 0.5$ [4]. And the applicability of other criteria listed in Table 2 still needs further assessments. For the flow boiling in 1.931 mm tube, the dominant mechanism has changed to be the convection boiling. Consequently, heat transfer coefficient increases gradually for the increasing flow velocity that is driven by the evaporation expansion. As shown in Fig. 2(c), the heat transfer coefficient for high heat flux increases at first, and then drops for the dryout. This trend is still same to that in 0.531, 0.834 and 1.042 mm micro-tubes.

4.1.2. The effect of heat flux on heat transfer coefficient

Fig. 3(a) & (b), (c) & (d), (e) & (f) and (g) & (h) illustrates the effect of heat flux on the heat transfer coefficients for 0.531, 0.834, 1.042 and 1.931 mm tubes, respectively. It can be seen that the influence varies with the tube diameter. For 0.531 mm micro-tube, the influence of heat flux on heat transfer coefficient is very small within the range of examined mass quality (see Fig. 3(a) and (b)). The heat transfer coefficients basically keep constant, except abrupt drop at high mass quality, which results from the partial dryout. For 0.834 mm micro-tube shown in Fig. 3(c) and (d), two regions can be observed: $x < 0.2$, heat transfer coefficient increases with the heat flux; $x > 0.2$, heat transfer

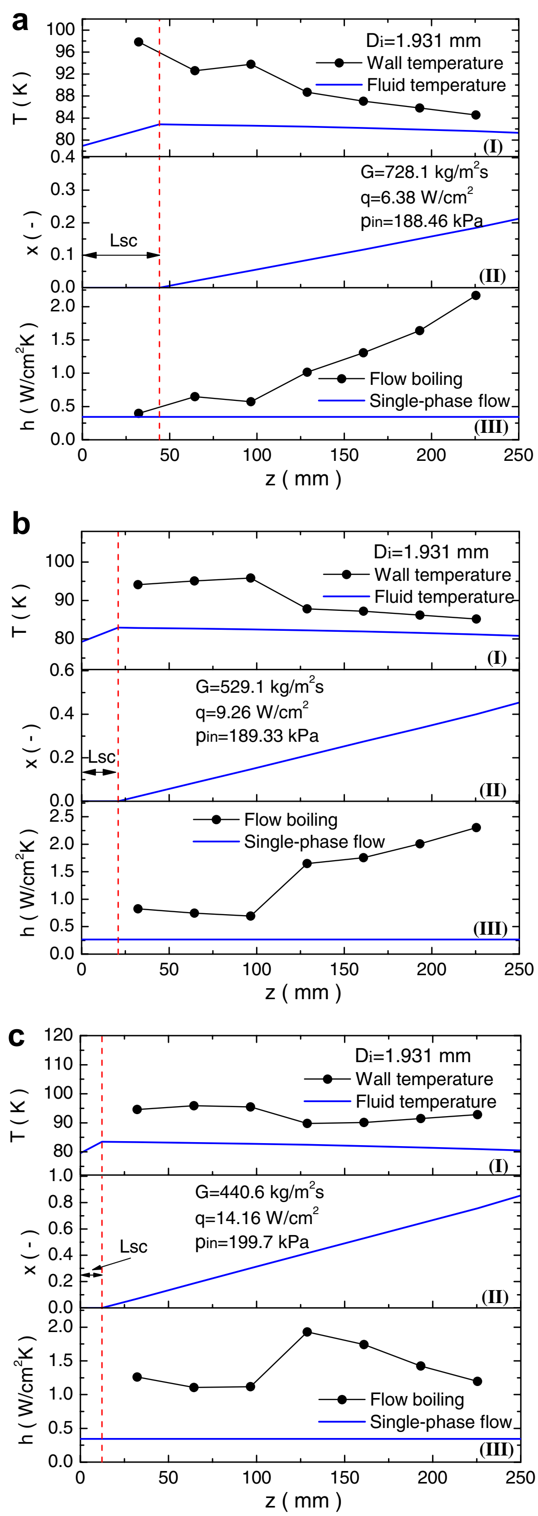

Fig. 2. Local flow boiling heat transfer characteristics for 1.931 mm tube at different heat fluxes: (a) low heat flux; (b) medium heat flux; (c) high heat flux.

coefficient is independent of the heat flux. For 1.042 mm micro-tube shown in Fig. 3(e) and (f), two apparent regions similar to the 0.834 mm micro-tube can be classified, but the boundary has changed to around $x = 0.3$. It should be noted that Fig. 3(g) and (h) include the effect of heat flux and mass flux simultaneously since mass flux decreases with heat flux in the experiments. The situations for the 1.931 mm tube are quite different from the above three micro-tubes. At $x < 0.2$, heat transfer coefficient increases with heat flux; however, at $x > 0.2$, the heat transfer coefficient is mainly dependent on mass flux, and decreases with heat flux. The effect further verifies that the 1.931 mm tube has been a macro-channel for the present experimental conditions.

4.1.3. The effect of mass flux on heat transfer coefficient

Fig. 4 shows the effect of mass flux on heat transfer coefficient. For 0.531 mm micro-tube, heat transfer coefficient is dependent on mass flux, and increase with the mass flux, as shown in Fig. 4(a). From Fig. 4(b), it can be seen that heat transfer coefficient is almost independent of mass flux at $x < 0.25$, but increases with mass flux at $x > 0.25$ for 1.042 mm micro-tube. The trend of 0.834 mm micro-tube is similar to that of 1.042 mm micro-tube. The effect of mass flux for 1.931 mm tube has been clarified at the end of Section 4.1.2, as shown in Fig. 4(g) and (h). At $x < 0.2$, heat transfer coefficient is independent of mass flux; however, at $x > 0.2$, the heat transfer coefficient is mainly dominated by mass flux, and increases with mass flux.

