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Subcooled flow boiling heat transfer of water in a circular tube under high heat fluxes and high mass fluxes

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ABSTRACT

Subcooled flow boiling under high heat flux and high mass flux (HHHM) conditions is commonly encountered in nuclear power engineering, for example, the heat removal technology for divertors in the International Thermonuclear Experimental Reactor (ITER). In the present study, subcooled flow boiling heat transfer of water was carried out experimentally in a uniformly heated vertical circular tube with an inner diameter of 9.0 mm under HHHM conditions. Heat transfer coefficients were presented from single-phase convection to fully developed nucleate boiling. The effects of parameters, including mass flux (G = 6000, 8000, and 10,000 kg/m^2 s), heat flux (q = 5–12.5 MW/m^2), system pressure (P = 3, 4.2, and 5 MPa), and thermodynamic vapor quality (x_{th} = −0.5 to −0.03), were discussed. Many previous heat transfer correlations available in the literature were assessed against our experimental data. Most of these correlations cannot predict the experimental data very well. A modified Chen correlation was developed, which predicted the total heat transfer coefficients with a mean average error of 1.11% and a root-mean-square error of 6.45%. A modified Lahey model was proposed to determine the contribution of nucleate boiling in the total heat transfer coefficient under HHHM conditions.

1. Introduction

Subcooled boiling is characterized by the appearance of bubbles initiating from the heater surface while the bulk temperature is still below the saturation. During subcooled flow boiling, a high heat flux can be obtained with a relatively low wall superheat. Compared to saturated flow boiling, subcooled boiling has higher heat transfer efficiency and better critical heat flux (CHF) performance, which have been confirmed by many previous experimental investigations [1,2]. As a result, subcooled boiling has a wide range of industrial applications, especially in nuclear power reactors.

In recent years, the subcooled boiling under HHHM conditions has been attracting much interest owing to the heat removal technology for divertors in the International Thermonuclear Experimental Reactor (ITER). These divertors can be subjected to extremely high-energy fluxes of up to 10 MW/m^2 from the plasma. Under the current design, subcooled water is used as a coolant for the ITER divertors, and various flow configurations have been proposed, for example, twisted-tape inserts in circular channels and hypervapotron for rectangular channels [3–5]. Although the actual cooling process in these configurations is much more complex, the fundamental mechanism of heat transfer is subcooled flow boiling of water.

Fig. 1 illustrates a typical pattern of subcooled flow boiling under HHHM conditions. The location A with occurrence of initial bubbles denotes the onset of nucleate boiling (ONB). The location B is called the onset of significant void (OSV), where the amount of vapor increases significantly. The location C is known as the fully developed boiling (FDB), where nucleate boiling is fully developed, and the wall temperature almost remains constant. The region between A and C is called the partially boiling (PB) which is the transitional region between the single phase (SP) and FDB. The location D is known as the departure from nucleate boiling (DNB), where the heating surface is covered by too much bubbles, and the wall temperature increases dramatically because of a sharp increase in heat-transfer resistance. In this study, the heat transfer before DNB is focused, especially the heat transfer correlations in the regions of PB and FDB.

In the open literature, many correlations have been proposed for subcooled water flow boiling heat transfer over a wide range of conditions. These correlations serve a useful purpose in the corresponding engineering applications and can be broadly classified into two categories: empirical correlations and mechanism-based correlations. The empirical correlations are usually obtained from

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Nomenclature

Bo	boiling number
d	diameter, m
f	friction factor
F	enhancement 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
L_{eff}	effective heating length, m
M	mass flow, kg/s
Nu	Nusselt number
P	pressure, MPa
Pr	Prandtl number
q	heat flux, MW/m^2
Re	Reynolds number
S	suppression factor
T	temperature, °C
ΔT_b	$T_w - T_b$, °C
ΔT_{sat}	$T_w - T_{sat}$, surface superheat, °C
ΔT_{sub}	$T_{sat} - T_b$, liquid subcooling, °C
x_{th}	thermodynamic vapor quality

