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ONSET OF NUCLEATE BOILING IN MINI AND MICROCHANNELS: A BRIEF REVIEW

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ABSTRACT

The present article summarizes the studies on the thermalhydraulic condition under which the onset of nucleate boiling (ONB) is triggered in subcooled flow boiling. Available correlations and experimental data show that the ONB is tended to be delayed in mini and microchannels. It is known that the ONB condition is significantly dependent on the surface condition even in conventional-sized channels. Accumulation of ONB data accompanied by the information on the surface condition is therefore considered of importance to elucidate the mechanisms of boiling incipience in microchannels. Discussion is also made for the bubble dynamics observed in mini and microchannels. It is indicated that the bubble behavior at ONB in mini and microchannels may significantly be different from that in conventional-sized channels and have greater impact on the system performance. Further studies on the bubble dynamics following nucleation at ONB are also requested to improve the design of heat transfer devices using mini and microchannels.

Keywords: *Microchannel, Subcooled flow boiling, Onset of nucleate boiling, Bubble dynamics.*

1. INTRODUCTION

The use of small diameter channels is a promising way to increase the heat transfer area per unit volume in heat exchangers. Furthermore, the coolant flow rate required for dissipating a given amount of heat can be reduced if the latent heat transfer is employed. Flow boiling in mini and microchannels is hence expected to be a promising way to achieve effective heat dissipation particularly from small areas (Kandlikar, 2006), and has received increasing attention mainly due to extremely high power density encountered in recent miniaturized electronic devices (Mudawar, 2001; Thome, 2004). Although there exist several important parameters in flow boiling including the heat transfer coefficient and critical heat flux (Thome, 2004; Bergles and Kandlikar, 2005; Roday and Jensen, 2009), the present article focuses on the onset of nucleate boiling (ONB) in mini and microchannels.

In subcooled flow boiling in conventional-sized channels, the vapor void fraction near the location of ONB can be positive only in the region close to the heated wall. In consequence, the void fraction just downstream of the point of ONB is small, and a rapid increase in the void fraction or the onset of significant void (OSV) occurs further downstream of the ONB point (Collier and Thome, 1994); the void fraction between the locations of ONB and OSV is hence usually neglected. However, since the location of ONB corresponds to the boundary between the single- and two-phase regions, pressure loss and heat transfer characteristics are different between upstream and downstream of the point of ONB. For instance, Basu et al. (2002) indicated that single-phase heat transfer prevails upstream of the ONB point, but the presence of bubbles permits various heat transfer mechanisms downstream of it. It is also reported that the bubble behavior at ONB can significantly be different depending on the experimental setup (Bibeau and Salcudean, 1994; Thorncroft et al., 1998; Okawa et al., 2005; Ahmadi et al., 2012). In consequence, many correlations and models have been developed so far to predict the location of ONB in subcooled flow boiling; some of them are discussed in the following section.

In mini and microchannels, several investigators reported that the wall superheats needed for boiling incipience can noticeably be higher than those predicted by the conventional correlations (Hapke et al., 2000; Kennedy et al., 2000; Martín-Callizo et al., 2007; Qi et al., 2007). Since the presence of bubbles alters the characteristics of the pressure loss and heat transfer as in the conventional-sized channels, accurate prediction of ONB is of importance in the design of the heat exchangers or the heat sinks using microchannels. Furthermore, once the ONB occurs in microchannels, a bubble can grow rapidly and most of the channel cross-section may be occupied by bubbles (Kandlikar and Balasubramanian, 2004; Hetsroni et al., 2005a; Barber et al., 2010). This phenomenon may cause the onset of flow instability leading to a decreased CHF value and significant oscillations of system pressure and heat transfer rate (Hetsroni et al., 2005a; Bergles and Kandlikar, 2005; Kuo and Peles, 2008). Absence of apparent partial boiling prior to fully-developed nucleate boiling (Peng and Wang, 1993) and a considerable wall temperature drop at ONB (Piasecka et al., 2004; Qi et al., 2007) were also reported. It is considered that the ONB may have greater impact on the system performance in the heat transfer devices using mini and microchannels.

The main purpose of the present brief review is to summarize available studies regarding the thermalhydraulic conditions under which nucleate boiling commences in forced-convective subcooled flow boiling. Since the bubble behavior in mini and microchannels can significantly be different from that observed in conventional-sized channels, studies concerning the bubble dynamics at ONB are also addressed.