4.1.4. The effect of pressure on heat transfer coefficient

The effect of pressure on heat transfer coefficient is shown in Fig. 5 for four tubes. It is found the increase of pressure causes the enhancement of heat transfer. This result is also consistent with that for nucleate flow boiling by Bao et al. [5]. The main reason is that the wall superheat for bubble nucleation drops with the increase of pressure, and the relationship can be demonstrated by the correlation [25]:

$$T_{\mathrm{w}} - T_{\mathrm{sat}} = \xi \left(\frac{q}{1.0 \times 10^6} \right)^{0.5} \exp\left(-\frac{p}{8.7 \times 10^6} \right), \tag{4}$$

where the constant $\xi = 30.65$. Moreover, the influence of pressure on the heat transfer coefficient turns unconspicuous with increasing mass quality. For 1.931 mm tube, heat transfer coefficient is nearly independent of the pressure at high mass quality region, as shown in Fig. 5(d).

4.1.5. The mechanism analysis for the flow boiling heat transfer in micro-tubes

Boiling heat transfer for the flow inside channel is governed by two mechanisms: nucleate boiling and convective boiling. The dominant mechanism can be postulated by analyzing the effect of heat flux, mass flux and mass quality on the heat transfer coefficients. In nucleate-boiling dominant region, the heat transfer is independent of mass flux and mass quality, increases with heat flux, and is sensitive to saturation pressure. In convective boiling region (where nucleate boiling appears to be largely suppressed), the heat

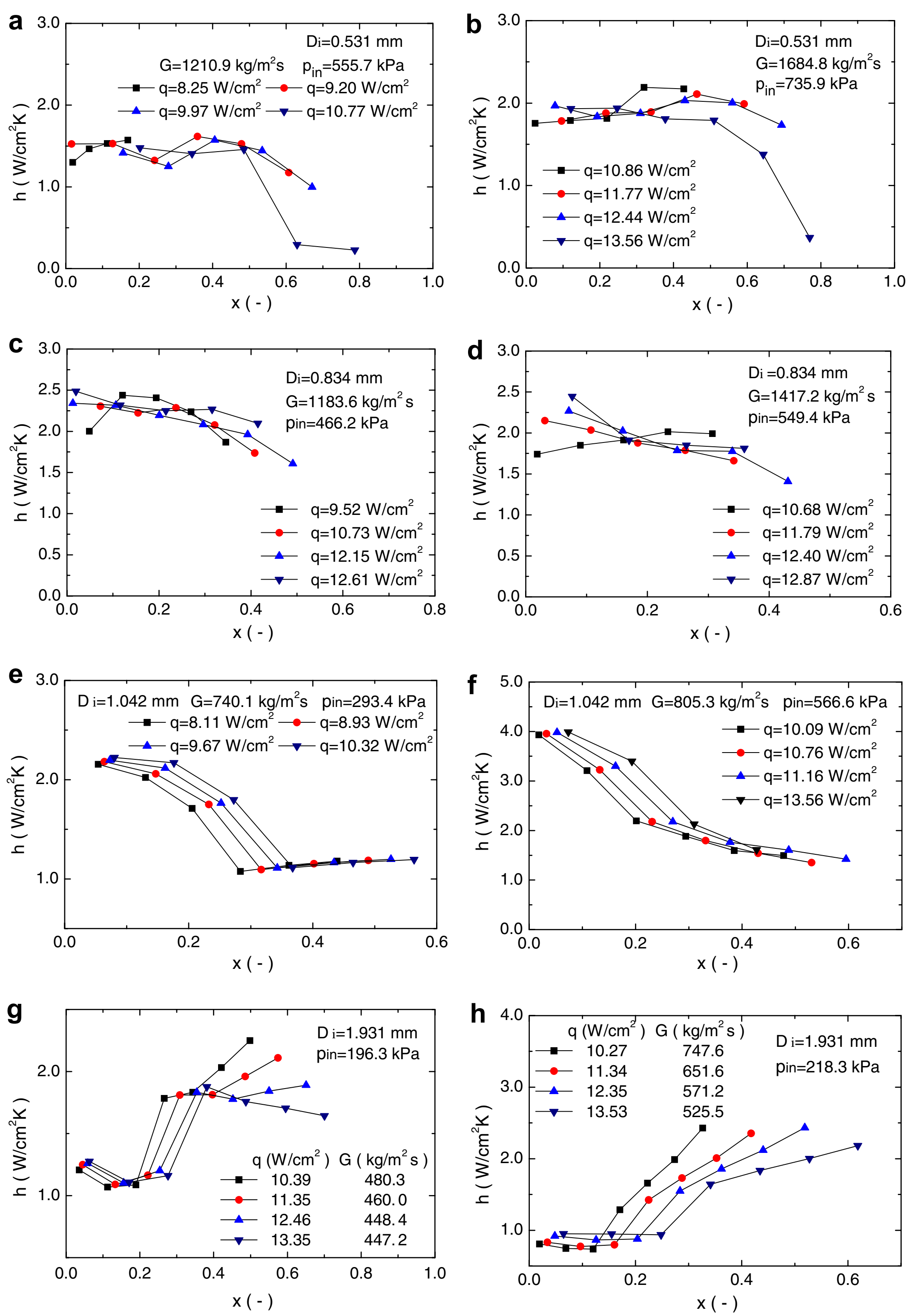

Fig. 3. The effect of heat flux on the heat transfer coefficient: (a, b) 0.531 mm micro-tube; (c, d) 0.834 mm micro-tube; (e, f) 1.042 mm micro-tube; (g, h) 1.931 mm tube.

transfer coefficient is independent of heat flux and increases with mass flux.

For 0.531 mm micro-tube, no significant nucleate-dominated region is found. This is because the detach diameter (0.6 mm for the pool boiling [29,30]) is nearly larger than the tube diameter. Once the bubble nucleates, confined bubble flow forms. The liquid film surrounding the confined bubble is so thin that the nucleate boiling is suppressed.

