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ONSET OF NUCLEATE BOILING AND INCIPIENT POINT OF NET VAPOR GENERATION IN NARROW CHANNEL

A. Gang HONG , B. Xiao YAN , C. Yanping HUANG and D. Zejun XIAO
CNNC Key Laboratory on Nuclear Reactor Thermal Hydraulics Technology, Chengdu, China

Abstract

An experimental study on onset of nucleate boiling (ONB) and incipient point of net vapor generation (IPNVG) in narrow rectangular channel was presented. Flow direction in the channel was vertical upward. The experimental results indicate that the classical correlations of ONB for conventional channels were not suitable for the present narrow rectangular channel. The wall superheat needed to initiate boiling is found to be higher for the same given values of heat and mass flux. The experimental results of IPNVG indicate that the heat flux, triggering net vapor generation in narrow rectangular channel, is litter lower than that calculated by correlations for conventional channels. The relative prediction error of q_{IPNVG} by Griffith model, Saha model and Sun model ranges from -17.9% to +9.6%. A new correlation was developed to predict the ONB in narrow rectangular channel. The proposed correlation predictions agreed well with the experimental data.

Introduction

Two-phase flow boiling in compact channel has attracted increasing interest in recent years. An important research content for the flow boiling in compact channel is to determine the onset of nucleate boiling (ONB) and incipient point of net vapor generation (IPNVG).

ONB marks the boundary between the single-phase and two-phase heat transfer regions. Hsu is the first to postulate the minimum superheat criterion for the ONB in pool boiling [1]. He proposed that the bubble nucleus would grow only if the minimum temperature surrounding the bubble is higher than the saturation temperature of the vapor inside the bubble. Then Sato and Matasumura [2], Bergles and Rohsenow [3]extended Hus's criterion to the flow boiling in conventional channels. Davis and Anderson [4]provided an analytical treatment of the approach of Bergles and Rohsenow [3], and introduced the contact angle as a variable in the prediction of ONB. More recently, Kandlikar [5] numerically computed the temperature at the location of the stagnation point around the bubble. That temperature was used as the minimum temperature in the ONB criterion. McAdems [6] postulated that the heat transfer at ONB is a turning point between single-phase convection and nucleate boiling. No matter by using the single-phase convective correlation or the nucleate boiling correlation, the prediction of heat transfer at the ONB point has the same value. There are many correlations to predict the wall superheat in the boiling incipience region [7,8]. Recently, Ghiaasiaan and Chedester [9] conducted a study on ONB with the tubes of diameters in the 0.1-1mm range. The results showed that the heat flux of ONB in the experiment is higher than the prediction by correlations for conventional channels. A semi-empirical method was proposed to predicting the boiling incipience in microtubes. Hapke investigated ONB in a vertical evaporator pipe with an internal diameter of 1.5 mm [10]. They found that the wall surface superheat in narrow channels is higher than in conventional channels when the ONB occurs. Wu [11] performed experiments in vertical narrow annuli with annular gap sizes of 0.95, 1.5 and 2mm. They found that the heat flux, triggering ONB in narrow annuli, is much lower than that calculated by correlations for conventional channels.

IPNVG is the point at which bubbles can depart from the wall before they suffer condensation. It has been proposed to be either hydrodynamically controlled or thermally controlled. Among the early proposals for thermally controlled departure are those by Griffith [12], Bowring [13], Levy [14]. Levy introduced a hydrodynamically based model, assuming that the bubble detachment is primarily the result of drag (or shear) force overcoming the surface tension force [14]. Saha and Zuber [15] postulated that both the hydrodynamic and the heat-transfer mechanisms may apply.

Literature review shows that although the ONB and IPNVG in conventional channel have been studied extensively, ONB and IPNVG in narrow channel are still under development. In this paper, an experimental study for ONB and IPNVG in narrow rectangular channel was carried out.