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2. ONB CORRELATIONS FOR GENERAL PURPOSES

The necessary condition for the boiling incipience postulated by Hsu (1962) has been used as the basis in many subsequent correlations for ONB. Considering a tiny bubble nucleus sitting at the mouse of a cavity as illustrated in Fig. 1, Hsu hypothesized that the bubble nucleus does not grow if the minimum temperature of the surrounding liquid is lower than the bubble temperature. It was assumed that the size of bubble nucleus r_b is proportional to the cavity mouth radius r_c and also dependent on the contact angle θ. Since the bubble temperature T_b is assumed to be equal to the saturation temperature corresponding to the pressure inside the nucleus, a decreased value of r_c or r_b leads to an increase in T_b from the Young-Laplace equation ($P_b - P_l = 2\sigma/r_b$) and the Clasius-Clapeyron equation ($dP/dT = \Delta h_V \rho_v / T_{SAT}$). On the other hand, the minimum liquid temperature at the tip of the bubble nucleus decreases with an increase in r_c due to sharp temperature gradient formed near the heated wall. In consequence, Hsu derived a quadratic equation to show that given the wall superheat ΔT_W and the liquid subcooling ΔT_{SUB}, the cavities within the following size range may be activated.

$$\{r_{c,\min}, r_{c,\max}\} = A\left[1 \mp \sqrt{1 - \frac{8\sigma T_{SAT}(1+\cos\theta)(\Delta T_W + \Delta T_{SUB})}{\Delta h_V \rho_v \delta \Delta T_W^2}}\right] \quad (1)$$

where δ denotes the thickness of the thermal layer in which the liquid temperature is higher than the bulk temperature, and A is given by

$$A = \frac{\delta \sin\theta \Delta T_W}{2(1+\cos\theta)(\Delta T_W + \Delta T_{SUB})} \quad (1')$$

Since no cavity can be activated if the discriminant of the quadratic equation is negative, the necessary condition for ONB is given by

$$\frac{8\sigma T_{SAT}(1+\cos\theta)(\Delta T_W + \Delta T_{SUB})}{\Delta h_V \rho_v \delta \Delta T_W^2} = 1 \quad (2)$$

Hsu noted that the ONB condition can deviate from Eq. 2 if the size range of the cavities on the heated surface is narrow, but claimed that Eq. 2 is still useful since the presence of cavities of a wide spectrum in sizes can be expected for most commercially available surfaces. For the value of θ, Hsu assumed that θ = 53° (cos θ = 0.6) for simplicity. Figure 1 however indicates that the distance of the bubble tip from the wall y_b increases with a decrease in θ. Reflecting this fact, Eq. 2 derived by Hsu suggests that the onset of nucleate boiling is delayed if the surface wettability is improved.

Sato and Matsumura (1963) developed a similar model independently of Hsu. They assumed a hemispherical bubble nucleus (θ = 90º) and linked the thermal layer thickness δ in Eq. 2 with the heat flux q_W. Assuming a linear temperature profile near the heated surface ($T_l = T_W - (q_W / k_l) y$), Eq. 2 is transformed to

$$q_W = \frac{\Delta h_V \rho_v k_l \Delta T_W^2}{8\sigma T_{SAT}} \quad (3)$$

Since the above equation defines the relation of q_W and ΔT_W at ONB, the ONB condition can be determined if it is combined with a heat transfer equation for single-phase flow, $q_W = h_{SP}(\Delta T_W + \Delta T_{SUB})$. Using the Dittus-Böelter correlation for the heat transfer coefficient h_{SP}, Sato and Matsumura compared the predictions by Eq. 3 with experimental data. The ranges of channel diameter and pressure were 5.8 to 12 mm and 0.1 to 14 MPa, respectively, and reasonably good agreements were reported. In this model, the critical cavity radius $r_{c,crit}$ at which the first bubble is formed is calculated as

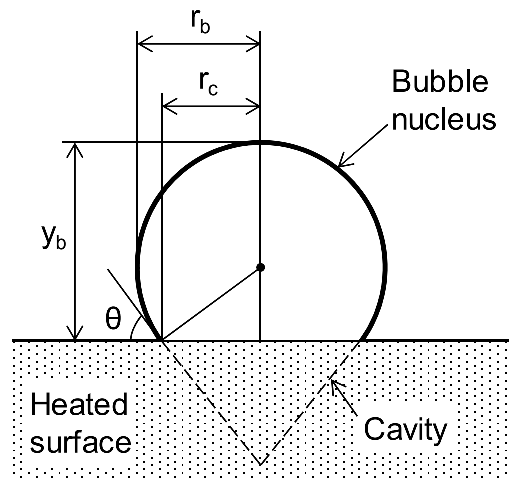

Fig. 1 Bubble nucleus sitting at the mouse of a cavity postulated by Hsu (1962).

$$r_{c,crit} = \sqrt{\frac{2k_l \sigma T_{SAT}}{\Delta h_V \rho_v q_W}} \quad (4)$$

If the properties of saturated water under the atmospheric pressure and $q_W = 0.2$ MW/m^2 are substituted to the above equation as a trial, $r_{c,crit}$ is calculated to be about 10 μm.

