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Experimental study of subcooled flow boiling heat transfer of water in a circular channel under one-side heating conditions

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ABSTRACT

Heat transfer experiments on subcooled water flow boiling were carried out in a vertical upward circular channel, which was set off-center in a rectangular nickel block. Particular attention was paid to the heat transfer of water under high and heat fluxes and high mass fluxes under one-side heating conditions, with respect to the heat removal technologies for the divertor in the International Thermonuclear Experimental Reactor (ITER). The test section was electrically heated by a large AC power supply with an effective heated length of 360 mm. The test parameters covered pressures of 3–5 MPa, mass fluxes of 3000–8000 $kg \cdot m^{-2} \cdot s^{-1}$, inlet bulk temperatures of 40–220 °C, and equivalent heat fluxes up to 8 $MW \cdot m^{-2}$. The effects of the parameters on the heat transfer coefficients have been discussed in detail, from single-phase forced convention to fully developed nucleate boiling. A series of heat transfer correlations were evaluated using the experimental data, and most of the correlations did not adequately fit the experimental results. A modified Liu-Winterton correlation and modified Jens-Lottes correlation were used to predict the heat transfer coefficients in the partially boiling region and fully developed boiling region, respectively. The average errors (AEs) of the two correlations were −0.28% and 0.6%, and the root mean square errors (RMSEs) of them were 7.93% and 2.89%.

1. Introduction

The realization and use of controlled fusion is well known to be promising method for solving the energy problem. Many engineering problems must be solved during the design and construction of the International Thermonuclear Experimental Reactor (ITER), which is a planned Tokamak reactor for exploring and studying the feasibility of controlled fusion technology. In a fusion reactor, the divertor is a crucial plasma facing component that contributes to the absorption of radiated one-side heating at high heat fluxes. A number of studies have focused on the optimization of the cooling structure for the divertor target, which is cooled by subcooled water at intermediate pressures (up to 5 MPa) under high mass flux and high heat flux conditions. Hence, it is important to investigate the heat transfer characteristics of subcooled water flow boiling under ITER conditions.

Lin et al. [1] developed a theoretical model for subcooled flow boiling heat transfer and conducted heat transfer experiments for the up-flow of boiling water through a vertical tube in the following validation range: $P = 6.9–15$ MPa, $G = 1000–4500$ $kg \cdot m^{-2} \cdot s^{-1}$, $q = 1.8–4.5$ $MW \cdot m^{-2}$. The predictions of the proposed model agree well with the experimental data, and the model is useful for both boiling water reactor (BWR) and pressurized water reactor (PWR) cases.

Sadaghiani et al. [2] experimentally studied subcooled flow boiling in horizontal microtubes and the effect of the heated length. The experiments were conducted with a working fluid over a mass flux range of 4000–7000 $kg \cdot m^{-2} \cdot s^{-1}$ in microtubes with lengths of 30–120 mm and a diameter of 0.6 mm. In this study, a force analysis related to two-phase flow was conducted to investigate the effect of forces on bubble dynamics.

Hasan et al. [3] experimentally investigated the subcooled flow boiling heat transfer of R-113a in an internally heated vertical annular channel. In the study, a multiple-hysteresis phenomenon was identified and an improvement to the Shah correlation for annuli was suggested using the experimental data.

Araki et al. [4] performed heat transfer experiments on the smooth circular and swirl tubes in the regions from non-boiling to high subcooled partial nucleate boiling. A new heat transfer correlation was proposed under one-side heating conditions for the subcooled partial nucleate boiling.

Schlosser and Boscary [5] performed high heat flux tests to determine a method for heat flux removal under NET/ITER relevant

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Nomenclature

A	area [m^2]
A_h	heated area [m^2]
A_f	flow area [m^2]
Bo	boiling number [–]
Cp	specific heat at constant pressure
D	tube diameter [m]
f	friction factor [–]
F	enhancement factor [–]
G	mass flux [kg·m^{-2}·s^{-1}]
h	heat transfer coefficient [kw·m^{-2}·K^{-1}]
H	enthalpy [kJ·kg^{-1}]
H_{lg}	latent heat of vaporization [J·kg^{-1}]
L	length [m]
L_h	heated length of tube [m]
Nu	Nusselt number [–]
P	pressure [MPa]
Q	power [kW]
Pr	Prandtl number [–]
q	heat flux [kW·m^{-2}]
q_l	local heat flux [kW·m^{-2}]
Re	Reynolds number [–]
S	suppression factor [–]
T	temperature [°C]
ΔT_b	T_w-T_b [°C]
ΔT_{sat}	T_w-T_{sat} [°C], wall superheat
ΔT_{sub}	T_{sat}-T_b [°C], degrees of subcooling
V	velocity [m·s^{-1}]
W	width [m]
x_{th}	thermodynamic vapor quality[–]