1. Experiments setup

1.1 Experimental loop

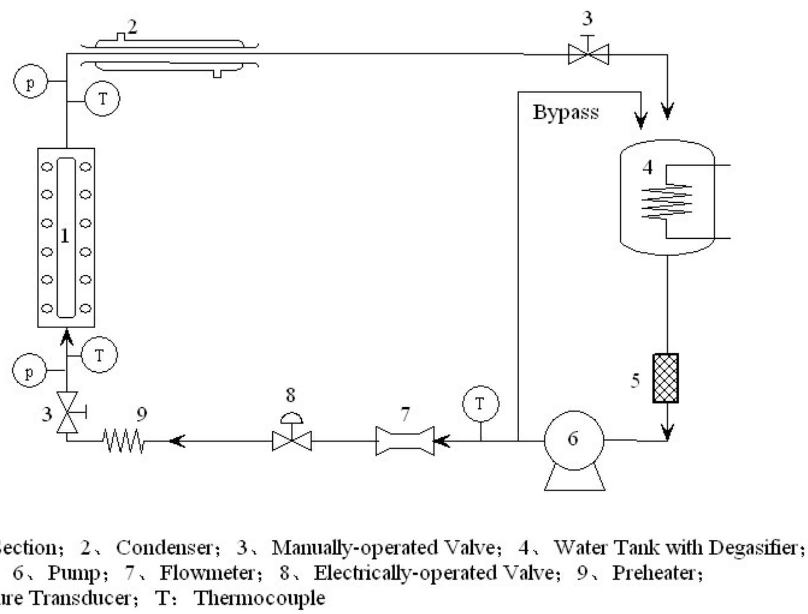


Fig. 1. Schematic diagram of experimental loop.

Table 1. Summary of thermal conditions

S. no.	Parameter	Range
1	p (MPa)	0.12-0.19
2	G (kg/(m^2·s)	290-840
3	q (kW/m^2)	33-184
4	ΔT_{sub} (K)	28-55

The experimental loop is shown schematically in Fig. 1. The flow direction in the test section is vertical upward. The subcooled water is held in the water degassing tank. The tank removes non-condensable solved gas by heating the water up to the saturation temperature. A piston pump drives the deionized water through the facility. The volumetric flow rate is measured with a venturi flowmeter. The water is preheated via a preheater, then directs into the test section. After exiting the test section, the vapor liquid mixture enters a condenser, which returns the water to a single-phase state. Then the water goes back to the water tank. The thermal conditions are shown in Table 1.

1.2 Test section

The schematic diagram of test section is described in Fig. 2. The test section was a rectangular channel with a cross section of 40 mm×2 mm. The length of the channel was 1200 mm. The aspect ratio (α=W/H) was 20. The hydraulic diameter, D_h=$4A_c/P$, was about 3.81mm. The heating plate was made of 0Cr18Ni10Ti stainless steel. Each side of the heating plate had the same thickness of 3 mm. The roughness of the heating plate was less than 3.2 μm. In order to avoid an excess of heating in the edge of channel, the test section had a chamfered edge. By using a 60 kW DC power supply, a large range of heat fluxes were applied to the test section.

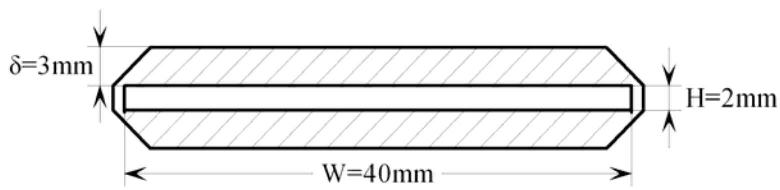


Fig. 2. Schematic diagram of test section.

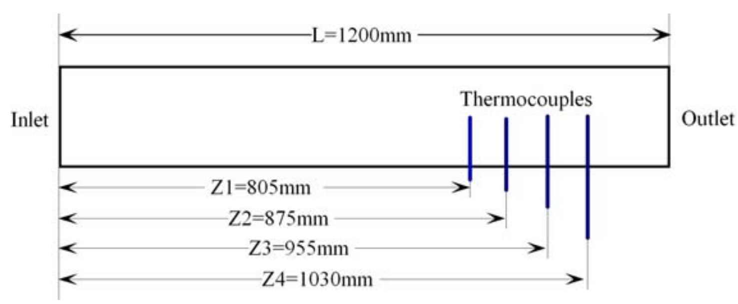


Fig. 3. Placement of thermocouples in test section (axial direction).

