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Subcooled flow boiling heat transfer of water in circular tubes with twisted-tape inserts under high heat fluxes

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ABSTRACT

This paper presents the heat transfer of subcooled water in swirl flow under high heat fluxes with respect to the heat removal technologies for the divertors in the International Thermonuclear Experimental Reactor (ITER). The experiments were conducted in a vertical circular tube that was heated uniformly with a large AC power supply. A twisted tape with a twist ratio of 2 or 4 was inserted into the circular tube to induce the swirl flow. The test parameters were as follows: heat flux q = 5–19.5 MW/m^2; system pressure P = 3, 4.2, 5 MPa; mass flux G = 6000, 8000, 10,000 kg/(m^2 s); and inlet bulk temperature $T_{b,i}$ = 50–200 °C. The heat transfer coefficients and boiling curves are obtained from single-phase forced convection to fully developed nucleate boiling. The influences of mass flux, heat flux, system pressure, thermodynamic quality, and inlet subcooling on heat transfer are discussed in detail. Special attention is paid to the effect of the twisted tape on subcooled heat transfer. More importantly, a wide set of heat transfer correlations are evaluated on the basis of our experimental data, and relevant recommendations for engineering applications are made according to their prediction accuracies.

1. Introduction

Thermonuclear fusion is a very promising means of solving the energy problem, and the International Thermonuclear Experimental Reactor (ITER) is the most technologically advanced machine in which net fusion energy is produced [1]. The ITER project is expected to operate a 500-MW fusion reactor and demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes.

However, plenty of new engineering problems must be solved due to the extreme working conditions in the ITER. One of these problems is the heat removal technology for the ITER divertors that can be subjected to extremely high-energy fluxes of up to 10 MW/m^2 from the plasma. Subcooled water is used as the cooling solution for the ITER divertors under the current design. Moreover, several techniques have been proposed to enhance heat transfer and achieve a sufficient margin of critical heat flux (CHF) [2].

Among these heat transfer enhancement (HTE) techniques, the insertion of twisted tape (TT) in circular tubes has received much attention [3–5]. TT provides a simple passive HTE technique by inducing a vortex motion and increasing the turbulence; this results in a higher heat transfer coefficient due to a thinner boundary layer. In the open literature, a large number of studies have been conducted on the thermo-hydraulic performance of TT [6–12]. In these studies, the main concern is to find the most efficient type of TT, and one of the important parameters is the overall efficiency η that represents the overall performance of different configurations. The η is defined as:

$$\eta = \frac{Nu/Nu_0}{(f/f_0)^{1/3}} \tag{1}$$

where Nu_0 and f_0 are the Nusselt number and friction factor of a plain tube, respectively. A review study on TT inserts is available in [13]. It should be noted that most of these studies are carried out under the conditions of laminar flow or turbulent flow with relatively low heat fluxes and mainly devoted to traditional industrial applications such as heat exchangers, chemical reactors, and refrigeration systems. Few studies have been performed on the heat transfer of subcooled water under the conditions relevant to application in the ITER, in which the emphasis is not on the overall efficiency but the two-phase heat transfer characteristics in swirl flow.

Although the actual heat transfer in swirl flow is much complex, the basic mechanism of heat transfer is still subcooled flow boiling. In the open literature, a number of studies have been performed on subcooled flow boiling under high heat fluxes. Ozdemir et al. [14]

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Nomenclature

d	diameter (m)
dP	pressure drop (Pa)
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)
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
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)
u	velocity (m/s)
W	tape width (m)
x_{th}	thermodynamic quality
y	twist ratio

Greek symbols

β	coefficient of volumetric expansion of liquid (1/°C)
δ	tape thickness (m)
η	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)
υ	specific volume (m^3/kg)

Subscripts

b	bulk
cal	calculated
exp	experimental
FDB	fully developed boiling
g	gas
h	hydraulic
i	inlet
l	liquid
NB	nucleate boiling
o	outlet
ONB	onset of nucleate boiling
sat	saturation
SP	single phase
sw	swirl
sub	subcooling
w	wall

studied the boiling heat transfer of water in microtubes at high mass fluxes. They found that high heat removal rates could be obtained at high mass flow rates under subcooled boiling conditions. The effects of mass flux, heat flux, local quality, and tube diameter on heat transfer coefficients were all discussed. Kaya et al. [15] investigated the flow boiling of water at high mass fluxes in microscale. In their experiments, ultra high heat flux (>100 MW/m^2) was obtained at high mass fluxes (>10,000 kg/m^2 s). Cikim et al. [16] studied the flow boiling in microtubes with cross-linked surface coatings at mass fluxes of 5000 and 20,000 kg/(m^2 s). They found that the coatings improved boiling heat transfer performance significantly because more active nucleation sites were provided by the porous structure. In summary, most of these studies on flow boiling under high heat fluxes were carried out in mini or micro channels. It is still insufficient for subcooled flow boiling of water in conventional channels under high mass and heat fluxes.

Yagov et al. [17–19] carried out many experiments on the thermal–hydraulic characteristics of subcooled boiling with TT inserts and proposed corresponding heat transfer correlations under the conditions of uniform heating and one-sided heating. Hata et al. [20–22] were also active in the field of subcooled water heat transfer in swirl flow boiling. They concluded that the heat transfer in TT tubes can be treated the same as that in plain tubes by the introduction of the swirl velocity and proposed a turbulent heat transfer correlation. It should be noted that the pressure ranges for the equations of Yagov et al. and Hata et al. are approximately 0.4–2.0 MPa and 0.8–1.0 MPa, respectively, which are relatively narrow and little lower than the current ITER design ranges (2.8–4.2 MPa) [5,23,24].

Baxi [25] examined thermal hydraulic issues associated with the design of water cooled divertors. The heat transfer from the coolant channel was divided into six different regimes, namely, (1) forced convection heat transfer, (2) onset of nucleate boiling, (3) nucleate boiling, (4) transition between nucleate boiling and CHF, (5) CHF, and (6) post-CHF region. Heat transfer correlations and procedures were recommended for these six regimes. A typical plot of heat transfer coefficient as a function of coolant channel wall temperature covering these six regimes was provided.

El-Morshedy and Hassanein [26] developed a mathematical model to simulate the steady state and transient thermal hydraulics of the ITER divertor module. They selected the Chen correlation [27] to calculate the heat transfer coefficient for subcooled boiling. Their model was validated by experimental data performed for both plain and twist tape coolant channel mockups during both steady and transient states. However, although the Chen correlation has been widely used in the study of saturated nucleate boiling and can be extended into subcooled flow boiling, this correlation is rarely applied in highly subcooled flow boiling in swirl flow under high heat fluxes. Therefore, the correlations need further assessment before they can be applied in thermal–hydraulic analysis and engineering designs.

The main objective of this study is to investigate the swirl flow boiling heat transfer of subcooled water in TT tubes under the conditions required by the ITER. A number of heat transfer data on subcooled water boiling in swirl flow are provided in this experiment, which could be valuable for the design of the water cooling system in the ITER. The experimental conditions are summarized in Table 1. The main contents of this paper are as follows. First, heat transfer coefficients and boiling curves are presented from single-phase convection to fully developed nucleate boiling. Second, the effects of mass flux, heat flux, system pressure, thermodynamic quality, inlet subcooling, and TT on heat transfer are discussed. Finally, a wide set of heat transfer correlations are assessed against our experimental data.