Greek Letters

η	thermal efficiency [%]
λ	thermal conductivity [W·m^{-1}·K^{-1}]
μ	dynamic viscosity [kg·m^{-1}·s^{-1}]
υ	kinematic viscosity [m^2·s^{-1}]
ρ	density [kg·m^{-3}]
σ	surface tension [N·m^{-1}]

Subscripts

b	bulk
cal	calculated
exp	experimental
FDB	fully developed boiling
i	inside of the test section
in	inlet of the test section
l	liquid
o	outside of the test section
ONB	onset of nucleated boiling
pb	pool boiling
sat	saturation
sub	subcooling
tp	two-phase
w	wall

conditions. In their studies, a choice of correlation was made and incorporated into finite element calculations to simulate heat transfer. In addition, an analysis was conducted for estimating the critical heat flux at the water wall.

Rzehak et al. [6,7] investigated the present capabilities of computational fluid dynamics (CFD) for wall boiling and proposed a computational model that combines an Euler/Euler two-phase flow description with heat flux partitioning. They considered tests under a variety of conditions involving liquid subcooling, flow rates, and heat fluxes.

From the investigations mentioned above, it can be seen that although much work has been done on heat transfer in subcooled water flow boiling over the past decades, most of the tests have been performed using circular tubes under uniform heat fluxes. Among the available published studies, there are few studies on heat transfer in subcooled water under high and non-uniform heat fluxes. Hence, because of a lack of experimental data, further studies are necessary for evaluating the characteristics of heat transfer and developing accurate correlations.

2. Experimental descriptions

2.1. Test loop

An experiment on the heat transfer characteristics of subcooled water flow boiling in circular channels under one-side heating conditions was carried out at the State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University. Fig. 1 shows a schematic of the test loop. Deionized water with a specific conductance of 0.5 μS·cm^{-1} was pumped using a high-pressure displacement pump with a maximum operating pressure of 40 MPa. The water then flowed successively through a filter to remove solid particles. Part of the water was returned to the feed water tank through a bypass, and the remaining water was driven via a main valve (to regulate the mass flux) and mass flow meter into a heat exchanger, where the feed water absorbed the heat of the fluid flowing from the test section. The water exiting the heat exchanger was heated in a preheater, it then flowed into the test section, where the heat transfer characteristics were studied. Finally, the water was returned to the feed water tank through an additional valve and rotameter, and recirculated after being cooled by a condenser.

2.2. Test section and measurement

Images of the test section are shown in Fig. 2. In the experimental study of Araki et al. [4] and Dedov et al. [8,9], the test sections were heated by the hydrogen ion beams and a scanning electron beam generated by an electron gun, respectively. By these ways, it is hard to get enough applied power and thermocouples may cause deviations of the heated power.

In order to simulate one-side heating conditions, the experiments were carried out in rectangular nickel blocks, in which heated water flowed vertically upward through off-center circular channels. The cross section of the test section was 15 × 14 mm, and the diameter of the flowing channel was 9 mm. The test section was electrically heated by low-voltage AC power with a maximum capacity of 250 kW, and the effective heated length was 360 mm. Two non-heated nickel alloy tubes were connected to the inlet and outlet of the test section to stabilize the fluid flow and eliminate the flow entrance effect. A schematic of the test section and wall temperature measurement point arrangement is shown in Fig. 3. To measure the local outside wall temperature, 48 pairs of K-type thermocouples with 0.2 mm diameters were spot welded on the outer surface of the nickel rectangular block.

The mass flow rate was measured using a Coriolis mass flow meter with a measuring range of 0.5–50 kg·min^{-1} and an accuracy of ±0.05%. A Rosemount-3051 capacitance-type pressure transmitter was used to measure the fluid pressure at the outlet of the test section, and the pressure drop over the test section was measured with a Rosemount-3051 capacitance-type pressure transmitter. A