Fig. 3 shows the placement of the thermocouples at axial distances of 805, 875, 955, and 1030 mm from the inlet, respectively. The channel was provided with 8 K-type thermocouples at the top and the bottom surfaces. These thermocouples were welded along the outer wall and reinforced by inorganic adhesives. The temperature of inlet and outlet fluid was measured by K-type thermocouples at the inlet and outlet positions.

2. Experimental procedure

Above all, the degassing process was started hours before the experiments. To initiate an experiment, the pump was first turned on and the flow rate was adjusted to the desired value. The pre-heater and temperature controller were then powered up and the fluid inlet temperature was set to the required degree of subcooling. Then the heater power supply was switched on and added heat flux linearly and slowly until ONB occurred at *Z*1 position. The determination of ONB and IPNVG will be discussed in section 4.1. The change rate of heat flux was less than 0.1 kW/m^2 per second. At the same time, the flow rate, temperature, pressure, and power input values were stored using the data acquisition system. The frequency of data capture rate was set as 0.1 Hz. After one experiment run, changed the thermal and heaving condition for additional tests, and then repeated the above procedures.

The outer wall temperatures were measured by thermocouples directly. The frequency of temperature capture rate was set as 0.1 Hz. The length and width of the heating plates are much larger than the thickness. Therefore, the measured outer wall temperatures can be converted to the inner wall temperatures by using the solution of one-dimensional heat conduction if the assumption is allowed that the transient temperature changes are very small.

3. Results and discussion

3.1 Determination of ONB and IPNVG

According to the mechanisms of heat transfer, for single-phase convection, the temperature of wall surface increases linearly by increasing heat flux gradually. Only when the temperature of the liquid near the wall exceeds the saturation temperature and reaches certain superheat, bubbles could generate. The temperature of wall surface keeps almost constant after the occurrence of ONB. Thus, the ONB can be identified as the point at which deviations from single-phase behavior is observed as a sudden change in temperature versus the heat flux. When boiling is first initiated only a limited number of nucleation sites are operating so that a proportion of the heat will continue to be transferred by normal single-phase processes between patches of bubbles. As the surface temperature increases, the number of bubble sites also increases and the area for single-phase heat transfer decreases. Finally, the whole surface is convered by bubble sites, boiling becomes full developed and the single phase component reduces to zero. So the second inflexion of wall temperature versus the heat flux can be indentified as the IPNVG.

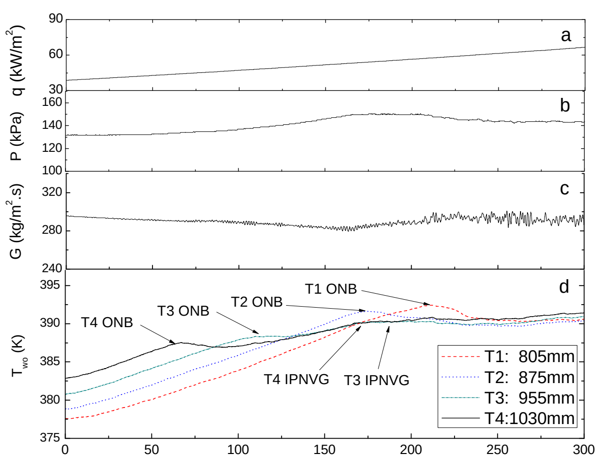


Fig. 4. Variation of the parameters at ONB and IPNVG: (a) heat flux; (b) pressure drop; (c) mass flux; (d) outer. wall temperature.