Davis and Anderson (1966) integrated the Clasius-Clapeyron equation strictly to derive a more precise expression for the ONB condition. If the pressure increment in a bubble nucleus is not significant, their expression reduces to

$$q_W = \frac{\Delta h_V \rho_v k_l \Delta T_W^2}{8\sigma T_{SAT}(1+\cos\theta)} \quad (5)$$

This equation is identical to Eq. 3 if θ is set to 90º. They also investigated the ONB condition when only small cavities are available on a heated surface. If the maximum cavity size $r_{c,max}$ is smaller than $r_{c,crit}$, the approximate expression for the ONB condition is given by

$$q_W = \frac{k_l \sin\theta}{r_{c,\max}(1+\cos\theta)}\left[\Delta T_W - \frac{2\sigma T_{SAT}\sin\theta}{\Delta h_V \rho_v r_{c,\max}}\right] \quad (6)$$

They showed that, for the data of flow boiling of benzene and water in a copper tube of smooth surface, Eq. 5 considerably underestimates the wall superheats at the boiling incipience in a liquid film but fairly good agreements are achieved if $r_{c,max}$ is set to 1 μm in Eq. 6 (the use of a complete version of Eq. 6 is recommended for water data in the original paper). The value of 1 μm was consistent with the observation result of the copper surface using a microscope. They concluded that specific information on the cavity size is needed to predict the ONB condition if a cavity size range available on the heated surface is limited.

Although a linear temperature profile within the thermal layer is postulated in the models mentioned above, it is obvious that the temperature field is affected by the presence of a bubble nucleus. Kandlikar et al. (1997) and Kandlikar (2006) further included the effect of bubble nucleus on the thermalhydraulic field around it by means of numerical simulation. It was shown that the ONB condition is expressed by the following equation if there is no lack of cavities of various sizes:

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$$q_W = \frac{\Delta h_V \rho_v k_l \Delta T_W^2}{8.8\sigma T_{SAT}} \tag{7}$$

If the most preferable cavity of $r_c = r_{crit}$ is not available on the surface, the ONB condition is given by

$$q_W = \frac{k_l \sin\theta_r}{1.1 r_{c,\max}}\left[\Delta T_W - \frac{2\sigma T_{SAT}\sin\theta_r}{\Delta h_V \rho_v r_{c,\max}}\right] \tag{8}$$

where θ_r is the receding contact angle.

Even if a cavity is available on a heated surface, it does not work as an active nucleation site unless it can entrap noncondensable gas or vapor in it (Collier and Thome, 1994). Since the condition of entrapment is dependent on the surface wettability as discussed by Yang and Kim (1988), the contact angle would be influential not only in the shape of bubble nucleus sitting on a cavity mouse but also in the size distribution of unflooded cavities. In view of this, Basu et al. (2002) introduced a correction factor F to the ONB criterion as

$$q_W = \frac{F^2 \Delta h_V \rho_v k_l \Delta T_W^2}{2\sigma T_{SAT}} \tag{9}$$

where F is the function of θ and determined from available experimental data as

$$F = 1 - \exp\left[-\left(\frac{\pi\theta}{180}\right)^3 - 0.5\left(\frac{\pi\theta}{180}\right)\right] \tag{10}$$

The validity of this correlation was tested against the experimental data for various combinations of fluids and surface materials; the resulting range of θ was 1 to 85º.

Because of complexity of the phenomenon and industrial importance, empirical correlations for water have also been developed of which the notable ones are shown below:

$$q_W = 0.00180 P^{1.156}(1.8\Delta T_W)^{2.83/P^{0.0234}} \tag{11}$$

$$q_W = 1949\Delta T_W^2 \exp(2.26\times10^{-7}P) \tag{12}$$

The original expressions were rewritten in the SI units in the above equations. Equation 11 by Bergles and Rohsenow (1964) was derived based on water data over a wide pressure range of 0.1 to 13.8 MPa. Celata et al. (1997) showed that Eq. 12 by Thom et al. (1965) provides good agreements with water subcooled flow boiling data obtained under high mass flux and high liquid subcooling conditions.