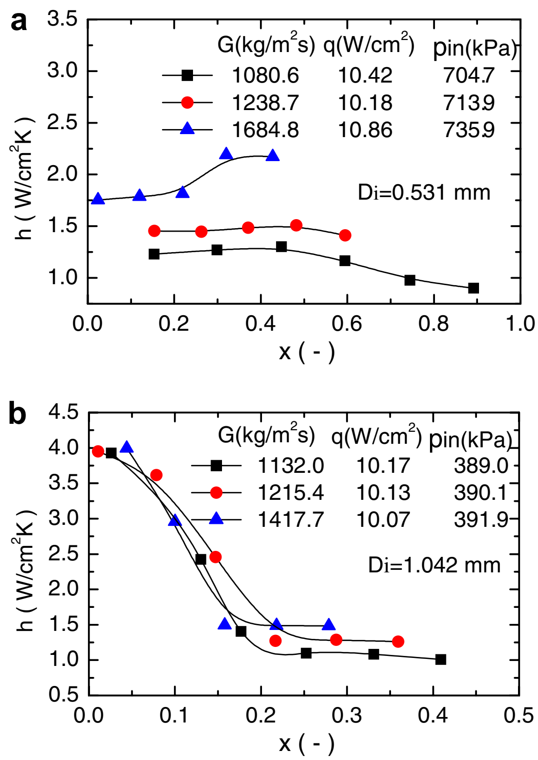

Fig. 4. The effect of mass flux on heat transfer coefficient: (a) 0.531 mm micro-tube; (b) 1.042 mm micro-tube.

With the increase of the tube diameter, the nucleate-dominated region appears at $x < 0.2$ and $x < 0.3$ for 0.834 mm and 1.042 mm micro-tubes, respectively. The nucleated bubbles may coalesce together, and form slug and churn flow. Hence, the nucleate boiling heat transfer is suppressed, and the dominant mechanism turns into the thin film evaporation. Heat is transferred from the wall through the thin film by the conduction and forced convection to the vapor/liquid interface, and then the evaporation at the interface takes the heat away. The heat transfer is enhanced by the increase of mass flux, indicating that the heat transfer is dependent on the flow convection. But it should be noted that heat transfer coefficient drops with the increase of mass quality. This trend is opposite to the convective evaporation mechanism occurring in the conventional channel. For example, heat transfer coefficient increases with mass quality at $x > 0.2$ for 1.931 mm tube. This kind of heat transfer enhancement results from the flow acceleration caused by the evaporation expansion. The phenomena that heat transfer efficient drops with the mass quality in so-called "convective-dominated region" in micro-channel are also observed by Qu and Mudawar [31]. They argued that strong droplet entrainment occur at low mass quality, continuous deposition of droplet leads to the decrease of heat transfer coefficient.

4.1.6. The heat transfer coefficient correlations

As shown in Fig. 6, the flow boiling heat transfer coefficients are compared with 4 correlations: Klimenko [32], Shah [33], Chen [34], and Tran [3] correlation. Detailed expressions for the correlations are listed in Table 3. Among them, Klimenko and Shah correlations are used for cryogens, Chen correlation is used for the flow boiling of traditional fluids in macro-channels, and Tran

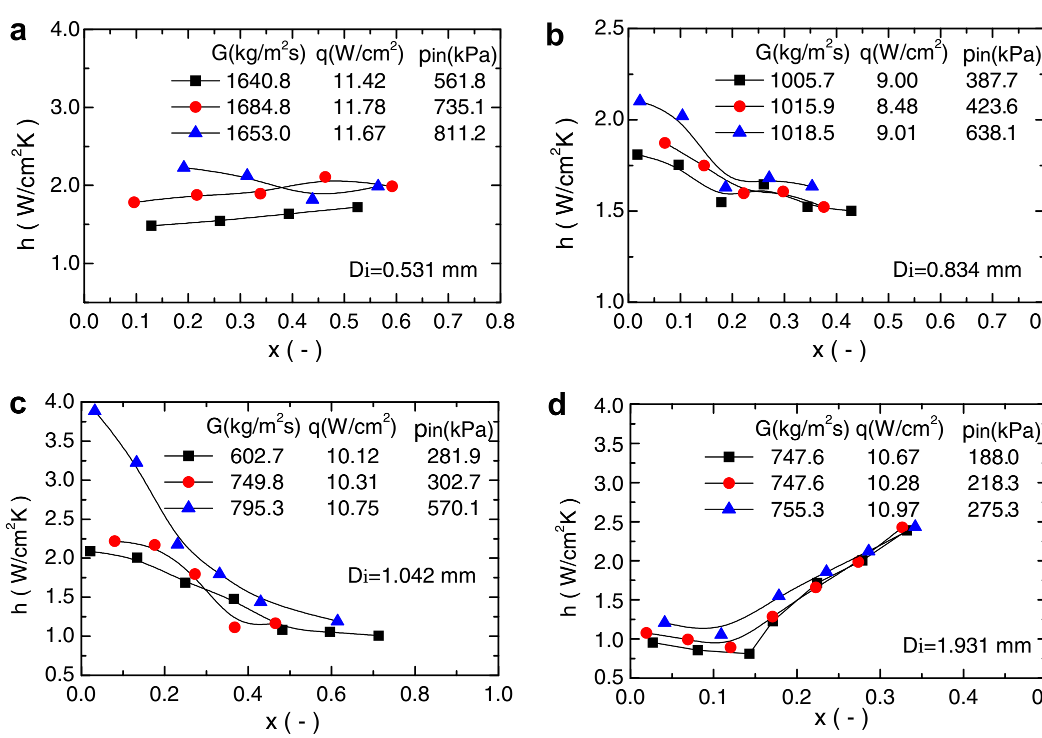

Fig. 5. The effect of pressure on heat transfer coefficient: (a) 0.531 mm micro-tube; (b) 0.834 mm micro-tube; (c) 1.042 mm micro-tube; (d) 1.931 mm tube.

