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ONB, OSV, and OFI for subcooled flow boiling through a narrow rectangular channel heated on one-side

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ABSTRACT

This paper presents an experimental investigation of the thermal hydraulic thresholds of the subcooled boiling instability in forced convective flow, such as the onset of nucleate boiling (ONB), the onset of significant void (OSV), and the onset of flow instability (OFI). The experiment was constrained to water flows in the upward direction under atmospheric pressure through a narrow rectangular channel heated on one-side having a gap of 2.35 mm, a width of 54 mm, and length of 566 mm. The heated length and width were 300 mm and 50 mm, respectively. The experiment was performed over a wide range of inlet temperature (35–65 °C), mass fluxes (118–1400 kg/(m^{2}s)), and heat fluxes (50–650 kW/m^2). Two experimental methods were adopted to achieve and identify the ONB, OSV, and OFI: (1) the constant mass flow rate approach and (2) the constant heat flux approach. The results showed consistency between the two methods. The ONB was identified through visualized monitoring using a high-speed camera and by using the slope of the wall temperature deviation method. The ONB was predicted by Jens and Lottes' correlation. The OSV was detected using the high-speed camera and the wall temperature–heat flux curve. Based on the experimental method, the OFI was identified using pressure drop and inlet pressure fluctuation. The data showed that the OSV and OFI could occur at similar points based on the experimental conditions. Furthermore, the OSV models, such as the modified Bowring model and Saha and Zuber's model, can be used to predict the OFI. Additionally, some OFI correlations showed good agreement with the present data. However, many other correlations underestimated the OFI results, which might have been a result of differences in the experimental parameters. Therefore, a new empirical correlation that predicted the present data and other experimental data within very good accuracy was suggested. The present study describes and discusses the influence of the experimental parameters; inlet subcooling, mass flow rate, and the imposed heat flux on the ONB, OSV, and OFI incipience.

1. Introduction

In the past decades, the use of subcooled flow boiling in narrow rectangular channels in compact volume systems has significantly grown, owing to its high heat transfer capabilities. Supercomputer systems, nuclear research reactors, heat exchangers, fusion energy, and many other applications are examples of compact volumes [1,2]. The subcooled flow boiling region lies between two distinct thermal hydraulic behaviors; onset of nucleate boiling (ONB) and onset of flow instability (OFI). Understanding and identifying these behaviors is very important for reliable and safe operation of any two-phase flow system. In subcooled flow boiling, the coolant enters the channel as a single-phase liquid with a highly subcooled temperature. As illustrated in Fig. 1, as the coolant flows through the channel, the bulk and wall temperatures increase. Once the wall temperature exceeds the saturation temperature of the coolant [3], nucleation occurs within small activated cavities on the heated surface. This phenomenon is known as the ONB, and it is the threshold point between single-phase and two-phase flow. The ONB is identified using wall temperature measurements and pressure drop monitoring; it is the point where the slope of the pressure drop-mass flow rate curve deviates from the single-phase line. In addition, the ONB is identified as the intersection point between single-phase and two-phase heat transfer on the wall temperature-heat flux curve. ONB is local phenomenon on the heated surface, which depends on the local thermal hydraulic parameters, regardless to geometry shapes of flows. After ONB, the generated bubbles condense directly when they are detached from the wall owing to the high degree of subcooling in the liquid core. However, if the departing bubbles survive condensation, the void fraction starts growing significantly [4], and a fully developed

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Nomenclature

A_h	heated area [m^2]
A_s	cross sectional area [m^2]
C_p	heat capacity [J/(kg K)]
D_h	hydraulic diameter [m]
G	mass flux [kg/(m^2 s)]
h	convective heat transfer coefficient [W/(m^2 K)]
L_h	heated length [m]
$\dot{m}$	mass flow rate [kg/s]
Nu	Nusselt number
P_h	heated perimeter
P_w	wetted perimeter
P	pressure [bar]
Pe	Peclet number = $PrRe$
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]

Greek symbols

μ	viscosity [kg/(s m)]
ρ	density [kg/m^3]

Subscripts

ONB	onset of nucleate boiling
OSV	onset of significant void
OFI	onset of flow instability
b	bulk
e	electrical
i	inlet
l	liquid
o	outlet
sat	saturation
sub	subcooled
th	thermal
TC	thermocouple
w	wall

nucleate boiling regime dominates. This phenomenon is known as the onset of significant void (OSV) or net vapor generation (NVG). Beyond the OSV, the heat transfer coefficient achieved its highest value, whereas the heated surface temperature remains constant and/or slightly reduced in some cases. The void fraction distribution affects the flow instability, heat transfer rate, and pressure drop of the flow systems. Therefore, with further increase in the void fraction, the mass and heat transfer conditions become unstable [5]. This phenomenon is called the onset of flow instability (OFI). The OFI is the restricted threshold point for two-phase flow for reliable and safe operation, especially if flow occurs in a narrow rectangular channel, to avoid any undesirable events, such as critical heat flux (CHF). Additionally, the OFI is defined as the minimum point on the pressure drop-mass flow rate curve [6], as illustrated on Fig. 2. The OFI is controlled by three components of pressure drop: the potential pressure drop, which stabilizes the system; the momentum pressure drop; and the friction pressure drop, which destabilize the system [7].

Several experimental and numerical studies have been performed to investigate the ONB behavior in conventional and narrow channels [8–12]. Based on the findings of these studies, various correlations have been proposed to estimate the ONB, such as the Bergles and Rohsenow [9], Jens and Lottes [10], and Thom et al. [11] correlations, as listed in Eqs. (1), (2) and (3), respectively.

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

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

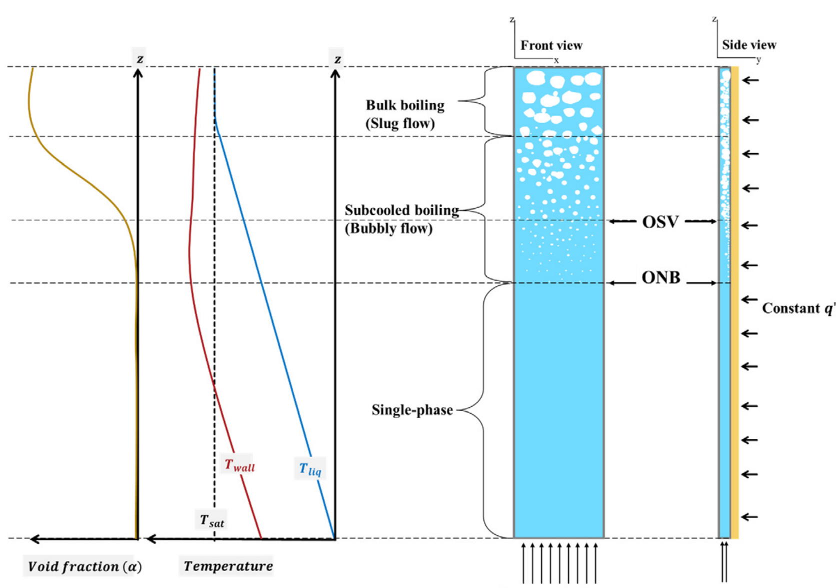

Fig. 1. Transition process from single-phase to two-phase flow.