International Journal of Heat and Mass Transfer 108 (2017) 1676–1688

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Experimental and numerical analysis of heat transfer to water at supercritical pressures

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ARTICLE INFO

Article history:
Received 25 May 2016
Received in revised form 10 November 2016
Accepted 23 December 2016

Keywords:
Supercritical water
Heat transfer
Smooth tube
Buoyancy effect
Acceleration effect

ABSTRACT

Heat transfer to supercritical water were investigated both experimentally and numerically. A 2-m long vertical upward smooth tube with a diameter of 19 mm was tested at pressures ranged from 11 to 32 MPa, values of mass flux from 170 to 800 $\mathrm{kg \cdot m^{-2} \cdot s^{-1}}$ and heat fluxes up to 600 $\mathrm{kW \cdot m^{-2}}$. Various dimensionless parameters representing effects of property variations, buoyancy and thermal induced acceleration were estimated. Some of them show unique and strong relations to heat transfer coefficient, while no single behavior of independence is obtained with the majority of them. This result indicates additional parameters are required in case these dimensionless parameters are applied to predict supercritical heat transfer. Based on the experimental data, six typical correlations were evaluated. It turns out that the Mokry et al. correlation and Bishop et al. correlation show the best performance in predicting heat transfer. The shear stress transport k-ω model was employed to numerical analysis. Results of numerical prediction show a good agreement with experimental data, which proves the suitability of the present model. According to the result, physical mechanisms of both enhanced and deteriorated heat transfer at supercritical pressure are revealed. The integral effect of specific heat and buoyancy effect are the main reasons resulting in the abnormal heat transfer.

1. Introduction

Large-capacity supercritical circulating fluidized bed (CFB) boilers have been widely applied to thermal power plants. To provide sufficient evaporating heating surface, a new boiler is designed in China with a particular furnace structure, namely annular furnace [1]. In the annular furnace, heat load is low, to ensure enough heat absorbing of the water wall, mass flux is designed to be relatively lower than that in the traditional coal-fired furnace. However, low mass flux leads to the safety risk of boiler operation. It is because numerous studies indicate that with a low ratio of mass flux to heat flux, abnormal heat transfer may occur in channels flowing with supercritical water. And it can lead to abrupt wall temperature rise, when the peak value exceeds the permissible range, the tube explosion occurs, resulting in a serious industrial accident. Thus, it is significant to investigate the performance of supercritical heat transfer in this designed tube for the boiler.

Supercritical water flowing in heated channels experiences sharp thermo-physical property variations at the transition across the pseudo-critical temperature [2]. It leads to unique performance of supercritical heat transfer. The steep property changes result in two type of abnormal heat transfer, namely enhanced heat transfer (HTE) and deteriorated heat transfer (HTD). The former leads to a peak in heat transfer coefficient (HTC) with value reaching 70 $\mathrm{kW \cdot m^{-2} \cdot K^{-1}}$, which means the heated tube is effectively cooled with a low wall temperature. It is highly beneficial to the supercritical boiler. According to many researchers, enhanced heat transfer is observed in their studies and they owe this result to dramatic property variations. However, little work has been done to reveal how the property variations promote the performance of heat transfer. When the latter occurs, the soaring wall temperature may damage the water wall tube. To prevent this phenomenon from happening, deteriorated heat transfer has drawn much attention with a view to keeping wall temperature within reasonable limits. Ackerman [3] believed that pseudo-film boiling, which was similar to film boiling, led to the deteriorated heat transfer at supercritical pressures. However, detailed analysis of the physical mechanism for this theory was not provided. As investigations went on, buoyancy and thermally induced flow acceleration seemed to be the main reason resulting in this deterioration, which has been explained by Jackson and Hall [4–6] in detail. They indicated that HTD at low mass fluxes is due to buoyancy effect. In their studies, HTD occurs in upward flow and disappears in downward flow and this result was explained to be the difference of

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.12.081

Nomenclature

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

Dimensionless numbers

Bo*	buoyancy parameter
error	data error
Gr	Grashof number
$\mathbf{K_v}$	flow acceleration parameter
Nu	Nusselt number
Pr	Prandtl number
$\overline{\mathbf{Pr}}$	Averaged Prandtl number
Re	Reynolds number
π_A	specific heat ratio
π_B	acceleration number proposed by Cheng et al.
π_C	buoyancy number proposed by Cheng et al.