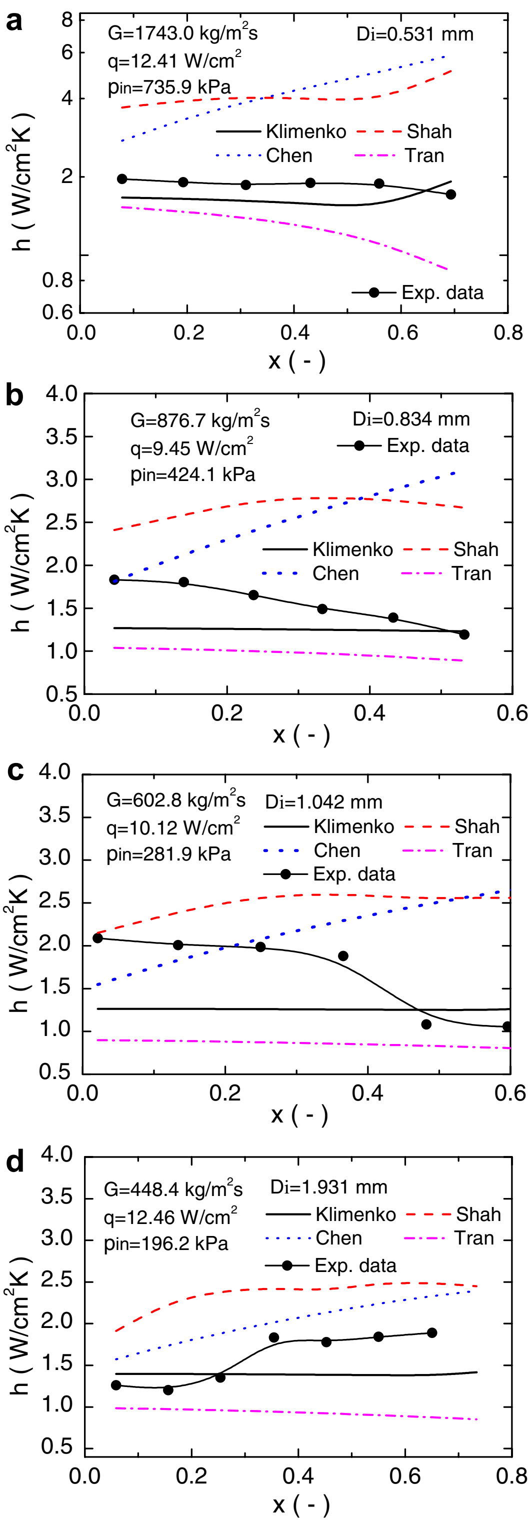

Fig. 6. Comparison of heat transfer coefficients with the predictions of four correlations: (a) Klimenko; (b) Shah; (c) Chen; (d) Tran.

Table 3
Correlations for flow boiling heat transfer coefficient

No.	Reference	Heat transfer coefficient, h_{Tp}	Remarks
1	Klimenko [32]	$Nu/Nu_{\mathrm{L}}=\begin{cases}1 & Bo_{*}<6\times10^{4}\\ 0.0041Bo_{*}^{0.5} & Bo_{*}>6\times10^{4}\end{cases}$ $Nu=\frac{hb}{k};\ b=[\sigma/g(\rho_{\mathrm{L}}-\rho_{\mathrm{G}})]^{1/2}$; $Bo_{*}=\frac{h_{fg}G}{q}[1+x(\rho_{\mathrm{L}}/\rho_{\mathrm{G}}-1)]$; $Nu_{\mathrm{L}}=0.0042Pe_{*}^{0.6}K_{\mathrm{p}}^{0.5}K_{\mathrm{S}}^{0.2};\ Pe^{*}=qb/(h_{\mathrm{fg}}\rho_{\mathrm{G}}a)$; a is thermal diffusivity $K_{\mathrm{p}}=p/[\sigma g(\rho_{\mathrm{L}}-\rho_{\mathrm{G}})]^{1/2};\ K_{\mathrm{S}}=\frac{(\rho c_{p}k)_{\mathrm{w}}}{(\rho c_{p}k)_{\mathrm{L}}}$	It is correlated from liquid nitrogen data, and includes the influence of wall properties
2	Shah [33]	$h_{\mathrm{Tp}}=\max(E,S)h_{\mathrm{L}}$; $h_{\mathrm{L}}=0.023Re_{\mathrm{L}}^{0.8}Pr_{\mathrm{L}}^{0.4}k_{\mathrm{L}}/D$; while $N>1.0, S=1.8/N^{0.8},\ E=230Bo^{0.5}$; $0.1<N\leqslant1.0,\ S=1.8/N^{0.8}$, $E=FBo^{0.5}\exp(2.74N^{-0.1})$; $N\leqslant0.1,\ S=1.8/N^{0.8}$, $E=FBo^{0.5}\exp(2.47N^{-0.15})$; $F=14.7\ (Bo\geqslant11\times10^{-4})$ or $F=15.43\ (Bo\leqslant11\times10^{-4})$; $N=\left(\frac{1-x}{x}\right)^{0.8}\left(\frac{\rho_{\mathrm{G}}}{\rho_{\mathrm{L}}}\right)^{0.5}, Bo=q/(Gh_{fg})$	This is a kind of asymptotic model, and has been evaluated by cryogen data
3	Chen [34]	$h_{\mathrm{Tp}}=Eh_{\mathrm{L}}+Sh_{\mathrm{nb}}$; $h_{\mathrm{L}}=0.023(Re_{\mathrm{L}})^{0.8}Pr_{\mathrm{L}}^{0.4}k_{\mathrm{L}}/D$, $h_{nb}=0.00122\left(\frac{k_{\mathrm{L}}^{0.79}c_{p,\mathrm{L}}^{0.45}\rho_{\mathrm{L}}^{0.49}}{\sigma^{0.5}\mu_{\mathrm{L}}^{0.29}h_{fg}^{0.24}\rho_{\mathrm{G}}^{0.24}}\right)\Delta T_{\mathrm{sat}}^{0.24}\Delta p_{\mathrm{sat}}^{0.75}$ $E=\left(1+\frac{1}{X^{0.5}}\right)^{1.78}$, $S=0.9622-0.5822\left[\tan^{-1}\left(\frac{Re_{\mathrm{L}}E^{1.25}}{6.18\times10^{4}}\right)\right]$, $Re_{\mathrm{L}}=\frac{G(1-x)D}{\mu_{\mathrm{L}}},\ X=\left(\frac{1-x}{x}\right)^{0.9}\left(\frac{\rho_{\mathrm{G}}}{\rho_{\mathrm{L}}}\right)^{0.5}\left(\frac{\mu_{\mathrm{L}}}{\mu_{\mathrm{G}}}\right)^{0.1}$	It is a summation model. Iterative calculation is needed for ΔT_{sat} and h_{Tp}
4	Tran et al. [3]	$h_{\mathrm{Tp}}=8.4\times10^{5}(Bo^{2}We_{\mathrm{L}})^{0.3}(\rho_{\mathrm{L}}/\rho_{\mathrm{G}})^{-0.4}$; $We_{\mathrm{L}}=\frac{G^{2}D}{\rho_{\mathrm{L}}\sigma}$	Micro-channel correlation

correlation is applicable to the flow boiling in micro-channel. It can be seen that none of the correlations yields good agreement for the data in 0.531, 0.834 and 1.042 mm micro-tube. Shah and Chen correlations even give opposite trends. For 1.931 mm tube, Shah and Chen correlations can provide correct trend to the variation of heat transfer coefficient with mass quality, i.e., heat transfer coefficient increases with mass quality.