As an example, the ONB criterions for water subcooled flow boiling calculated by the correlations shown above are compared under the condition of D = 10 mm, P = 0.1 MPa, G = 1000 kg/m^{2}s, ΔT_{SUB} = 20 K, θ = θ_r = 45º and $r_{c,max}$ = 1 μm in Fig. 2. The black curve in the figure indicates the heat transfer equation for single-phase flow simply calculated using the following widely-used correlation for the heat transfer coefficient.

$$Nu = 0.023 Re^{0.8} Pr^{0.4} \tag{13}$$

where Nu, Re and Pr are the Nusselt, Reynolds, and Prandtl numbers, respectively. The intersection of each correlation with the heat transfer equation is commonly assumed to correspond to the ONB condition. It can be seen that the calculated results by Eqs. 6 and 8 are considerably different from those by other correlations. This indicates the possibility that ΔT_W and q_W at ONB can take significantly higher values if a cavity size range on the heated surface is limited. In order to investigate the effect of surface wettability, the value of θ was changed parametrically in Eq. 5 by Davis and Anderson (1966) and Eq. 9 by Basu et al. (2002). The results are delineated in Fig. 3. It can be seen that the effect of θ is rather insignificant in Eq. 5 but slight decrease in θ leads to a significant increase in the values of ΔT_W and q_W at ONB in Eq. 9 particularly when θ is small, suggesting that considerable portion of cavities cannot be activated due to flooding in the case of hydrophilic heated surfaces.

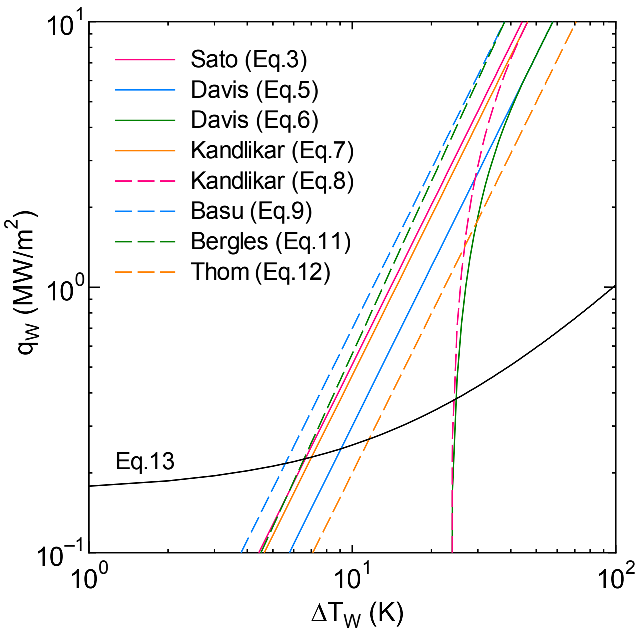

Fig. 2 Comparison of the existing ONB correlations for general purposes under the condition of D = 10 mm, P = 0.1 MPa, G = 1000 kg/m^{2}s, ΔT_{SUB} = 20 K, θ = θ_r = 45º and $r_{c,max}$ = 1 μm.

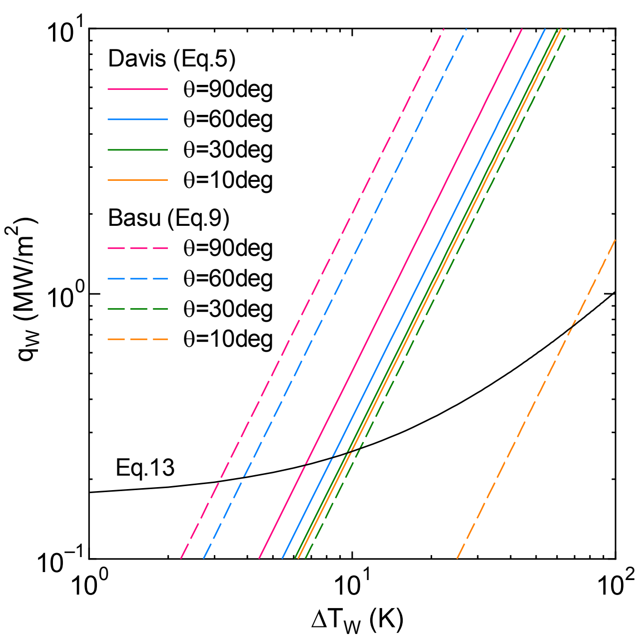

Fig. 3 Dependence of the ONB condition on the contact angle θ estimated by the correlations developed by Davis and Anderson (Eq. 5) and Basu et al. (Eq. 9).