Greek symbols

η	thermal efficiency, %
λ	thermal conductivity, W/(m K)
μ	dynamic viscosity, kg/(m s)
ν	kinematic viscosity, m^2/s
ρ	density, kg/m^3
σ	surface tension, N/m

Subscripts

b	bulk
cal	calculated
exp	experimental
fc	forced convection
fdb	fully developed boiling
g	gas
i	inner, inlet
l	liquid
nb	nucleate boiling
o	outer, outlet
ONB	onset of nucleate boiling
OSV	onset of significant void
pb	pool boiling
sat	saturation
sp	single-phase
sub	subcooling
tp	two-phase
w	wall

the fitting of subcooled boiling curves and give an explicit relationship between several parameters, for example, $q = f(\Delta T_{sat})$. However, the application ranges of these empirical correlations are usually limited, and few of them can be consistent with the ITER's requirement. Therefore, they cannot be applied in new situations without further assessments. The mechanism-based correlations attempt to describe the behavior of bubbles and try to connect the macroscopic boiling phenomena with the microscopic process of heat and mass transport. However, the last few decades have not witnessed much success of these correlations developed by various models due to the complexity of boiling phenomenon.

Table 1
Experimental conditions.

Experimental conditions	Characteristics
Heating mode	Electrically heated
Heating power (preheater)	<430 kW
Heating power (test section)	<180 kW
Heat flux	5–12.5 MW/m^2
Inlet bulk temperature	50–200 °C
Mass flux	6000–10,000 kg/(m^2 s)
Pressure	3–5 MPa

Hata et al. [6–8] systematically measured the steady state nucleate boiling heat transfer of subcooled water flow boiling under HHHM conditions in both horizontal and vertical circular tubes. A number of FDB heat transfer correlations were compared with their experimental data. Empirical heat transfer correlations for FDB were derived from corresponding boiling curves.

El-Morshedy and Hassanein [9,10] developed a mathematical model to simulate the thermal hydraulics of the ITER divertor module under conditions of steady and transient states. The Chen correlation [11] was extended to calculate the heat transfer coefficient in subcooled boiling. Their model was validated by experimental data performed for both plain and twisted-tape coolant channel mockups during both steady and transient states.

Ying et al. [12] addressed a 3D CFD simulation to study the subcooled flow boiling heat transfer with hypervapotron configurations for the ITER first wall designs. They used the Bergles–Rohsenow correlation to mark the transition from forced convection to nucleate boiling and the Thom correlation for the prediction of nucleate boiling heat flux.

Kaya et al. [13] studied the boiling heat transfer of water in microtubes at high mass fluxes. In their experiments, ultra-high heat flux (>100 MW/m^2) was obtained at high mass fluxes (>10,000 kg/m^2 s). They also discussed the effects of mass flux, heat flux, local quality, and tube diameter on heat transfer coefficients. Cikim et al. [14] studied the flow boiling in microtubes with cross-linked surface coatings at mass fluxes of 5000 and 20,000 kg/(m^2 s). They observed that heat transfer performance was significantly improved by the porous structure.

Although many studies have been conducted on the subcooled water flow boiling under HHHM conditions, most of them were carried out experimentally in mini or micro channels or by numerical simulations. Experimental studies on the subcooled water flow boiling in conventional channels under HHHM conditions are still insufficient due to rather high experimental requirements, mainly the large heating capacity (typically 1 MW) and high pumping capacity (typically 5000 kg/h). In this study, we investigated the heat transfer of subcooled water flow in a uniformly heated vertical circular tube under the parameter conditions required by the ITER. The experimental conditions are shown in Table 1. The objective of this study is to develop a database, assess the existing heat transfer correlations against our experimental data, and then propose a new correlation for subcooled water flow boiling under HHHM conditions.

2. Literature review on subcooled flow boiling heat transfer correlations

2.1. Empirical heat transfer correlations for FDB

The empirical heat transfer correlations for FDB are generally obtained from a curve fitting method. This type of correlation usually gives an explicit functional relationship between the wall superheat and parameter factors, in the form of $\Delta T_{sat} = f(q, P, G,$