In Fig. 7, all data for four tubes are compared with the four referred correlations. In general, Klimenko correlation underestimates the experimental data, indicating the heat transfer coefficient is larger than that in macro-channel. It is suggested that Shah model over-predicts the data symmetrically, which is not applicable to the present operational conditions. For 0.531, 0.834 and 1.042 mm micro-tubes, Chen correlation can predict the experimental data at low quality region, which is dominated by nucleate boiling heat transfer. The deviation becomes large with the increase of mass quality because Chen correlation gives opposite trend of heat transfer coefficient with mass quality to the experiment. The prediction of Chen correlation accords with the data for 1.931 mm tube well, which shows that the flow boiling behaviors are similar to those in macro-channel. Comparatively, Tran correlation used for the micro-channel provides more accurate estimation for 0.531, 0.834, and 1.042 mm micro-tubes than for 1.931 mm tube.

To facilitate the design and application of cryogenic microsystem, a new correlation for flow boiling heat

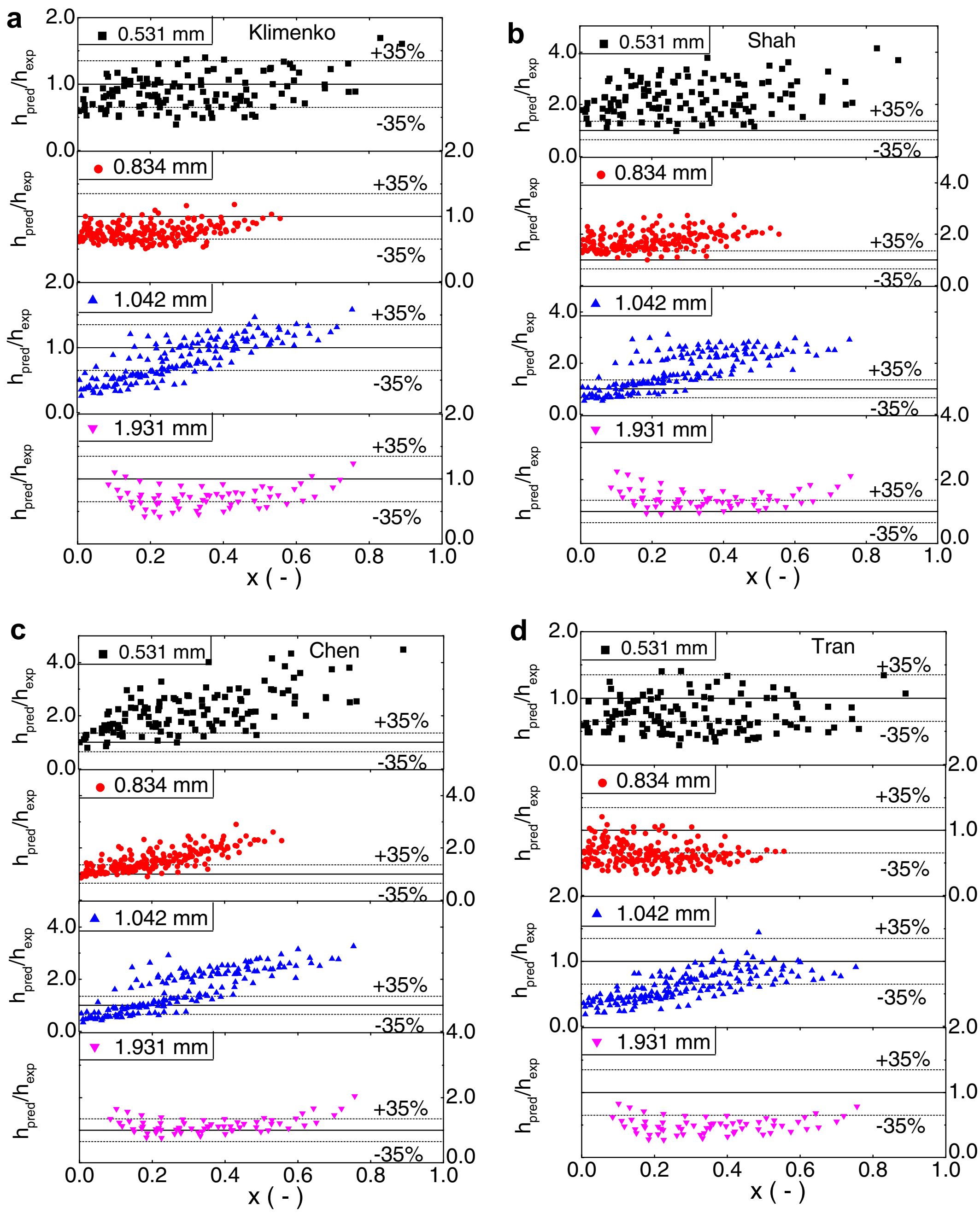

Fig. 7. Comparison of all the flow boiling heat transfer coefficients data with the prediction of four correlations: (a) Klimenko; (b) Shah; (c) Chen; (d) Tran.

transfer coefficient is proposed based on the present experimental data and analysis. At first, the flow boiling is divided into two regions according to the mass quality: $x < 0.3$, low mass quality region; $x > 0.3$, high mass quality region. The mass quality boundary may be just a reference, $x = 0.3$ is only a probable value determined by most experimental data, for example, the data as shown in Fig. 3(e) and (f).