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3. STUDIES ON THE ONSET OF NUCLEATE BOILING IN MINI AND MICROCHANNELS

3.1 Models and Correlations

Several investigators proposed the correlations for the ONB condition in mini and microchannels. Ghiaasiaan and Chedester (2002) found that the correlations by Bergles and Rohsenow (1964) and Sato and Matsumura (1963) tend to underestimate the ONB heat flux reported for water subcooled flow boiling in small-diameter tubes of D = 1 to 1.45 mm (Inasaka et al., 1989; Kennedy et al., 2000). Ghiaasiaan and Chedester (2002) then considered that the liquid temperature at the tip of the bubble nucleus should be higher than the bubble temperature for the nucleus to grow as supposed by Hsu (1962), but hypothesized that the suppressing effect of the thermocapillary (Marangoni) force acting on the bubble nucleus should further be balanced by the aerodynamic force on it. To include this additional effect, they introduced an empirical coefficient C to Eq. 3 as

$$q_W = \frac{\Delta h_V \rho_v k_l \Delta T_W^2}{8C\sigma T_{SAT}} \tag{14}$$

and assumed that C is the function of the following dimensionless parameter ξ representing the ratio of the thermocapillary force to the aerodynamic force.

$$\xi = \frac{\sigma_{SAT} - \sigma_W}{\rho_l U^2 r_{c,crit}} \tag{15}$$

where σ_{SAT} and σ_W denote the values of the surface tension coefficient at T_{SAT} and T_W, respectively, and $r_{c,crit}$ is calculated by Eq. 4. The functional form of C was determined empirically using the ONB data reported by Inasaka et al. (1989) and Kennedy et al. (2000) as

$$C = \max(1, 22\xi^{0.765}) \tag{16}$$

It can be seen that for small values of ξ, the value of C is 1 and Eq. 14 reduces to Eq. 3 by Sato and Matsumura. On the other hand, the calculated values of ξ were within 0.01 to 10 for the above databases, indicating that C can take very high values in some experimental conditions. Based on the results of numerical simulation, Zhuan and Wang (2010) also discussed the importance of the Marangoni heat transfer at the onset of nucleate boiling in microchannels.

Qu and Mudawar (2002) observed that even at incipient boiling, bubbles grew to detachment size before departing into the liquid flow in water subcooled flow boiling in a rectangular microchannel. Then, they considered that the classical ONB criterion may not be adequate for describing the incipience conditions in microchannels, and took a different approach to predict the incipient boiling heat flux. Since the bubbles departed into the liquid flow even at ONB, they first calculated the bubble departure diameter from the balance of the forces acting on a bubble. The drag and surface tension forces were considered as the main components. Two-dimensional temperature field within the rectangular channel was then calculated and the heat flux at which the lowest temperature around the departing bubble just exceeded the saturation temperature was postulated to be the incipient boiling heat flux. Hence, their model has a resemblance to the bubble departure models that are usually used for the prediction of the net vapor generation in subcooled flow boiling in conventional-sized channels (Levy, 1965; Winterton, 1984). It was shown that the calculated incipient boiling heat fluxes were in good agreement with their experimental data for water subcooled flow boiling in a horizontal rectangular channel of 0.231 mm wide and 0.712 mm deep.

Liu et al. (2005) followed the treatment by Davis and Anderson (1966) but made a modification on the superheat equation to derive the following expression for the ONB condition:

$$q_W = \frac{\Delta h_V \rho_v k_l}{2\sigma(1+\cos\theta)}\left[T_W + T_{SAT} - 2\sqrt{T_W T_{SAT}}\right] \tag{17}$$

Comparisons were made for the water data for the rectangular channel of 0.275 mm wide and 0.254 mm deep accumulated by themselves and those by Qu and Mudawar (2002). Although Eq. 17 tended to overestimate the incipient boiling heat flux slightly, the predictions agreed with the experimental data within ±20%.

Qi et al. (2007) performed the measurements of ONB condition for liquid nitrogen flowing in round tubes of 0.531 to 1.931 mm in diameter. They found that the correlations by Thom (Eq. 12) and Liu et al. (Eq. 17) underestimate the wall superheat and the heat flux at ONB measured in their experiments. It was however reported that the correlation by Thom correctly predicts the measured tendencies and a good agreement can be achieved if the model constant in Eq. 12 is adjusted as

$$q_W = 1064\Delta T_W^2 \exp(2.26\times 10^{-7} P) \tag{18}$$

The ONB correlations for mini and microchannels proposed by Liu et al. (Eq. 17) and Qi et al. (Eq. 18) are shown in Fig. 4. Here, D is reduced to 1 mm but other conditions are the same as those used in Fig. 2; Eqs. 3, 5 and 6 are also displayed in the same figure for comparison. Since the Reynolds number is rather small ($Re \approx 3500$), the heat transfer equation for fully-developed laminar flow (Nu = 4.36) are also depicted. It can be confirmed that the correlation by Liu et al. is very close to Eq. 5 as also indicated by the authors. Although the correlation by Qi et al. predicts relatively higher values of ΔT_W and q_W, the values are still less than those calculated by Eq. 6, in which the maximum cavity radius is assumed to be 1 μm.