Fig. 4 shows a sample of the variations of mass flux, pressure drop and outer wall temperature at ONB. As heat flux increases linearly and slowly, there is a sudden drop of wall temperature with the amplitude of 1-3 K at ONB, which is called the temperature hysteresis. The transition of heat transfer mechanism from single-phase forced convection to two-phase flow boiling result in the temperature hysteresis. It is well known that after the boiling incipience, a bubble will nucleate, grow and depart from the active nucleate cavity at the heating wall, and the vaporization causes apparent volume expansion. The pressure drop due to acceleration and friction is increased and the pressure drop due to gravity is decreased. As shown in Fig. 4(b), the outlet pressure increases at first, and then stabilized. That is because the increase of pressure drop due to acceleration and gravity dominates at first, and then the decrease of the gravitational pressure drop is equal to the increase of frictional and accelerated pressure drop. The variation of pressure drop affects the mass flux. The Fig. 4(c) shows the variation of mass flux. The mass flux trend is opposite to the pressure trend. From Fig. 4(d), it can be seen that ONB and IPNVG occurs at the outlet first, and moves upstream gradually with the increase of heat flux. Meanwhile, the wall temperature at ONB and IPNVG gradually increases when the ONB and IPNVG moves upstream.

3.2 Compared to existed correlations

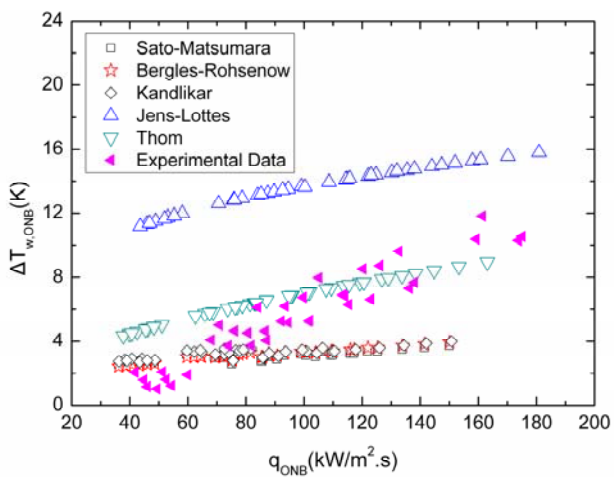


Fig. 5. Comparison between predicted and experimental data of ONB.

Many researchers have carried out researches on ONB and developed many correlations for conventional channels. As indicated in section 1, correlations which proposed by Sato and Matasumura [2], Bergles and Rohsenow [3] and Kandlikar et al [5] are based on Hsu's model [1].

Based on the model of McAdems [6], correlations of Jens-Lottes [7] and Thom [8] are used to calculate wall superheat at ONB.

In order to predict ONB, the above correlations should be used simultaneously with an equation for the single-phase convective heat transfer. The heat transfer coefficient is obtained from widely used correlations such as Dittus and Boelte [16].

Fig. 5 shows the relation between heat flux and wall superheat at ONB obtained from the experimental data and the above five correlations. As shown in Fig. 5, the calculated heat flux and wall superheat based on Hsu's model [1] are much higher than the calculated data based on McAdems's model [6]. There are two reasons for this result. First, Hsu's model [1] assumes that above the superheat required to initiate nucleation, a finite range of cavities can become active sites. In fact, most of the heating surface fails to fit this feature. Second, McAdems's [6] model assumes that, no matter by using the single-phase convective correlation or the nucleate boiling correlation, the prediction of heat transfer at ONB has the same value. The heat transfer correlations used to calculate the wall superheat at ONB were empirical. Compared with the classical correlations by Sato and Matasumura [2]; Bergles and Rohsenow [3]; Kandlikar[5], a satisfying agreement exists only for heat fluxes of about 60-80 kW/m^2. The wall superheat needed to initiate boiling is found to be higher for the same given values of heat and mass flux. The same trend for boiling incipience in minichannels is reported by Hapke [10]; Claudi [17]. They consider that the thermocapillary force in minichannels, which would suppress the bubbles that tend to form on the wall cavities, relates this increase. Li and Cheng [18] found that the large mass flux might suppress the bubble nucleation in the microchannels. The wall superheat calculated by correlation of Jens-Lottes [7] is much higher than experimental data. The wall superheat predicted by correlation of Thom [8] is higher than the experimental data in low heat flux. It is shown that the correlations for conventional channels cannot be used in narrow rectangular channel. A new correlation for predicting the ONB in narrow rectangular channel must be developed to predict the experimental data.