In the correlation, the boiling number, Bo, expressed as

$$Bo = \frac{q}{Gh_{fg}} \tag{5}$$

is used for combining two important parameters, q and G. The ratio of the inertia to the surface tension forces, Weber number ($We = DG^2/(\rho_L\sigma)$), which is usually used to study flow pattern in micro-channel, is also included. Martinelli parameter, X, is used because it contain the parameter of mass quality, x, and X can be written as

$$X = \left(\frac{1-x}{x}\right)^{0.9}\left(\frac{\rho_G}{\rho_L}\right)^{0.5}\left(\frac{\mu_L}{\mu_G}\right)^{0.1}. \tag{6}$$

Dimensionless parameter, K_p, defined as

$$K_p = p/[\sigma g(\rho_L - \rho_G)]^{1/2} \tag{7}$$

is introduced to take the effect of pressure into account. The effect of tube diameter is taken into account through the confinement number, *Co*. Finally, the new correlation is proposed as

$$Nu_{\mathrm{Tp}} = 1059.83Bo^{0.454}We^{0.045}K_{\mathrm{p}}^{0.106}X^{0.107}Co^{-1.825} \quad \text{for } x < 0.3, \tag{8a}$$

$$Nu_{\mathrm{Tp}} = 0.0042Bo^{-0.872}We^{-0.059}K_{\mathrm{p}}^{0.293}X^{0.065}Co^{-1.704} \quad \text{for } x \geqslant 0.3, \tag{8b}$$

where $Nu_{\mathrm{Tp}} = h_{\mathrm{Tp}}D/k_{\mathrm{L}}$.

Total 455 data for 0.531, 0.834 and 1.042 mm micro-tubes are compared with the new correlation in Fig. 8. It can be observed that the flow boiling heat transfer coefficients are well predicted by the new correlation within the error bars of ±30%. The total mean absolute error (MAE) for this correlation, defined as

$$\mathrm{MAE} = \frac{1}{M}\sum\frac{|Nu_{\mathrm{Tp,exp}} - Nu_{\mathrm{Tp,pred}}|}{Nu_{\mathrm{Tp,exp}}} \times 100\% \tag{9}$$

is 13.7% for the number of data $M = 455$.

The new correlation owns a uniform style, and the constants vary for different mass quality regions. It enables to explain two heat transfer mechanisms. At $x < 0.3$, the dominated heat transfer mechanism is nucleation boiling, and the heat transfer coefficient increases with heat flux, but decrease with mass flux. To clarify this point, substituting *Bo* and *We* in Eq. (8a) makes the correlation being transformed to be as

$$Nu_{\mathrm{Tp}} = 1059.83q^{0.454}G^{-0.364}h_{fg}^{-0.454}(D/\rho\sigma)^{0.045}K_{p}^{0.106}X^{0.107}Co^{-1.825}. \tag{10}$$

In other words, heat transfer coefficient is proportional to $q^{0.454}$ and $G^{-0.364}$. However, it is should be noted that nucleate boiling in the micro-tubes has been suppressed because the exponent of heat flux is only 0.454, which is apparently lower than 0.6 for conventional channel [32]. It is suggested that high mass flux suppresses the nucleate

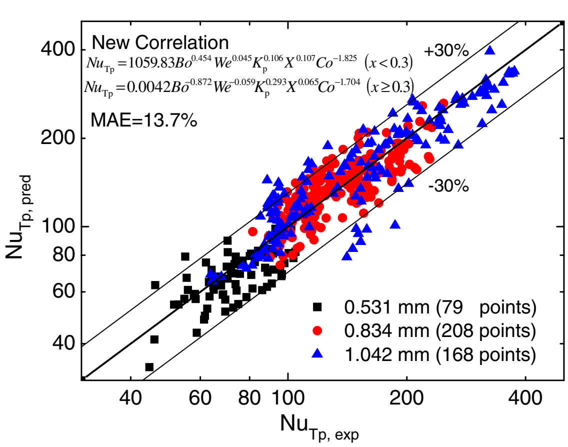

Fig. 8. Comparison of the experimental heat transfer coefficients to the new correlation.

boiling, and decreases the heat transfer coefficient at low mass quality region.

Correspondingly, Eq. (8b) used for high mass quality region can be written as

$$Nu_{\mathrm{Tp}} = 0.0042q^{-0..872}G^{0.754}h_{fg}^{0.872}(D/\rho\sigma)^{-0.059}K_{p}^{0.293}X^{0.065}Co^{-1.704}. \tag{11}$$

It is surprising that Nu_{Tp} is proportional to $G^{0.754}$, which is nearly equal to $G^{0.8}$ for the single-phase forced convection heat transfer coefficient given by Dittus–Boelter [35] as

$$Nu = 0.023G^{0.8}(D/\mu)^{0.8}Pr^{0.4}. \tag{12}$$

This proves that the dominant heat transfer mechanism in high mass quality region is convection. Moreover, the trend that flow boiling heat transfer coefficient is reversely proportional to heat flux also confirms the convection-dominated mechanism.

The effect of pressure on the heat transfer coefficient can be specified according to Eq. (8). The increase of pressure causes the augmentation of heat transfer coefficient in both regions. Due to the suppression of high mass flux in micro-tubes, however, the augmentation at low quality region is lower than for pool nucleate boiling ($Nu \sim p^{0.75}$ [34]) and flow boiling in conventional channel ($Nu \sim p^{0.5}$ [32]).

Eq. (8) also shows the effect of Martinelli parameter on the heat transfer coefficients, $Nu_{\mathrm{Tp}} \sim X^{0.107}$ and $Nu_{\mathrm{Tp}} \sim X^{0.065}$ for low and high mass quality regions, respectively. The exponent of X is positive for both regions, which means the heat transfer coefficients are proportional to Martinelli parameter. The trend is a typical feature for the micro-channels because the exponent of X is negative for the conventional channel. Actually, Martinelli parameter is an indicator of mass quality, and it decreases with increasing mass quality as depicted by Eq. (6). Hence, the relationship between mass quality and heat transfer coefficients can be deduced. Heat transfer coefficients drop with the increase of mass quality, which accords with other experimental results in micro-channels [3,6,11,14,31].

The effect of micro-tube diameter also can be deduced from Eqs. (8a) and (8b) as

$$Nu_{\mathrm{Tp}} \sim Co^{-1.825} \quad \text{for } x < 0.3, \tag{13a}$$

$$Nu_{\mathrm{Tp}} \sim Co^{-1.704} \quad \text{for } x \geqslant 0.3. \tag{13b}$$

For both regions, the heat transfer coefficients decrease with the decreasing micro-tube diameter and the increasing confinement number, *Co*, which means heat transfer is deteriorated by the small micro-tube diameter. Saitoh et al. [36] also found the flow boiling heat transfer coefficients for 1.12 mm micro-tube are higher than those for 0.51 mm micro-tube at $G = 300\ \mathrm{kg/m^2\ s}$, $q = 27$–$29\ \mathrm{W/cm^2}$. But this point may not affect the application of micro-channels heat exchangers, because the largest advantage of micro-channels is the adaptability to the compact configurations, i.e., large heat transfer surface can be obtained within a certain volume.