Noted that although the heat transfer correlations widely accepted for single-phase flow in conventional-sized channels are displayed in Fig. 4, inadequacy of these correlations for the flow in microchannels has been indicated by many investigators (Ghiaasiaan and Chedester, 2002; Morini, 2004; Hetsroni et al., 2005b; Rosa et al., 2009). It should hence be noted that, in addition to the ONB correlation, development of reliable heat transfer correlation is needed for the accurate prediction of the boiling incipience in microchannels.

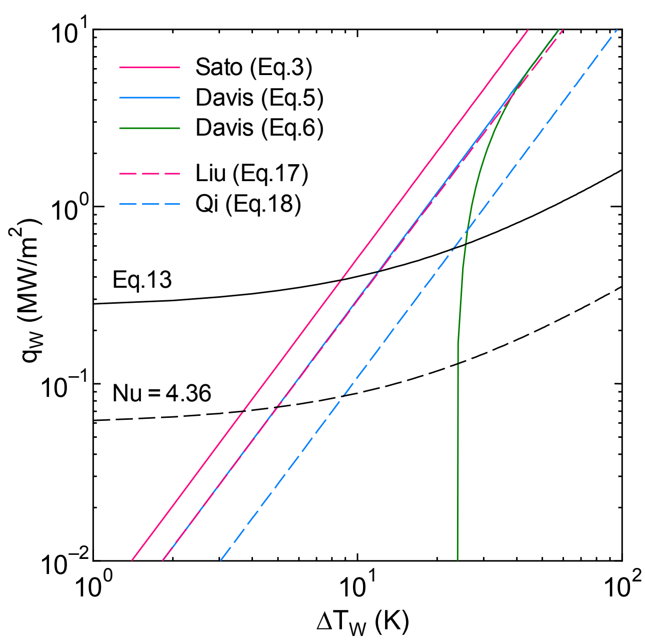

Fig. 4 Comparison of the ONB correlations for mini and microchannels (D = 1 mm, other conditions are the same as those in Fig. 2).

Table 1 Examples of ONB data in mini and microchannels available in literature.

References	*Fluid*	*Material of heated surface*	*Channel geometry*	*Determination method of ONB*	*Comments*
Inasaka et al. (1989)	Water	Stainless steel 304	Round tubes of 1 mm in diameter	Variation of pressure loss	• q_W at ONB agreed with the correlation by Bergles and Rohsenow fairly well.
Hapke et al. (2000)	Water	Nickel base alloy	Round tube of 1.5 mm in diameter	Variation of wall temperature	• ΔT_W at ONB was tended to be underestimated by the correlations by Sato and Matsumura and by Bergles and Rohsenow particularly at high heat fluxes.
Kennedy et al. (2000)	Water	Copper	Round tubes of 1.17 and 1.45 mm in diameter	Variation of pressure gradient	• q_W at ONB was underestimated by the correlation by Bergles and Rohsenow. • Experiments were conducted at elevated pressures up to 1 MPa.
Qu and Mudawar (2002)	Water	Copper	21 parallel rectangular channels of 231 µm wide and 712 µm deep	Visual observation	• A mechanistic model based on a bubble departure criterion was developed.
Lee et al. (2004)	Water	Silicon	Single trapezoidal channel (103 µm in upper base, 59 µm in lower base and 30 µm in height)	Visual observation	• ΔT_W and q_W at ONB agreed with Eq. 6 if $r_{c,max}$ was set to 1.5 to 4 µm. • Information on the surface roughness was reported.
Liu et al. (2005)	Water	Copper	25 parallel rectangular channels of 275 µm wide and 636 µm deep	Visual observation	• q_W at ONB was slightly overestimated by the correlation following the treatment by Davis and Anderson.
Wu et al. (2006)	Water	Silicon	8 parallel trapezoidal channels (200 µm in upper base, 136 µm in lower base and 49 µm in height)	Visual observation	• Relation between ONB and OFI was investigated.
Martín-Callizo et al. (2007)	R-134a	Stainless steel 316	Round tubes of 0.83, 1.22 and 1.70 mm in diameter	Variation of wall temperature	• ΔT_W at ONB was underestimated by the correlations by Sato and Matsumura and by Bergles and Rohsenow. • Significant temperature undershoot at ONB was reported.
Qi et al. (2007)	Liquid nitrogen	Stainless steel 304	Round tubes of 0.531, 0.834, 1.042 and 1.931 mm in diameter	Variation of wall temperature	• ΔT_W and q_W at ONB were underestimated by the correlations by Liu et al. and Thom et al.
Kuo and Peles (2008)	Water	Silicon	5 parallel rectangular channels of 200 µm wide and 253 µm deep	Variation of wall temperature	• q_W at ONB decreased for the surfaces with artificial reentrant cavities.
Kuo and Peles (2009a)	HFE-7000	Silicon	5 parallel rectangular channels of 200 µm wide and 250 µm deep	Visual observation	• q_W at ONB decreased for the surfaces with artificial reentrant cavities.
Lee et al. (2011)	Water	Silicon	Single square or rectangular channels (100 µm wide and 100 µm high; 100 µm wide and 48 µm high)	Visual observation	• Single artificial cavities of cylindrical shape with conical inlet were used for nucleation.