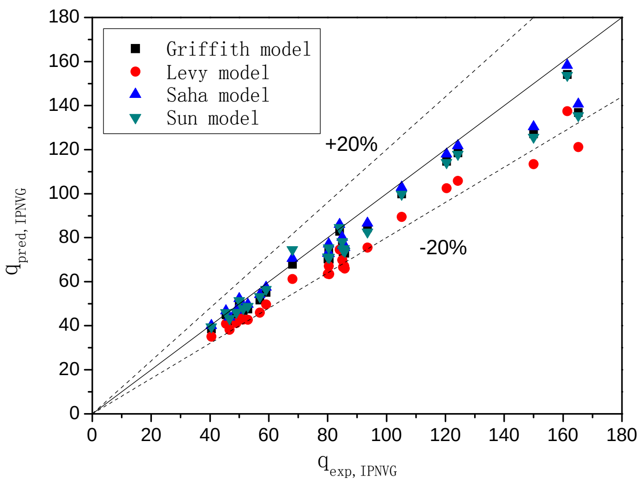


Fig. 6. Comparison between predicted and experimental data of IPNVG

Fig.6 illustrate the comparisons of the predictions by Griffith model [12], Levy model [14], Saha model [15] and Sun model [19] with the experimental data respectively. It can be found that the calculated results of IPNVG by Levy model [14] are lower than the other model. The relative prediction error of q_{IPNVG} by Griffith model [12], Saha model [15] and Sun model [19] ranges from -17.9% to +9.6%. So these models are suitable for the present narrow rectangular channel.

3.3 Experimental correlation for ONB

In this section, a new correlation is developed for predicting the ONB in narrow rectangular channel. The bubbles develop from the heated wall are influenced by heat flux. Forced convection of single-phase liquid also has a strong influence on this process. Therefore, the factors affecting the wall superheat at ONB may be the mass flux *G*, heat flux *q*, the system pressure *p*, and the gap size *H*. Thus, the wall superheat of ONB can be expressed by the following type of function.

$$\Delta T_{ONB} = T_{wi} - T_{sat} = f\left(G, H, p, q\right) \tag{1}$$

Dimensionless parameters are introduced to develop the correlation. The influence of the mass flux and the gap size on flow boiling heat transfer in narrow channels can be expressed by the Reynolds number[20]. Basing on the gap size *H* as the characteristic dimension, Reynolds number *Re* can be defined as follows.

$$\mathrm{Re} = \frac{GH}{\mu_l} \tag{2}$$

Dimensionless heat flux is defined as

$$q^* = \frac{q}{Gh_{\lg}} \tag{3}$$

Dimensionless wall superheat is defined as

$$\Delta T_w^{\ *} = \frac{\Delta T_w}{T_{sat}} = \frac{T_{wi} - T_{sat}}{T_{sat}} \tag{4}$$

The density ratio ρ_g/ρ_l reflects the effect of the pressure. The unit of T used in correlation (4) is ℃.

By curve fitting the experimental data, $\Delta T^*_{w,ONB}$ can be expressed as follows.

$$\Delta T^*_{w,ONB} = 0.05\,\mathrm{Re}^{1.156}\left(\frac{\rho_g}{\rho_l}\right)^{-0.413} q^{*\ 1.321}_{ONB} \tag{5}$$

In most case, with the given inlet pressure, inlet temperature, channel length and mass flux, the wall temperature and heat flux at ONB need to be determined. Therefore, an iterating process is required. The wall temperature can be calculated by heat transfer equation.

