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Experimental and numerical investigation on heat transfer of ultra-supercritical water in vertical upward tube under uniform and non-uniform heating

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ABSTRACT

Heat transfer of ultra-supercritical water in vertical upward tube under uniform heating was investigated experimentally and numerically. For comparison, similar studies under non-uniform heating were also simulated. The effects of specific heat ratio, buoyancy and acceleration on the heat transfer of ultra-supercritical water were discussed according to the experimental data. Results show that these dimensionless parameters have no single relationship of independence with the heat transfer coefficient which indicates that using them directly to predict heat transfer is inaccurate. The shear stress transport k-ω model was used in the numerical simulation. Results concur with the experimental data to a high degree, which proves that the model has strong applicability in predicting heat transfer. The mechanisms of heat transfer enhancement and deterioration were analyzed through simulation results, and the integral of specific heat in the boundary layer and the buoyancy effect were confirmed to be their main factors, respectively. Furthermore, the differences between the uniform and non-uniform heating were also revealed. The wall temperature of smooth tube under non-uniform heating shows a parabola distribution, and the peak value occurs at the midpoint of the heated side. Moreover, the peak value of the wall temperature is higher under non-uniform heating than that under uniform heating; however, the heat flux is higher when heat transfer deterioration occurs.

1. Introduction

The growing worldwide demand for energy has driven the recent rapid development of power and energy technologies. Ultra-supercritical circulating fluidized bed (CFB) boilers are widely used due to their advantages of high heat transfer rate, high heat intensity, strong fuel adaptability and effective desulfurization. Moreover, supercritical water-cooled reactor (SCWR) is one of the six most promising candidate reactor technologies identified by the Fourth Generation International Forum [1]. Mastering the flow and heat transfer characteristics of ultra-supercritical water has important significance for the development, design and operation of ultra-supercritical CFB boilers and SCWRs [2].

A uniform standard for the division of the boundary between supercritical and ultra-supercritical water is not available. In the present work, water with pressure higher than 24 MPa is called ultra-supercritical water. Given the drastic change in the physical properties of water near the pseudo critical point (Fig. 1), ultra-supercritical water has special heat transfer characteristics, which are manifested in two aspects, namely, heat transfer enhancement (HTE) and heat transfer deterioration (HTD). HTE will result in a rapid increase of heat transfer coefficient (HTC), which can sufficiently cool the heated tube wall and is beneficial to the normal operation of an ultra-supercritical CFB boiler. HTE is widely studied because of this advantage. However, analysis of the mechanism in previous studies is limited. In comparison with HTE, HTD will cause the tube wall temperature to soar, which will threaten the safe operation of ultra-supercritical CFB boiler. Therefore, research has further focused on how to keep the wall temperature within a safe range, to avoid the occurrence of HTD. Shitsman [3,4] found that HTD often occurred at low mass flux conditions, and Ackerman [5] claimed that a type of boiling named "pseudo- film" led to the occurrence of HTD. Unfortunately, none of them made explanations and analyses. Hall [6] found that HTD occurred in the upward flow, but disappeared in the downward flow which he believed is caused by buoyancy. Jackson [7,8] further explained this phenomenon, and claimed that buoyancy caused the convective heat transfer to change and the specific change was from variable property forced convection to mixed convection. Jackson et al.

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Nomenclature

C_p	specific heat at constant pressure, J·kg^{-1}·K^{-1}
T	temperature, °C
d	diameter, m
E	input voltage, V
I	input current, A
Q_E	input electric power, W
g	gravitational acceleration, m·s^{-2}
h	enthalpy, J·kg^{-1}
Δh	added enthalpy, J·s^{-1}
k	turbulent kinetic energy, m^2·s^{-2}
K	thermal conductivity, W·m^{-2}· K^{-1}
L	length of experimental section, m
P	pressure, Pa
q	inner wall heat flux, W·m^{-2}
G	mass flux, kg·m^{-2}·s^{-1}
u	axial velocity, m/s

