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Onset of Nucleate Boiling for subcooled flow through a one-side heated narrow rectangular channel

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ABSTRACT

Onset of Nucleate Boiling (ONB) is an important limit in the design of nuclear reactors and most flow boiling systems. Preventing the ONB occurrence protects systems from unfavorable thermal hydraulic events, such as Onset of Flow Instability (OFI) and Critical Heat Flux (CHF). In this study, a simultaneous measurement and visualization experiment on the ONB is carried out for a narrow rectangular channel heated from one side. The rectangular channel has a thickness of 2.35 mm, width of 54 mm, and length of 560 mm. The experiment is conducted for upward flow direction under nearly atmospheric pressure. The inlet conditions are chosen to cover a wide range of operational conditions: inlet temperature (35–65 °C) and mass flow rate (0.015–0.130 kg/s). Based on the inlet flow conditions, a uniform heat flux (50–800 kW/m^2) is applied in a stepwise manner to the heated surface. The slope of the wall temperature versus the heat flux curve decreases at the ONB point. Ten thermocouples (TCs) are installed into the heated block to measure the wall temperature distribution. On the other hand, a high-speed camera is used to visualize the ONB point and compare it with the wall temperature deviation point. Based on the experimental data, the influence of mass flow rate and inlet temperature on the bubble behavior along the test section is observed. The results show a new trend for the influence of inlet temperature on the superheated temperature of the wall at the ONB point. A similar trend is observed using CFX analysis for the test section. The present results are compared with other experimental studies conducted by different research institutes, with different ONB heat flux correlations such as in the studies of Jens and Lottes (1951), Bergles and Rohsenow (1964), and Thom et al. (1965). The correlations underestimate the experimental results. Therefore, a new correlation is developed to predict the ONB heat flux, which has good agreement with the experimental data within an error of ±16.5%.

1. Introduction

Onset of Nucleate Boiling (ONB) is defined as the first location on the heated surface where a bubble can exist. If the bubble detaches from the surface while the average bulk temperature remains below the saturation value, this phenomenon is called subcooled boiling. Although subcooled boiling is highly efficient for a convective heat transfer process, the two-phase flow is undesirable in the nuclear research reactor. An accurate estimation of the ONB incipient is very important for the safety of research reactors. The safety is compromised due to the fluctuation in the reactivity because of a void fraction feedback, which arises even if a small amount of bubbles exists in the reactor coolant channel. The generated bubbles may aggregate on the heated surface and form a vapor film, which prevents the coolant from reaching the heated surface and hence causes fuel damage. Therefore, preventing ONB can avoid any unfavorable events or accidents involving flow instability or fuel damage.

Several studies were carried out to analyze the ONB incipient on the heated surfaces for different geometries, flow conditions, and heating conditions (Hsu, 1962; Davis and Anderson, 1966; Sudo et al., 1986). Several mathematical equations were proposed to estimate the ONB heat flux and the wall-superheated temperature during the initiation of ONB. The correlations that were proposed by Bergles and Rohsenow (1964), Jens and Lottes (1951), and Thom et al. (1965) are widely used; they are expressed in Eqs. (1)–(3) as follows, respectively

$$\Delta T_{ONB} = \frac{5}{9}\left[\frac{q''_{ONB}}{1082P^{1.156}}\right]^{\frac{P^{0.0234}}{2.16}} \quad (1)$$

$$\Delta T_{ONB} = 25\left[\frac{q''_{ONB}}{10^6}\right]^{0.25} \exp\left(-\frac{P}{6.2}\right) \quad (2)$$

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Nomenclature

A_h	Heated area, [m^2]
C_p	Heat capacity, [J/kg/K]
D_h	Hydraulic diameter, [m]
L_h	Heated length, [m]
$\dot{m}$	Mass flow rate, [kg/s]
h	Convective heat transfer coefficient, [$W/m^2/K$]
Gz	Graetz number = $\frac{RePrD_h}{z}$
Nu	Nusselt number
P	Pressure, [bar]
Pr	Prandtl Number = $\frac{\mu C_p}{k}$
Q	Power, [W]
Re	Reynolds number = $\frac{\rho v D_h}{\mu}$
T	Temperature, [°C]
k	Thermal conductivity, [W/m/K]
q''	Heat flux, [W/m^2]
t	Thickness, [m]
z	Distance in the axial direction, [m]

Greek symbols

μ	Viscosity, [kg/s/m]
ρ	Density, [kg/m^3]

