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Experimental investigation on heat transfer deterioration of supercritical pressure water in vertically-upward internally-ribbed tubes

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ABSTRACT

This paper presented an experimental investigation into heat transfer deterioration (HTD) characteristics of supercritical pressure water (SCW) flowing vertically upward in eight internally-ribbed tubes (IRT). The experiment was carried out at the following operating conditions: pressures from 25 to 28 MPa, mass velocities from 400 to 800 kg m^{-2} s^{-1}, and inner wall heat fluxes from 400 to 1000 kW m^{-2}. The results show that HTD of SCW might occur in the large specific heat region (LSHR) with increasing of q/G, but the increase of pressure could suppress the severity of HTD in the test IRTs. Based on the experimental data, the differences of heat transfer behavior among a series of IRTs, and the differences between IRTs and smooth tubes were compared separately. To explain the mechanism of unusual heat transfer, the buoyancy effect and flow acceleration were further analyzed based on the previous criteria. It was found that the dimensionless number $\overline{Gr}_b/Re_b^{2.7}$ in all IRTs was much larger than that in smooth tubes under HTD occurrence, while dimensionless number Kv_t for flow acceleration in all test IRTs was much less than the threshold value when HTD came out in smooth tubes for SCW. Therefore, a new improved heat transfer criterion by adding the rib geometry parameters of IRTs was proposed for predicating HTD of SCW according to the experimental data. Also, after evaluating the existing heat transfer coefficient (HTC) correlations of SCW for IRTs, it was found that all previous correlations cannot accurately predict HTC and wall temperature profiles of IRTs at HTD conditions. Thus, an improved HTC predicating correlation for HTD was proposed regarding to the effect of rib geometry and buoyancy that can be to precisely predict wall temperatures and HTCs in various IRTs. Meanwhile, the new correlation was also verified to be more effective than the previous correlations.

1. Introduction

Supercritical pressure fossil fired unit technology has been widely employed in the power industry owing to its advantages of high thermal efficiency and high utilization rate of the prime cost compared with other thermal power plants [1–5]. With the development of vertically-upward water-wall technology under low mass velocity condition, the internally-ribbed tube (IRT) has been widely applied in the water-wall tubes of boilers, especially in those of supercritical pressure Circulating Fluidized Bed (CFB) boilers and W-type flame boilers due to its excellent performances of enhancing heat transfer and preventing departure from Nucleate Boiling (DNB) [6,7]. Fig. 1 shows the schematic diagram of IRT, where the rib geometry of the IRTs includes the mean tube diameter d, rib height e, pitch P, rib width B, rib number N, and lead angle L.

When the pressure exceeds the critical pressure (22.064 MPa), the physical properties of water vary continuously with the increase of temperature without experiencing liquid–vapor phase change, which are considerably different from those of the subcritical pressure water. At the vicinity of the pseudo-critical temperature, the specific heat of supercritical pressure water (SCW) shows a large peak, as shown in Fig. 2. According to the definition in Refs. [8,9], the region where c_p is larger than 8.4 kJ kg^{-1} K^{-1} is called large specific heat region (LSHR) (1715–2721 kJ kg^{-1}). In such LSHR, thermo-physical properties of SCW exhibit rapid and drastic variations, resulting in heat transfer of SCW quite particular compared with that of the subcritical pressure water [10].

From the 1960s, a large number of investigations have been carried out on the flow and heat transfer characteristics of SCW [11–18]. According to these existing studies [15], two unusual heat transfer models of SCW occur in the LSHR: (1) the heat transfer

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Nomenclature

B	rib width [mm]
c_p	specific heat [kJ kg^{-1} K^{-1}]
d	diameter [mm]
e	rib height [mm]
G	mass velocity [kg m^{-2} s^{-1}]
H	enthalpy [kJ kg^{-1}]
L	helix angle of the rib [°]
N	number of ribs [–]
p	pressure [MPa]
P	pitch [mm]
q	internal wall heat flux [kW m^{-2}]
t	temperature [°C]

