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Research Paper

Pressure drop for highly subcooled water flow boiling under high heat and mass fluxes

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HIGHLIGHTS

- Subcooled boiling pressure drop was investigated experimentally under extreme heating conditions.
- A number of existing correlations for subcooled boiling pressure drop were assessed.
- A new correlation was proposed to predict subcooled boiling pressure drop for high-heat-flux applications.

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ABSTRACT

Pressure drop is one of the most important thermal-hydraulic issues for the cooling system of high heat flux components, such as the plasma-facing divertors in fusion reactors. Experimental studies were carried out to investigate the pressure drop of highly subcooled water flow boiling in a vertical circular tube (d = 9 mm, L_H = 400 mm) under high heat and mass fluxes. The operating parameters covered the range of heat fluxes (0–12.5 MW/m^2), mass fluxes (6000–10,000 kg/m^2 s), pressures (3–5 MPa), and liquid subcooling (6–224 °C). The parameter effects on subcooled boiling pressure drop were discussed. It was observed that subcooled boiling pressure drop increased with increasing heat and mass fluxes but decreased with increasing pressure. Available correlations for subcooled boiling pressure drop were compared with the experimental data. The results indicate that these correlations cannot well predict our data mainly due to the variations in operating parameters and working fluids. Therefore, a new correlation is proposed to calculate subcooled boiling pressure drop for high-heat-flux applications. The new correlation is presented as a function of boiling number, Jacob number, and density ratio. The new correlation predicts the experimental data within an accuracy of ±20%.

1. Introduction

Subcooled flow boiling has received considerable attention in high-heat-flux engineering applications, such as plasma facing components of fusion reactors, core cooling of pressurized water reactors, engine cooling, and high power electronic applications [1,2]. For example, the plasma-facing divertors in the International Thermonuclear Experimental Reactor (ITER) can be subjected to extremely high-heat-flux loads with typical value of 10 MW/m^2. Previous studies have proved that subcooled water flow boiling can accommodate such high heat fluxes provided that the mass flux and subcooling of the coolant are high enough [3,4]. Therefore, it is essential to acquire the knowledge of highly subcooled water flow boiling under high heat and mass fluxes for thermal hydraulic designs.

In recent years, a number of studies have been performed on the heat transfer [5–8] and critical heat flux (CHF) [9–11] characteristics of subcooled flow boiling because the thermal hydraulics of subcooled-water-cooled components are generally limited by the two constraints. However, pressure drop, one of basic issues in thermal-hydraulic analysis, is not given enough consideration, and relevant studies are still inadequate, especially under high heat and mass fluxes.

Although a number of experimental studies have been devoted to study two-phase pressure drop under various conditions, only a limited amount of experiments have been performed on subcooled boiling pressure drop, especially for highly subcooled flow boiling at high heat and mass fluxes conditions. The high heat flux has strong effects on heat transfer pattern and flow distribution, and thus significantly affects subcooled boiling pressure drop. The

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Nomenclature

Bo	boiling number
c_p	specific heat, J/kg K
d	diameter, m
f	friction factor
G	mass flux, kg/m^2 s
h	heat transfer coefficient, kW/m^2 K
H	enthalpy, J/kg
H_{fg}	latent heat of vaporization, J/kg
Ja	Jacob number
L	length, m
M	mass flow, kg/s
Nu	Nusselt number
p	pressure, MPa
Δp	pressure drop, kPa
q	heat flux, MW/m^2
Re	Reynolds number
T	temperature, °C
x	vapor mass quality

Greek symbols

α	void fraction
η	thermal efficiency
λ	thermal conductivity, W/m K
ρ	density, kg/m^3

Subscripts

a	accelerational
ad	adiabatic
b	bulk
cal	calculated
exp	experimental
f	frictional
g	gas, gravitational
H	heated
i	inlet
l	liquid
o	outlet
ONB	onset of nucleate boiling
sat	saturation
sb	subcooled
sub	subcooling
th	thermodynamic
tot	total

subcooling of bulk liquid is so high that the void fraction is low all through the flow channel. Moreover, the bubble behaviors (such as bubble generation, sliding, and coalescence) tend to be more complicated in the interaction between the strong heating effect and high subcooling. Therefore, the pressure drop of highly subcooled flow boiling at high heat fluxes is different from that of conventional two-phase flow. Although there are a large number of correlations for two-phase pressure drop, the correlations for subcooled boiling pressure drop are still unsatisfactory indeed, especially under strong heating conditions (10 MW/m^2 level).