Subscripts

L	Laminar
ONB	Onset of Nucleate Boiling
T	Turbulent
b	Bulk
e	Electrical
i	inlet
l	Liquid
o	outlet
sat	Saturation
sub	Subcooled
th	Thermal
w	Wall

$$\Delta T_{ONB} = 22.65 \left[\frac{q''_{ONB}}{10^6}\right]^{0.5} \exp\left(-\frac{P}{8.7}\right) \quad (3)$$

Different experimental methods have been used to estimate ONB occurrence such as pressure drop measurements, wall temperature measurements, local heat transfer coefficient, and direct visualization. Celata et al. (1997) studied the ONB experimentally for a high liquid velocity. They plotted the theoretical single-phase diabatic to adiabatic pressure drop ratio versus the heat flux together with the experimental data, and they concluded that the ONB is the point at which the theoretical single-phase curve deviates from the experimental data. Similarly, for high-subcooled flow boiling, Tong et al. (1997) defined the inflection point of the pressure drop curve versus the heat flux to be the ONB incipient point. Ghiaasiaan and Chedester (2002) argued that the boiling starts when the measured pressure drop line deviates from the calculated one of the single-phase flow. However, Wang et al. (2014) noticed that the point at which the pressure drop deviates is not in accordance with the ONB incipient.

Several researchers identified the ONB incipient via measuring the axial wall temperature distribution. Hapke et al. (2000) used this technique for a mini-channel flow system. The wall temperature increases from the inlet toward the outlet of the channel and reaches a minimum degree of superheated, which is sufficient to produce bubbles at the heated surface. Thereafter, the wall temperature remains constant and/or decreases slowly, as the coolant temperature is almost constant within the saturated value. Su et al. (2005) conducted research to study the boiling incipient for a forced flow in narrow channels, and they specified the ONB point as the first turning point of the wall temperature versus the axial location curve. This method is used for different flow conditions and different flow geometries. Siddiqui et al. (2010) used an annular thermosiphon test section to study the boiling incipient for a vertical upward flow. They concluded that the ONB incipient mainly depends on the heat flux and wall temperature distribution that can meet the superheat requirements to produce bubbles on the heated surface. Therefore, the geometry profile plays an important role for the ONB occurrence, which controls the heat flux distribution. Ahmadi et al. (2009) conducted an experimental study on the ONB for an annular flow. They used two methods to identify the ONB incipient; the first one is the deviation point of the heat transfer characteristic at a fixed position, and in the second method, they investigated the wall temperature variation with the increase in the heat flux. On the other hand, at the same heat flux with increasing mass flux, the wall temperature remains almost constant in the two-phase flow region. However, it decreases in the single-phase region (Bang et al., 2004). This is another way to identify the ONB incipient. Recently, Castiglione et al. (2016) experimentally observed the ONB within the internal combustion engine cooling system using the inlet and outlet coolant pressure and temperature, wall temperature deviation with the reduction in the mass flow rate. At constant power, the temperature linearly increases as the mass flow rate reduces in the single-phase flow, however and after the ONB, the temperature rapidly increases with the reduction in the mass flow rate. In addition to the aforementioned methods for identifying the ONB incipient, the variation in the heat transfer characteristics with the mass flux can be used to determine the ONB incipient. The heat transfer coefficient deceases when the mass flow rate decreases in the single-phase flow. However, after the ONB, the heat transfer suddenly increases as the mass flow rate diminishes. Recently, Wang et al. (2014) used the four different methods to identify the ONB incipient in order to investigate the consistency of the results using the following different approaches: a) the variation in the pressure drop with the mass flux, b) the variation in the pressure drop with the heat flux, c) the variation in the heat transfer coefficient with the mass flux, and d) the variation in the heat transfer coefficient with the heat flux. The authors concluded that there are no significant differences among these methods. From literature, it is evident that the pressure drop measurements can be used to determine the ONB point for high mass flow rates. However, the wall temperature measurement method shows the ONB incipient more accurately, especially for low mass flow rates.

The influences of the inlet pressure, inlet temperature, mass flux, and heat flux on the ONB incipient were observed in the previous studies. There is no significant effect of the inlet pressure on the ONB point. Similarly, no clear explanation is given for the effect of inlet temperature variation. On the other hand, the ONB parameters are directly proportional to the mass flux. These variables directly provide a macroscopic view for the ONB behavior on the heated surface. However, visualization and digital photography using high-speed cameras are used to inspect the bubble dynamics at the microscopic scale for parameters such as bubble diameter, nucleation site density, and bubble generation frequency. Yin