It should be noted that the new correlation is applicable for 0.531, 0.834 and 1.042 mm micro-tubes. For 1.931 mm tube, the heat transfer characteristics, as shown in Figs. 3(g) & (h), 5(d) and 6(d), are quite different from those in other three micro-tubes. In Fig. 7(c), Chen correlation presents the best prediction to the flow boiling heat transfer coefficient in this tube. Hence, it is confirmed that the 1.931 mm tube belongs to the macro-channel according to the heat transfer characteristics.

4.2. Critical heat flux (CHF)

4.2.1. Wall temperature and heat transfer coefficient at CHF

The wall temperature and heat transfer coefficient at CHF for 0.531 mm micro-tube are shown in Fig. 9. With a slight increase of heat flux from 10.36 to 10.76 W/cm^2, the wall temperature at the end of the micro-tube, T7, soars to 132.0 K, which indicating the occurrence of the CHF. This sudden increase of wall temperature may lead to catastrophic system failure. Moreover, it is found that the CHF always occurs first at the end of the micro-tube. The vapor backflow mentioned by Qu and Mudawar [20] does not appear in the present experiments because no apparent variation for the inlet fluid temperature is measured before and after the CHF. The main reason is that the present tubes are much longer than those in Qu and Mudawar [20], and the mass flux is also comparatively larger. As shown in Fig. 9(b), the heat transfer coefficients drop abruptly at the end of the micro-tube, even turns lower than those for the single-phase flow. The similar trends are found for the other three experimental tubes.

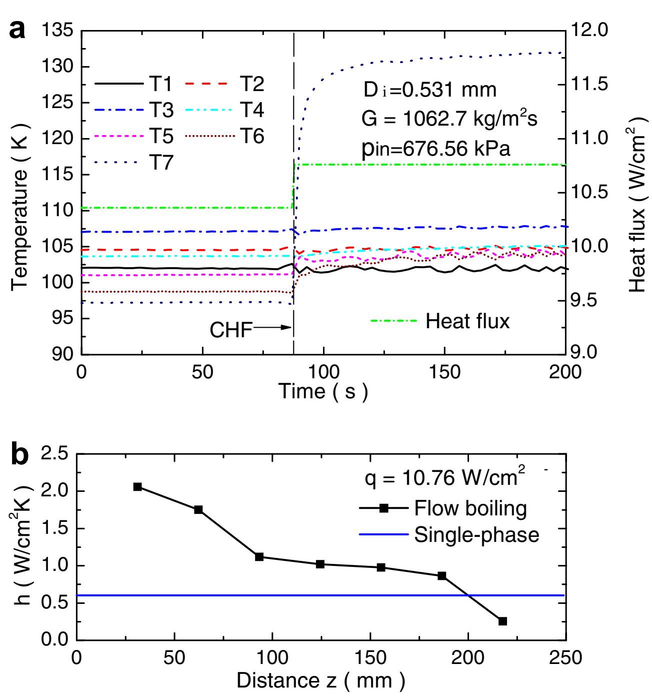

Fig. 9. The wall temperature and heat transfer coefficient at CHF for 0.531 mm micro-tube.

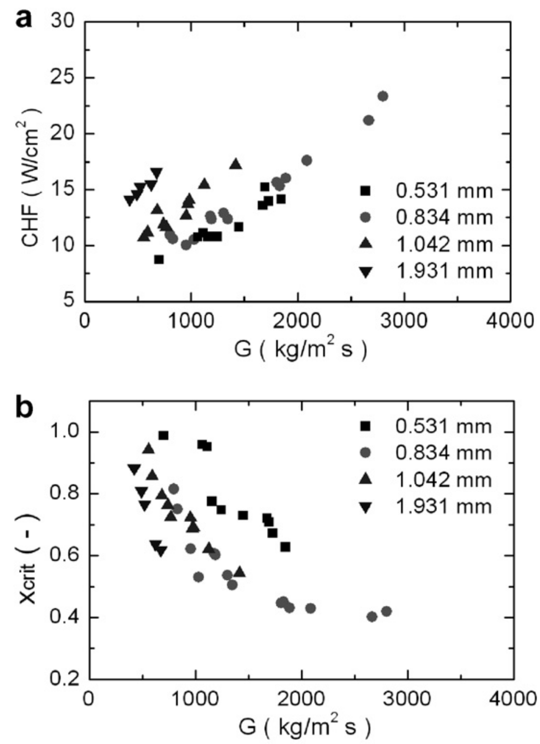

Fig. 10. Variation of CHF and critical quality with mass flux: (a) CHF versus mass flux; (b) critical mass quality versus mass flux.

4.2.2. The variations of CHF and critical mass quality (CMQ) with mass flux

The variations of CHF and critical mass quality (CMQ) with mass flux are depicted in Fig. 10. For all the tubes, CHF increases with the mass flux. This is easily understood because large heat flux is required to reach the same mass quality for high mass flux. As show in Fig. 10(a), it seems that the larger the diameter is, the higher the CHF is for the same mass flux. Actually, it does not exclude the influence of L/D and inlet subcooling. The sole effect of the tube diameter on CHF will be studied in following section. The CMQ for the micro-tube is much higher that for the macro-channel. For example, it even reaches 0.988 for 0.531 mm micro-tube at $G = 698.9$ kg/m^2 s.

CMQ decreases with the increase of the mass flux, which indicates that CHF is governed by the liquid film near the inner wall, i.e., liquid-film-dominated mechanism. Many observations [6,11,12,37] have demonstrated that the two-phase flow pattern at the outlet of the mini and micro-channels is the annular flow. The annular flow is characterized by the existence of one thin liquid film flowing on the heated wall, a vapor core in the center of the channel, and an amount of entrained droplets in the core. CHF occurs while the liquid film is dryout or torn. Hence, high mass flux may be prone to tear the liquid film, and results in CHF at low CMQ.