$$T_{wi}(z) = T_l(z) + \frac{q}{h_l(z)} \tag{6}$$

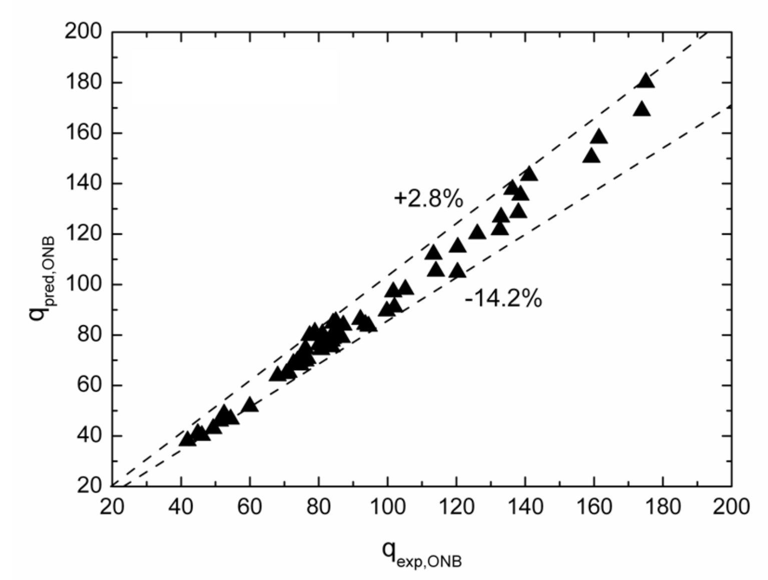
Where $h_l(z)$ can be obtained by a widely used turbulent convective heat transfer correlation [16].

$$Nu = \frac{h_l D_h}{\lambda} = 0.023 Re^{0.8} Pr^{0.4} \tag{7}$$

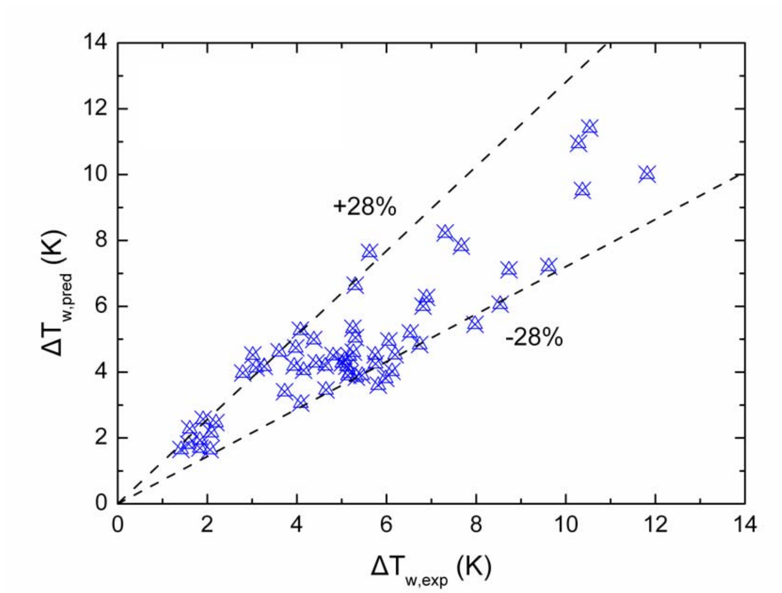
Here $T_l(z)$ is the local mean liquid temperature , and can be calculated by:

$$T_l(z) = T_{l,in} + \frac{q}{GA_c C_p} \cdot P \cdot z \cdot \tag{8}$$

The performance of the correlations is shown in Fig. 7(a) and Fig. 7(b). The figure suggests that the data agree well with the prediction. The relative prediction error of q_{ONB} ranges from -14.2% to +2.8%. The relative prediction error of $\Delta T_{\mathrm{w,ONB}}$ ranges from -28% to +28%.



(a)



(b)

Fig. 7. Comparison between predicted and measured data under static conditions: (a) qONB, (b) $\Delta T_{\mathrm{w,ONB}}$

4. Conclusions

An experimental study into ONB and IPNVG in a rectangular narrow channel was carried out. The correlations of ONB for conventional channels were not suitable for the present narrow rectangular channel. A new correlation for predicting the ONB in narrow rectangular channel was developed.

The proposed correlation predictions yielded good agreement with the experimental data. The relative prediction error of q_{IPNVG} by Griffith model [12], Saha model [15] and Sun model [19] ranges from -17.9% to +9.6%.These models are suitable for predicting IPNVG at the present narrow rectangular channel.

5. References

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