3.2 Experimental Works

Listed in Table 1 are the examples of available experimental data of the ONB condition in mini and microchannels. Although the result of comparison is not always reported, ΔT_W and q_W at ONB are usually higher than those predicted by conventional correlations (Hapke et al., 2000; Kennedy et al., 2000; Martín-Callizo et al., 2007; Qi et al., 2007) with a certain number of exceptions (Inasaka et al., 1989; Liu et al., 2005). Even if the nucleation site density is constant, the total number of nucleation sites should be smaller in a microchannel because of its small surface area. Furthermore, since sophisticated methods are frequently adopted in the fabrication process, the surface of microchannel tends to be very smooth. For example, in the case of the microheaters fabricated by Lin (1998) using MEMS (micro-electro-mechanical system), the root mean square surface roughness was measured to be 6.5 nm. In this extreme case, bubbles might be generated by homogeneous nucleation rather than heterogeneous nucleation. The lack of large cavities is hence considered to be one of the major reasons of the delay of ONB frequently encountered in microchannels. In fact, Lee et al. (2004) reported that Eq. 3 underestimated their experimental data of the incipient boiling heat flux in a trapezoidal microchannel, but reasonably good agreement was achieved if $r_{c,max}$ was set to 1.5 to 4 μm in Eq. 6. These values were consistent with the maximum roughness of the heated surface measured using an atomic force microscope. Lee et al. (2011) also reported that the nucleation incipient conditions at single artificial cavities in their square and rectangular microchannels were well matched with the classical theory presented in section 2 of this article. Kuo and Peles (2008; 2009a) reported that the incipient boiling heat fluxes measured for the heated surfaces with artificial reentrant cavities were generally lower than those for a plane surface. This observation would also be the evidence that the ONB condition in microchannels is particularly sensitive to the surface condition.

Effect of the surface wettability should also be taken into consideration since cavities may be flooded due to the combinations of fluid and surface material of low contact angles. Although the effect of contact angle on the boiling incipience are discussed by several researchers (Basu et al, 2002; Qu and Mudawar, 2002; Li and Cheng, 2004), the ONB data in microchannels are usually not accompanied by the information regarding the surface wettability. In the case of microchannels, specific information on the surface properties is considered to be of particular importance to predict the ONB condition since the presence of cavities of a wide spectrum in sizes may not be expected.

An additional concern in predicting the ONB condition in microchannels would be the effect of channel geometry. Since a wide variety of cross-sectional shapes are adopted in microchannels as shown in Table 1, the heat flux, wall superheat and liquid velocity may vary in the circumferential direction (Qu and Mudawar, 2002; Li and Cheng, 2004). Sufficient attention should also be paid for the effect of the cross-sectional shape of the flow channel.

3.3 Bubble Dynamics at ONB

Lee et al. (2004) measured the bubble dynamics in a trapezoidal microchannel of 103 μm in upper base, 59 μm in lower base and 30 μm in height; the material of heated surface was silicon and the working fluid was deionized water. In their experiment, bubbles were generated at the side walls, and grew at the nucleation site before sliding along the heated surface. The measured bubble departure diameters were within 19 to 47 μm and correlated by the modified Levy's model (1967) fairly well, suggesting that the bubble departure was governed by the balance of drag and surface tension forces acting on a bubble. Fu et al. (2010) observed the bubble behavior in the flow boiling of liquid nitrogen in a vertical quartz glass tube of 1.3 to 1.5 mm in diameter. They also observed that bubbles first grew at the nucleation sites and then slid along the wall. Since the size of the sliding bubbles immediately became comparable with the tube size, bubble detachment from the heated surface was usually not observed. Alternatively, they observed slug bubbles. It was reported that the bubble diameter first increased almost linearly with time, but the growth rate of the bubble in the axial direction had abrupt jump when the bubble size became comparable to the tube diameter.