Fig. 1 demonstrates a general feature of pressure drop of subcooled flow boiling in a uniformly heated tube under constant inlet conditions. The pressure drop curve can be generally divided into three regions: single-phase, parting boiling, and fully developed boiling (FDB). In the single-phase region, pressure drop decreases with increasing heat flux due to a reduction in fluid viscosity. The region of partial boiling region begins at the point of onset of nucleate boiling (ONB), where bubble occurs near the exit of the tube. With increasing heat flux, more bubbles occur in the downstream section, which balances the decreased pressure drop of upstream single-phase flow. The pressure drop begins to increase gradually when the bubble effect prevails. Previous studies have indicated that the minimum point of the pressure drop curve does not coincide exactly with the ONB [12]. Generally, the ONB occurs prior to the minimum point of pressure drop. The region of fully developed boiling starts at the point of net vapor generation (NVG), where bubble departs from the wall. The pressure drop increases sharply due to an increasing void fraction, until the tube is burned out at the CHF point.

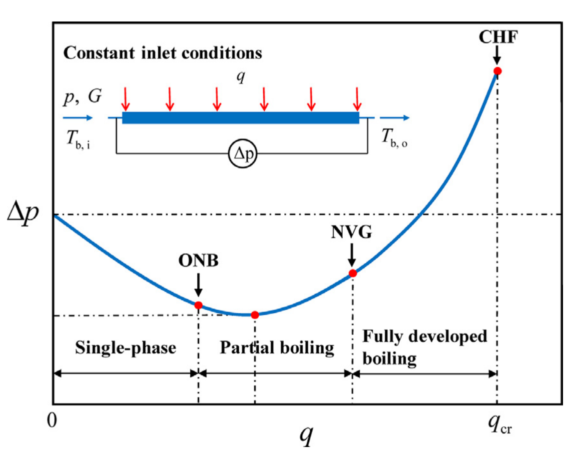

Fig. 1. General features of pressure drop for subcooled flow boiling in heated channels.

2. Literature survey

A pressure drop multiplier Φ^2 (Eq. (1)) is commonly used to correlate experimental data in the studies of subcooled boiling pressure drop. The Φ^2 is the ratio of subcooled boiling pressure drop to adiabatic single-phase pressure drop at the same mass flux. Obviously, the Φ^2 is equal to 1 when heat flux is zero.

$$\Phi^2 = \frac{\Delta p}{\Delta p_{ad}} \tag{1}$$

In the open literature, several studies have been conducted on subcooled boiling pressure drop. The researchers measured subcooled boiling pressures drops under certain conditions and developed several empirical correlations, in which the pressure drop multiplier Φ^2 was commonly used, as shown in Table 1.

Reynolds [13] was one of the earliest researchers to measure subcooled boiling pressure drop. His experiments was conducted in a horizontal tube (d = 9.5 mm). The parameter ranges were q = 0.3–0.95 MW/m^2, G = 2100–3000 kg/m^2 s, and p = 0.31–0.69 MPa. A correlation was obtained and expressed as $\Phi^2 = \cosh[(14.51q + 1.2)L_{sb}/L_{sat}]$. However, this equation would yield large prediction error at high heat fluxes.

Owens–Schrock [14] studied the pressure drop of subcooled water flow boiling in two small vertical tubes. They developed an empirical correlation, in which the total pressure drop data were included, i.e. the frictional, accelerational, and gravitational pressure drops, as presented in Table 1.