Dimensionless numbers

π_A	specific heat ratio
π_B	acceleration number proposed by Cheng et al.
π_C	buoyancy number proposed by Cheng et al.
Nu	Nusselt number
Re	Reynolds number
Pr	Prandtl number

Greek letters

β	thermal expansion coefficient, K^{-1}
η	heat efficiency of the experimental section
λ	thermal conductivity, W·m^{-1}·K^{-1}
ω	specific turbulent dissipation rate, 1/s

Subscripts

a	average
b	bulk
in	inner
max	maximum
out	outer
w	wall
wi	inner wall
h	heated
adi	adiabatic

Abbreviations/Acronyms

CFB	circulating fluidized bed
SST	shear stress transport
Exp.	experimental
HTC	heat transfer coefficient
HTD	heat transfer deterioration
HTE	heat transfer enhancement

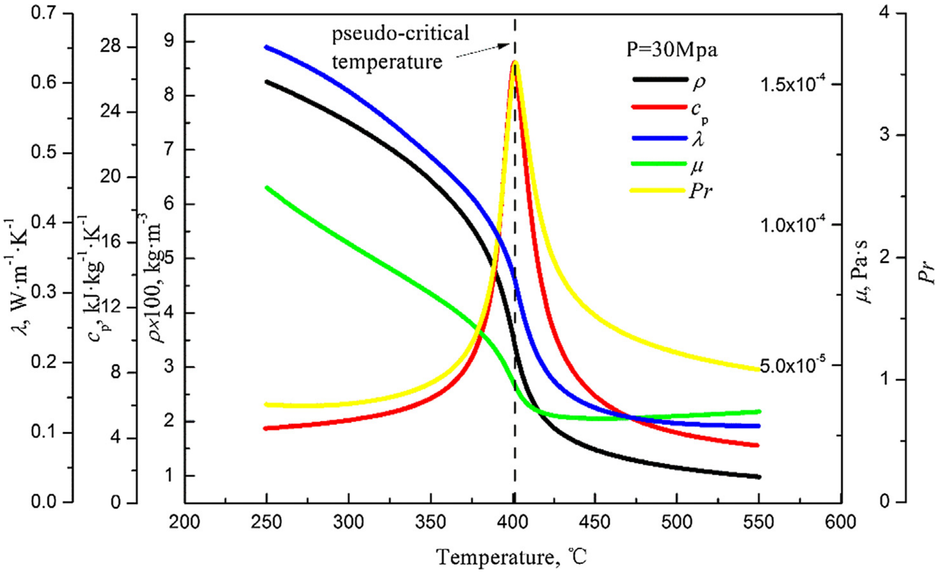

Fig. 1. Physical properties of water at pressure of 30 MPa.

utilized a two-layer model to describe the phenomenon further [3,9–11]. They indicated that given the sharp decrease of the fluid density in the boundary layer, it was far lower than the average density of the bulk flow, such that a strong buoyancy was formed in the boundary layer, which led to the occurrence of HTD. Moreover, Shiralkar [12] discovered another type of HTD, which occurred at relatively high mass and heat fluxes, and could also appear at downward flows. HTD occurred when the heat mass was relatively high, and the steam side temperature was lower than the pseudo critical temperature. Moreover, the author believed that the thermal acceleration was the main reason for this phenomenon. In the previous studies of the heat transfer of ultra-supercritical water, the influences of pressure, heat flux and mass flux were often considered [13–15], however, the change of water physical property, buoyancy and acceleration effect play a major role in the heat transfer at the aforementioned ultra-supercritical pressure. Cheng et al. [16] developed thermal acceleration and buoyancy parameters to study the effects of buoyancy and acceleration on heat transfer in supercritical water. Zhao et al. [17] improved the correlation proposed by the former and introduced another dimensionless parameter. Raman et al. [18] summed up and analyzed the dimensionless parameters and correlations proposed by other scholars. He believed that they performed well in their testing conditions and were not accurate in the near critical region. Liu et al. [19] also proposed different expressions of dimensionless parameters to study the effects of acceleration and buoyancy on forced and mixed