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Experimental study on heat transfer to the supercritical water upward flow in a vertical tube with internal helical ribs

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ABSTRACT

This paper presents some results of experimental research performed at the Hi-TaP-XJTU test loop on heat transfer to the supercritical water (SCW) upward flow in a vertical tube with internal helical ribs. The experiments include a large range of regime parameters: P = 22.5–28 MPa, G = 400–1000 kg/(m^2 s), q = 300–700 kW/m^2. These present data were compared with those known for smooth tubes and other types of ribbed tubes both under the heat transfer deterioration (HTD) and without it. The heat transfer coefficient (HTC) in the test ribbed tube is by 1.41–1.85 and 1.34 times higher as compared with smooth tubes and ribbed tubes of other types in the cases without HTD. The critical heat flux of HTD in the test ribbed tube is 1.8 times of that in the smooth tube, and the ratio of the critical heat flux to the mass flux is at least 1.13 times higher than ribbed tubes of other types. Moreover, the ratio of HTC in the test ribbed tube to that in the smooth tube in the large specific heat region (LSHR) is significantly larger than that beyond the LSHR region. The mechanism of heat transfer enhancement taking place in the tube with internal helical ribs was analyzed as well. Finally, the HTC piecewise correlation for the upward SCW flow in this tube was developed, which includes three equations for the following separated regions of the bulk fluid enthalpy: (1) $H < 1700$ kJ/kg, (2) $1700 \leqslant H \leqslant 2700$ kJ/kg, (3) $H > 2700$ kJ/kg. It is of type $Nu/Nu_s = C\mathrm{Re}^m\mathrm{Pr}^n$, where Nu_s is the Nusselt number for a smooth tube determined by the Mokry–Pioro correlation and C is the numerical constant for the separate enthalpy region.

1. Introduction

Supercritical water (SCW) has been used in various industry applications, such as the supercritical pressure water-cooled reactors (SCWR) and ultra-supercritical power plant boilers, etc. The thermal efficiency of thermal power plants and nuclear power plants will be significantly improved when the live steam parameters (pressure and temperature) are increased to supercritical parameters level [1,2]. For substantiation of safety and optimal design of SCWRs and ultra-supercritical boilers, research on heat transfer to SCW flow plays a key role [3–5].

Investigation on heat transfer to SCW flow has been conducted since 1950s, and several detailed review work have been reported to date [6–12]. There does not exist liquid–vapor phase transition at supercritical pressures, but supercritical fluids have unique properties. The specific heat of SCW has a maximum value for a given pressure, and the temperature corresponding to this maximum is usually defined as the pseudo critical temperature (t_{pc}) [9]. The specific heat of SCW in the region near t_{pc} is much larger than that far from the region. The region near t_{pc}, where the value of the specific heat is greater than 8.4 kJ/(kg K) was defined as the large specific heat region (LSHR) [13,14]. In the LSHR, the thermo physical properties of SCW change drastically, making the heat transfer to SCW flow different from that of the single-phase flow at subcritical pressures [15].

In general, three heat transfer modes of fluids at supercritical pressures were recorded and defined [9]: (1) normal heat transfer; (2) improved heat transfer, characterized by higher values of the heat transfer coefficient (HTC) and apparently lower values of wall temperature than those at the normal heat transfer, (3) deteriorated heat transfer, characterized by lower values of the HTC and apparently higher values of wall temperature than those at the normal heat transfer.

According to the latest review work [6–12], it was found that the existing investigation on heat transfer of supercritical fluids was mainly conducted in smooth tubes. However, the tube with internal helical ribs (hereinafter referred to as "the ribbed tube") has been widely used in the vertical water walls of boilers in the power plants and other related heat exchangers, due to its excellent heat transfer performance, so it is very necessary to study the heat transfer of water in the ribbed tube.

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Nomenclature

Cp	specific heat
d	diameter
e	rib height
G	mass flux
H	bulk fluid enthalpy
h	heat transfer coefficient
Ns	number of ribs
P	pressure
p	pitch
q	internal wall heat flux
t	temperature
L	rib width

Greek symbols

α	helix angle of the rib
λ	thermal conductivity
ρ	density

Subscripts

ave	average
b	bulk fluid
cal	calculated
exp	experimental
pc	pseudo critical
s	smooth tube
w	wall

Abbreviations

CHF	critical heat flux
HER	high enthalpy region
Hi-TaP-XJTU	**Hi**gh **T**emperature **a**nd High **P**ressure two phase flow and heat transfer test loop in **X**i'an **J**iao**t**ong **U**niversity
HTC	heat transfer coefficient
HTD	heat transfer deterioration
HTE	heat transfer enhancement
ID	inside diameter
LER	low enthalpy region
LSHR	large specific heat region
SCW	supercritical water
SCWR	supercritical pressure water-cooled reactors