4.2.3. Comparison of CHF data with the correlations

The experimental CHF is compared with the correlation by Katto [24]

$$\frac{q_{\mathrm{CHF}}}{Gh_{fg}} = 0.10\left(\frac{\rho_{\mathrm{G}}}{\rho_{\mathrm{L}}}\right)^{0.133}\left(\frac{1}{We}\right)^{0.333}\frac{1}{1+0.03L/D} \tag{14}$$

and the correlation proposed recently by Zhang et al. [21] for water in minichannel

$$\frac{q_{\mathrm{CHF}}}{Gh_{fg}} = 0.0352[We + 0.0119(L/D)^{2.31}(\rho_{\mathrm{G}}/\rho_{\mathrm{L}})^{0.36}]^{-0.295} \cdot (L/D)^{-0.311}[2.05(\rho_{\mathrm{G}}/\rho_{\mathrm{L}})^{0.17} - x_{\mathrm{eq,in}}] \tag{15}$$

in Fig. 11. It can be seen that Katto model obviously underestimates the experimental data, which means that the present CHF in micro-tube is dramatically higher than that for the traditional channel. For 0.531, 0.834, 1.042 and 1.931 mm tubes, the average value of $q_{\mathrm{CHF,pred}}/q_{\mathrm{CHF,exp}}$ is 0.216, 0.276, 0.283 and 0.339, respectively. Zhang model correlated from the data of water in minichannels also underpredicts the present data systematically.

Consequently, a new correlation based on Katto correlation is proposed as

$$\frac{q_{\mathrm{CHF}}}{Gh_{fg}} = (0.214 + 0.140Co)\left(\frac{\rho_{\mathrm{G}}}{\rho_{\mathrm{L}}}\right)^{0.133}\left(\frac{1}{We}\right)^{0.333}\frac{1}{1+0.03L/D}. \tag{16}$$

From Fig. 11, it can be seen that the new correlation can yield good agreement with the data, and MAE is 7.38%. To take the effect of tube diameter on CHF into account, Co is included in the new correlation. In the present experiments, four test tubes are kept a constant tube length (250 mm), which means the configuration parameter, L/D, varies with different tube diameters. Keeping L/D as a constant, its influence on CHF can be excluded, and the sole effect of tube diameter can be obtained from Eq. (16), $q_{\mathrm{CHF}} \sim (0.241 + 0.140Co)D^{-0.333}$. With the increase of Co, i.e., the decrease of channel diameter, CHF increases gradually. Celata et al. [38] also investigated the effect of tube diameter on the CHF, and found CHF for micro-channel can be very large, and is inversely proportional to the channel diameter.

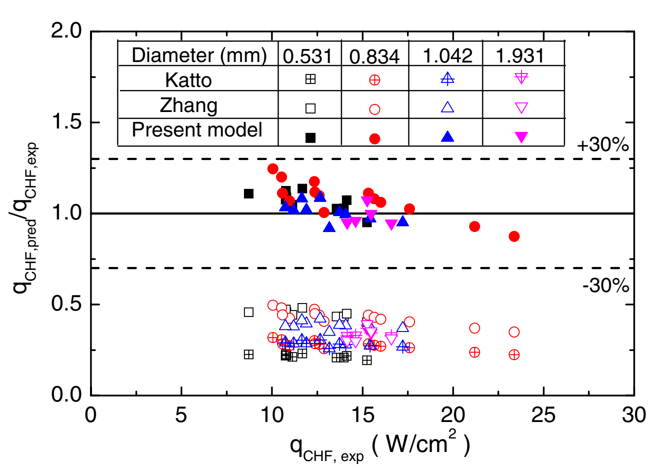

Fig. 11. Comparison of the experimental CHF to the previous and present correlations.

5. Conclusions

The flow boiling characteristics of liquid nitrogen in micro-tubes with the diameters of 0.531, 0.834, 1.042 and 1.931 mm are investigated experimentally. The main contents are related to the flow boiling heat transfer characteristics and CHF. Main conclusions are drawn as follows:

(1) The wall temperatures exhibit a kind of fold line style, i.e., the wall temperature increases in the single-phase flow region, drops abruptly at ONB and then decreases monotonically in the two-phase flow region. The decrease of wall temperature along the tube in flow boiling region is a result of large two-phase flow pressure drop, which causes the saturated pressure and temperature decrease gradually.
(2) The flow boiling in micro-tubes can be divided into two regions by investigating the influence of heat flux, mass flux and pressure. For low mass quality region, heat transfer is governed by nucleate boiling, and heat transfer coefficient is dependent on heat flux and pressure, but insensitive to mass flux. For high mass quality region, heat transfer is dominated by convection evaporation, and heat transfer coefficient is dominated by mass flux, insensitive to heat flux.
(3) For 1.931 mm tube, heat transfer behaviors are quite different from those for 0.531, 0.834 and 1.042 mm micro-tubes. The heat transfer coefficient increases with mass quality at low and medium heat flux, and can be well predicted by Chen correlation for conventional channels. The tube with a diameter of 1.931 mm is considered to be macro-channel for the present experimental conditions. And $Co = 0.5$ is proven to be one reasonable criterion of macro and micro-channel.
(4) None of the four correlations can predict the heat transfer coefficients for 0.531, 0.834 and 1.042 mm micro-tubes. New correlation proposed can provide accurate prediction to the experimental heat transfer coefficients with a MAE of 13.7%. Since it includes Co, Bo, We, K_{p} and X, the effect of tube diameter, heat flux, mass flux, pressure and mass quality on the heat transfer coefficients can be clarified.
(5) CHF increases with the mass flux, whereas critical mass quality decreases with mass flux. It is found that CHF is governed by the liquid film near the inner wall, i.e., liquid-film-dominated mechanism. The present experimental CHF is higher than that for macro-channels, and neither Katto correlation or Zhang correlation can predict the data well. The modified model based on Katto correlation can give out satisfactory prediction with a MAE of 7.38%.

Acknowledgements

This research is jointly supported by A Foundation for the Author of National Excellent Doctoral Dissertation of PR China (200236), National Natural Science Foundation of China (50776057 and 50436030) and NCET.

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