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Numerical investigation on the mixed convection and heat transfer of supercritical water in horizontal tubes in the large specific heat region

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ABSTRACT

Numerical simulation is performed in the present study to get further insight into the mechanism of heat transfer phenomena of water in $\varnothing 32 \times 3$ mm horizontal smooth tubes under supercritical pressures. Both the heat transfer enhancement (HTE) and heat transfer deterioration (HTD) in the so-called large specific heat region (LSHR) of supercritical fluids are analyzed based on the numerical results. The governing equations of the fluid are solved on fixed three-dimensional grid systems, and the RNG-k–ε model with enhanced wall treatment method is employed to handle the coupled wall-to-fluid heat transfer. The numerical results are compared with the corresponding experimental data, and a good agreement is achieved, indicating good accuracy and reliability of the numerical method used in this study. Variation of the tube inner wall temperature and the local heat transfer coefficient with a few parameters, such as the local water enthalpy, the water mass flow rate and the heat flux on the tube wall, are obtained under various conditions. It is showed that in the large specific heat region (LSHR), there exists strong non-uniformity in the circumferential distribution of the tube inner wall temperature, and as well, the heat flux on the inner tube wall are distinctly non-uniform along the tube wall circumference. Further analysis of the numerical data shows that the above-mentioned non-uniformity is mainly due to the rapid change in fluid properties, which results complex secondary flows and mixed convection in the supercritical fluid. Based on the numerical results, a critical value is obtained for the parameter $Gr/Re^{2.7}$, which is believed to be a key parameter affecting the secondary flow in the LSHR. In the present study, the critical value for $Gr/Re^{2.7}$ is determined to be 1.5×10^{-5}, above which the HTD phenomenon may be observed.

1. Introduction

Increasing demand for electricity has been driving the rapid development of technologies in power and energy production in the world. As one of the advanced coal-consumption technologies, supercritical (ultra-supercritical) pressure boilers have been widely used, especially in China because it has good deal of advantages, such as the large capacity, relatively low energy cost, low pollutant emission and high efficiency. Furthermore, supercritical water-cooled reactors (SCWRs) have been accepted as one of the six most promising reactor concepts considered in the Generation IV International Forum (GIF) [1]. In this case, the flow and heat transfer characteristics of supercritical pressure water becomes important for both the design and operation of related systems operating at supercritical pressures.

Early studies on the flow and heat transfer of supercritical fluid [2,3] have shown that there exists a so-called large specific heat region for water, which is usually defined as a region with the specific heat of water larger than 8.4 kJ/(kg·K) at constant pressures (as shown in Fig. 1). Although the supercritical pressure water does not experience phase change, its thermo-physical properties however exhibit drastic and fast variation with temperatures in the LSHR, showing some behavior similar to that of the sub-critical pressure water. It is believed that such behavior may result in complex cross-mixing of the fluid in channels and lead to the uneven circumferential distribution of wall temperature and thermal stress in the tube wall, and may finally cause troubles in the operation of the related facilities. Accordingly, understanding of mechanism behind the complicated heat transfer phenomena of supercritical water in the LSHR is very important for apparatus operated under supercritical pressures.

A number of experimental investigations on the forced convection of supercritical fluids including water, CO_2 and others flowing inside channels have been fulfilled in the 1950s–1990s. The research about supercritical water that finished by Swenson et al. [4], Shitsman [5–8], Ackerman [9], Ornatskiy et al. [10], Yamagata et al. [11], Kitoh et al. [12], Kirillov [13], Jackson [14,15], and so on, and a series of review of the experimental studies has been reported by Pioro and Duffey [16–19], etc. In China, a high pressure

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Nomenclature

P	pressure, MPa
T	temperature, K
G	mass flux, kg·m^{-2}·s^{-1}
q	heat flux, kW·m^{-2}
q'	inner-wall heat flux, kW·m^{-2}
H	bulk enthalpy, kJ·kg^{-1}
c_p	specific heat at constant pressure, kJ·kg^{-1}·K^{-1}
h	heat transfer coefficient, kW·m^{-2}·K^{-1}
D	tube diameter, m
g	gravity, m·s^{-2}
Greek letters	
λ	thermal conductivity, W·m^{-1}·K^{-1}
μ	viscosity, kg·m^{-1}·s^{-1}
ρ	density, kg·m^{-3}
Non-dimensional numbers	
Re	Reynolds number ($\mathrm{Re} = \frac{\rho_b u D}{\mu_b}$)
Pr	Prandtl number ($\mathrm{Pr} = \frac{\mu_b \times C_p}{\lambda_b}$)
Gr	Grashof number ($Gr = \frac{(\rho_w - \rho_b)\rho_b g D_h^3}{\mu_b^2}$)
Subscript	
w	inner-wall
b	bulk
Abbreviation	
SCWR	supercritical water-cooled reactor
HTD	heat transfer deterioration
HTE	heat transfer enhancement
HTC	heat transfer coefficient