Investigation on the heat transfer of subcritical water has shown that compared with the smooth tube, the ribbed tube can distinctly enhance the heat transfer of water and other fluids. Specially, it can effectively restrain the film boiling under conditions with even very low mass flux and quite high vapor quality at subcritical pressures [16–19]. In addition, investigations on the degree and mechanism of heat transfer enhancement (HTE) of the ribbed tube at subcritical pressures have also been reported in quite a lot of literature. Köhler [20] studied the effect of the helical internal ribs on the heat transfer and pressure drop of water in one kind ribbed tube at system pressures of 5–21 MPa, and found that the HTE of the ribbed tube was closely related to the rotational flow formed in the tube. Cheng [21–23] had conducted much research on heat transfer and pressure resistance of such fluids as water and kerosene at subcritical pressures. Based on these researches, it was found that the heat transfer coefficient (HTC) of single-phase flow, the HTC of flow boiling, and the critical heat flux (CHF) in the ribbed tube were all enhanced obviously as compared with smooth tubes. The degree of enhancement in water flow was different depending on the regime conditions. The HTC value in ribbed tubes was increased by 1.6–2.0 times under flow boiling and 1.2–1.6 times at the single-phase flow. The type of working fluids (e.g. water or kerosene) had a different effect on this enhancement. Besides the pressure drop increase was also taken place in ribbed tubes.

Unlike the investigation of fluids in ribbed tubes at subcritical pressures, experimental investigation was limited for the heat transfer to water flow in the ribbed tube at supercritical pressures. The heat transfer to supercritical water (SCW) flow in ribbed tubes with specific tube structures was experimentally investigated separately [24–33], as listed in Table 1.

Note that the heat transfer and pressure drop to SCW flow are quite different in ribbed tubes with different rib structures, as similar to that at subcritical pressures. In order to get insight into the heat transfer capability of the ribbed tube at supercritical pressures, it is necessary to compare the heat transfer to SCW flow in the ribbed tube with that in the smooth tube. Such comparisons have been qualitatively made on the wall temperature. It was found that the wall temperature of the ribbed tube was lower than that of the smooth tube [31], and the deteriorated heat transfer of SCW can be avoided in the ribbed tube [24,29,32], indicating that the ribbed tube can enhance the heat transfer of SCW as compared to the smooth tube. However, little work has been conducted to quantitatively study the degree of heat transfer enhancement (HTE) of the ribbed tube at supercritical pressures, and also, the HTE mechanism still needs further study.

Moreover, it should be noted that based on the experimental studies, a few correlations have been developed for the HTC to SCW flow in the specific ribbed tubes, as listed in Table 2. Here $\overline{\Pr} = \overline{C_p} \cdot \mu/\lambda$ is the averaged Prandtl number and $\overline{C_p} = (H_w - H_b)/(T_w - T_b)$ is the averaged specific heat. The experimental conditions for these correlations are given in Table 1.

The modified Dittus-Boelter equation was used by Iwabuchi [26] and Griem [27] to develop the HTC correlations in ribbed tubes for SCW flow, see Table 2. The Griem correlation was developed for two pressure ranges taking into account the selected specific heat $C_{p,sel}$. Chen [28] has proposed correlations in the four-head ribbed tube analyzing the different regions of the bulk fluid enthalpy bounded by the pseudo critical enthalpy. He and his colleagues have performed a lot of investigations on heat transfer to SCW flow both in smooth and ribbed tubes of different geometry since 1990s at the **Hi**gh **T**emperature **a**nd High **P**ressure two phase flow and heat transfer test loop in **X**i'an **J**iao**t**ong **U**niversity (Hi-TaP-XJTU) [29–33]. Based on the Chen correlations, three researchers [30–33] have developed a set of the HTC correlations for the SCW flow in other specific ribbed tubes.

As shown in Fig. 1, all above-mentioned correlations are true only for the test ribbed tubes with specific geometry. They could not be applied for the purposes of practical engineering design and improving the fundamental knowledge on thermohydraulics of SCW flows in ribbed tubes. Therefore it is necessary to establish an universal correlation for different ribbed tubes in the future.

The present paper is aimed to provide the necessary experimental data for designing of the vertical water wall of boilers with a new type of ribbed tubes and the optimized structural parameters. These data obtained at the Hi-TaP-XJTU test loop were compared with those known for smooth tubes and other types of ribbed tubes both under the heat transfer deterioration (HTD) and without it. The mechanism of heat transfer enhancement taking place in the tube with internal helical ribs was analyzed as well. Finally, the