Greek letters

β	thermal expansion coefficient, K^{-1}
η	heat efficiency of test section
λ	thermal conductivity, W·m^{-1}·K^{-1}
μ	dynamic viscosity, N·s·m^{-2}
ρ	density, kg·m^{-3}
τ	viscous stress tensor
ω	turbulent frequency, s^{-1}

Subscripts

b	bulk
cal	calculation
dev	deviation
exp	experimental
in	inner
max	maximum
min	minimum
out	outer
pc	pseudo critical
w	wall
wi	inside wall

Abbreviations/Acronyms

CFB	circulating fluidized bed
CFD	computational fluid dynamics
Exp.	experimental
HTC	heat transfer coefficient
HTD	heat transfer deterioration
HTE	heat transfer enhancement
SST	shear stress transport
ST	smooth tube

direction of buoyancy force between the two flow patterns. To clarify this phenomenon, they proposed the two-layer theory and it was consistent with experimental phenomena in some researches [7–11]. Another type of HTD appears at high mass flux and high heat flux, which can occur in both upward and downward flows. Thermally induced flow acceleration may be the main reason for this deterioration according to Shiralkar [12]. Effect of various parameters on supercritical heat transfer including pressure, heat flux, and mass flux have been extensively investigated in previous work. And the common conclusion is that heat transfer is enhanced with decreasing pressure, increasing mass flux and reducing heat flux. However, as mentioned above, property variations, buoyancy and acceleration effect are significantly related to heat transfer at supercritical pressure. Thus, study of various dimensionless parameters representing these negligible effects is necessary.

Apart from experimental analysis, numerical simulations have also been performed to study heat transfer of supercritical fluids. Early works used relatively simple mixing length model to predict heat transfer [13–15]. The latter studies focused on the applying of various low Reynolds number k-ε models [16,17]. However, the reproduction of heat transfer by k-ε models is sometimes excellent and sometimes poor [2]. The reason for the inconsistent behavior are not completely understood and further investigation are required. Based on the DNS data, Kim et al. [18] made a comparison between 11 low Reynolds number models. Whereas, he found that none of them could provide a satisfactory prediction with enough accuracy. Thus, he recommended the k-ε-v^2-f model due to its superior accuracy, which failed to predict the subsequent heat recovery after HTD [19]. Recently, the shear stress transport (SST) k-ω model was tested by [20–23]. According to them, the SST model showed good performance in reproducing HTD caused by either buoyancy or acceleration effect. Therefore, in the present study, the SST model is adopted to numerically analyze heat transfer of supercritical water. However, previous studies mainly focused on channels with smaller diameter when compared to that of tube arranged in water wall. Some studies [24–26] also indicated that tube diameter played an important role in heat transfer. HTD seems to be more prone to occur in tubes with larger diameters.

The primary goal of the present paper is to experimentally and numerically analyze the heat transfer of supercritical water in a low mass flux tube with large diameter. Physical mechanisms of both enhanced and deteriorated heat transfer are revealed with numerical results. Effect of various dimensionless parameters are studied extensively. Based on the experimental data, the typical correlations for predicting supercritical heat transfer are evaluated.

2. Experimental apparatus and procedure

2.1. Experimental system

The experimental system is schematically illustrated in Fig. 1. Deionized water in the water tank is pumped using a ram-type pump with a maximum operating pressure of 40 MPa. A portion of the water returns to the tank through the bypass, and the remaining portion flows into the heat exchanger designed for heat recovery and absorbs the heat of the hot water coming from the outlet of the test section. Subsequently, the water reaches the preheater and the vertical test section, which are directly heated by ac power supplies with high current and low voltage. Mass flux and pressure are controlled precisely by adjusting the valves. Afterward, the water is cooled in the condenser with cold water from the cooling tower and flows back to the tank for recycling.