Kandlikar (2006) made a discussion concerning the rapid growth of a bubble following nucleation in microchannels. The heat transfer equation for single-phase flow is expressed by

$$q_W = h_{SP}(\Delta T_W + \Delta T_{SUB}) \tag{20}$$

He showed that in microchannels, the liquid subcooling ΔT_{SUB} at ONB tends to be small because of the high heat transfer coefficient and can become negative (superheated) in some cases. This trend is intensified when the cavities of preferable sizes are not available on the heated surface since the value of ΔT_W can be high. Once nucleation is triggered in this low subcooling or superheated environment, the bubble may experience a rapid growth as observed by Hetsroni et al. (2005a) and Kandlikar (2006). Lee et al. (2011) also observed that the bubble behavior after nucleation was significantly dependent on the wall superheat at ONB and the bubble grew in an explosive manner when the superheat was higher. This phenomenon is of importance in the design of microchannel heat sinks. For example, Steinke and Kandlikar (2004) expected that the rapid bubble growth was the main cause of anomalous heat transfer coefficients measured at low vapor qualities in their experiment using 6 parallel microchannels of 0.214 mm wide and 0.2 mm deep. Since rapidly growing bubble may occupy most of the channel cross-section in microchannels, the rapid bubble growth can induce a pressure spike to cause transient flow reversal toward the inlet of the microchannel (Kandlikar, 2006; Kuo and Peles, 2008). Barber et al. (2010) investigated the relation between the pressure fluctuation and the bubble growth process in detail using FC-72 as the working fluid. It was shown that the periodic pressure fluctuations could be explained in terms of the bubble dynamics. It is therefore considered that the ONB likely to lead to the onset of flow instability (OFI) in microchannels. In fact, Wu et al. (2006) reported that the conditions of ONB and OFI were much closer in the microchannels and the two conditions almost coincided at high heat fluxes. Several methods were therefore proposed to reduce the wall superheat at ONB and to mitigate the flow instability (Kandlikar, 2006; Kuo and Peles, 2008, 2009b; Liu et al., 2010).

4. CONCLUSIONS

Available studies concerning the onset of nucleate boiling (ONB) in subcooled flow boiling were briefly reviewed. The ONB correlations developed for general purposes indicate that the thermalhydraulic conditions at ONB are significantly dependent on the surface properties such as the size distribution of cavies and the contact angle. The delay of ONB frequently observed in mini and microchannels would partly be attributed to a relatively small number of cavities available on a heated surface. There might however be additional factors that influence the ONB condition in microchannels. It is considered that further accumulation of the ONB data accompanied by the information on the surface properties is of particular importance to elucidate the mechanisms of boiling incipience in mini and microchannels.

Because of the small channel size and the possible high wall superheat, bubbles formed at ONB may occupy most of the channel cross-section and experience unexpectedly high growth rate in microchannels. In consequence, bubble dynamics at ONB may have significant impact on the whole system. Understanding of the bubble behavior following nucleation and the development of the efficient method to mitigate the delay of ONB are also of importance to improve the system performance of the heat transfer devices using mini and microchannels.

NOMENCLATURE

D	channel diameter (m)
G	mass flux (kg/m^2·s)
h	heat transfer coefficient (W/m^2·K)
k	thermal conductivity (W/m·K)
Nu	Nusselt number (dimensionless)
P	Pressure (N/m^2)
Pr	Prandtl number (dimensionless)
q_W	heat flux (W/m^2)
Re	Reynolds number (dimensionless)
r_b	radius of bubble nucleus (m)
r_c	radius of cavity mouth (m)
T	temperature (K)
U	mean velocity (m/s)
y	distance from the wall (m)

Greek Symbols

Δh_V	latent heat of vaporization (J/kg)
ΔT_W	wall superheat (K)

ΔT_{SUB}	liquid subcooling (K)
δ	thermal layer thickness (m)
θ	contact angle (degree)
ρ	density (kg/m^3)
σ	surface tension (N/m)

Subscripts

b	bubble
crit	critical
l	liquid phase
max	maximum
min	minimum
r	receding
SAT	saturation
SP	single phase
v	vapor phase
W	wall

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