Greek symbols

β	thermo-expansion coefficient [K^{-1}]
λ	thermal conductivity [W m^{-1} K^{-1}]
μ	dynamic viscosity [Pa s]
ρ	density [kg m^{-3}]
υ	kinematic viscosity coefficient [m^2 s^{-1}]

Subscripts

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

Abbreviations

CHF	critical heat flux [kW m^{-2}]
Hi-TaP-XJTU	High Temperature and High Pressure two phase flow and heat transfer test loop in Xi'an Jiaotong University
HTC	heat transfer coefficient [kW m^{-2} K^{-1}]
HTD	heat transfer deterioration
HTE	heat transfer enhancement
IRT	internally-ribbed tube
LSHR	large specific heat region
SCW	supercritical pressure water

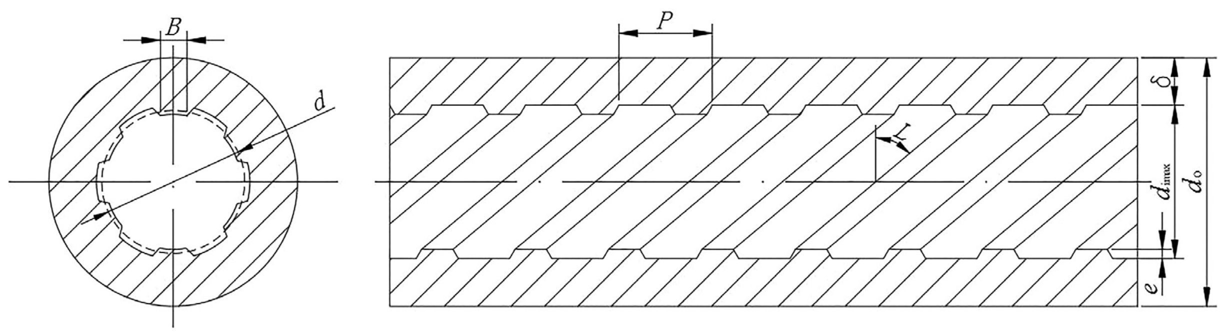

Fig. 1. The schematic diagram of internally ribbed tube.

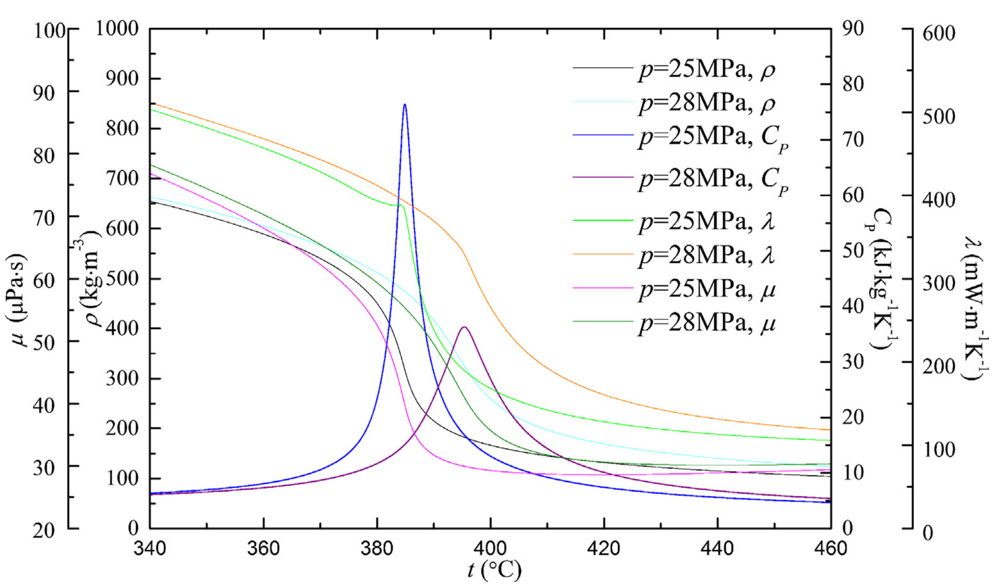

Fig. 2. Thermo-physical property profiles of SCW under p = 25 MPa and p = 28 MPa within pseudo-critical range.