water test loop has been established in Xi'an Jiaotong University and several tests have been performed on this loop [20–24]. Earlier studies about supercritical CO_2 carried by Petukhov et al. [25], Shitsman [26], Adebiyi and Hall [27], Kilomov et al. [28] mostly focused on heat transfer and pressure drop under heating conditions in the large diameter channels (macro-channels).In recent years, a number of studies have been conducted for the cooling of supercritical CO_2 in both macro-channels and micro-channels, such as that fulfilled by Cheng et al. [29], Dang and Hihara [30], Liao and Zhao [31]. Generally, both the heat transfer enhancement (HTE) and the heat transfer deterioration (HTD) of supercritical fluid in heating ducts have been observed [9,16,17,19,32–38]. Typically, at high mass flux with relatively low heat flux, the HTE is considered to occur, and the measured heat transfer coefficient is generally higher than the value predicted by the Dittus–Boelter equation [39]. However, with the increase of heat flux, the enhancement of heat transfer can be reduced, and when the ratio of the heat flux to mass flux is considerably high, the HTD may occur with a sharp decrease in the heat transfer coefficients (HTCs) or a rapid increase in the wall temperatures of tubes.

As mentioned above, thermal physical properties of supercritical fluids are highly sensitive to temperature in the LSHR. In other words, small changes in temperature would result in large changes in properties, especially within the boundary layer on the heated or cooled wall. Thus, the influence of the varying properties of the fluid in the boundary layer upon the heat and mass transfer needs to be analyzed. However, this is hard to be carried out in practical applications because the temperature profile in the boundary layer is not readily obtained from experiments. Undoubtedly the numerical calculation can offer great convenience for getting insight into the complex heat transfer phenomena and heat transfer performance of the supercritical fluids, especially that in the so called LSHR.

Over the past decade, the rapidly increasing in computing power available to researchers has made it possible to try to reveal the detailed structures of supercritical fluids flow and heat transfer. A few of commercial computational fluid dynamics (CFD) codes were used to study the heat transfer characteristics of supercritical water [40–45]. Roelof [43] analyzed the features of supercritical water flow in upward circular tubes at supercritical pressures by FLUENT® with a few turbulence models and gave a reasonable explanation of the difference between simulation results and experimental data. Cheng et al. [44] studied heat transfer of supercritical water in triangular and square lattice bundles using CFX software. Yang et al. [45] investigated heat transfer of supercritical

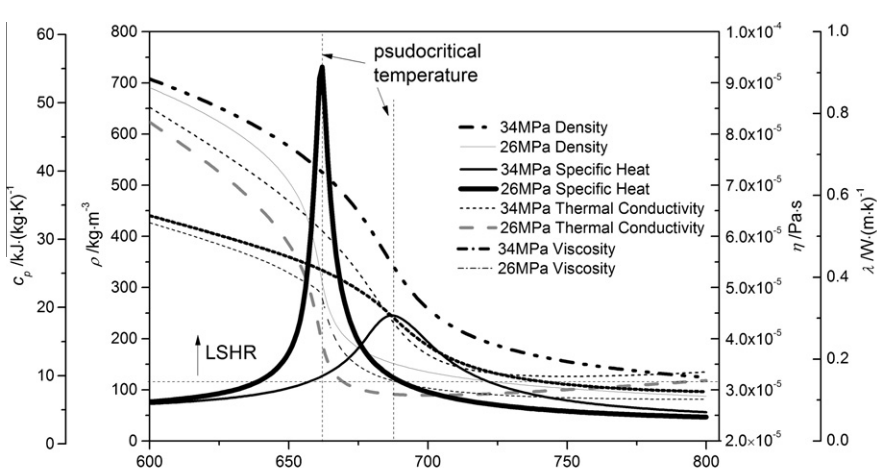

Fig. 1. The thermo-physical properties of water at a pressure of 26 MPa and 34 MPa.