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Heat transfer characteristics of supercritical pressure water in vertical upward annuli

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HIGHLIGHTS

- Effects of annular gap size on heat transfer are investigated.
- Wire-wrapped spacer has local and global effects on heat transfer.
- Influence of buoyancy on heat transfer is evaluated.
- Heat transfer correlations were assessed against annuli test data.

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ABSTRACT

Heat transfer characteristics of supercritical pressure water in vertical-upward annuli with annular gaps of 4 mm and 6 mm were investigated experimentally. The inner heated rod has an outer diameter of 8 mm with an effective heated length of 1400 mm. Experimental parameters covered the pressures of 23–28 MPa, mass fluxes of 350–1000 kg/m^{2}s, heat fluxes of 200–1000 kW/m^2 and inlet bulk temperature up to 400 °C. According to the experimental data, the effects of heat flux and mass flux on heat transfer of supercritical water were analyzed. Experimental results showed that heat transfer of various heat fluxes and mass fluxes in annuli are similar with those in tubes. Compare the heat transfer differences in the two annular gaps, it was found that heat transfer in 6 mm gap channel is better than that in 4 mm gap channel, especially in the pseudo-critical enthalpy region. Experimental results also showed that the spiral spacer, which was arranged on the outer surface of the heated rod, has a positive effect on enhancing local heat transfer. However, this enhanced phenomenon seems stronger in 4 mm gap compared to that in 6 mm gap. The criterion of Jackson–Hall was selected to distinguish the effect of buoyancy in annular channels. Predicted results demonstrated that this criterion achieves good agreements against the experimental data at various mass fluxes and pressures. The present paper compared the experimental data with eight heat transfer correlations for supercritical pressure water. It was found that the correlations of Jackson, Bishop and Cheng are most close to the test data for normal heat transfer region, whereas only the correlation of Cheng seems acceptable when heat transfer deterioration occurs.

1. Introduction

The Supercritical Water-cooled Reactor (SCWR) is promising since it has been selected as one of six candidates of Generation IV nuclear reactors (US, 2002). SCWR has the potential advantages of high thermal efficiency, effective nuclear fuel utilization, simplified plant systems and economic competitiveness in comparison with conventional light water reactors (LWRs). Ever since the representative reactor concept of SCWR was proposed by Oka and Koshizuka (2000) and Oka (2003), a lot of fundamental research studies have been performed in extensive engineering fields, such as reactor design, thermal hydraulics, nuclear physics and materials etc. In the thermal hydraulic design of SCWR, it is important to know the detailed heat transfer characteristics of supercritical water under various flow conditions.

Although there is no phase change at supercritical pressure and the boiling crisis could be avoided fundamentally, supercritical water experiences a drastic property-variation process at the vicinity of the pseudo-critical temperature (Fig. 1), varying from a high density, liquid-like fluid to a low density, vapor-like fluid. This

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Nomenclature

c_p	specific heat [kJ/kg K]
$\overline{c_p}$	integrated specific heat, $(H_w - H_b)/(t_w - t_b)$ [kJ/kg K]
d_h	hydraulic diameter [m]
g	gravity [m/s^2]
G	mass flux [kg/m^2 s]
Gr	Grashof number, $\left((\rho_b - \rho_w) d_h{}^3 g\right)/\rho\nu^2$ [–]
$\overline{Gr}$	averaged Grashof number, $\left((\rho_b - \overline{\rho}) d_h{}^3 g\right)/\rho\nu^2$ [–]
H	enthalpy [kJ/kg]
K	temperature [K]
l	heated length [m]
Nu	Nusselt number, $(h \times d_h)/\lambda$ [–]
P	pressure [MPa]
Pr	Prandtl number [–]
$\overline{Pr}$	averaged Prandtl number, $\left((H_w - H_b)/(t_w - t_b)\right)\left(\mu_b/\lambda_b\right)$ [–]
q	heat flux [kW/m^2]
Re	Reynolds number [–]
t	temperature [°C]

Greek letters

β	thermal expansion coefficient [1/K]
μ	kinematic viscosity [m^2/s]
λ	thermal conductivity [W/m K]
υ	dynamic viscosity [Pa s]
ρ	density [kg/m^3]
$\overline{\rho}$	integrated density, $1/(t_w - t_b)\int_{t_b}^{t_w} \rho dt$ [kg/m^3]

subscripts

b	bulk
cal	calculated
exp	experimental
f	film, based on $(t_b + t_w)/2$
pc	pseudo-critical
w	wall

abbreviations

ms	measuring position

drastic variation leads to large non-uniform heat transfer over the flow channel and causes unusual heat transfer behaviors. In addition, the sharp change in fluid density brings about considerable buoyancy effect as well as thermal acceleration, which may result in heat transfer deterioration. Because the optimal design of rod bundle in a nuclear reactor requires an accurate prediction of heat transfer of the coolant and the rod temperature, a complete understanding of heat transfer characteristics of supercritical water in geometries relevant to nuclear reactor channel is essential to the design of SCWR fuel bundle.

Research activities on heat transfer of supercritical water have been performed since the 1950s. Several early experiments of Goldmann (1961), Shitsman (1963), Bishop et al. (1964), Swenson et al. (1965) and Yamagata et al. (1972) investigated local forced convection heat transfer in heated tube geometries at various heat fluxes and mass fluxes. They pointed out that heat transfer enhancement usually occurs when the bulk temperature is slightly lower than the pseudo-critical temperature while the wall temperature is higher than the pseudo-critical temperature. Moreover, they also found that enhanced heat transfer occurs at low heat fluxes but is impaired by increasing heat flux. The findings of Bazargan (2001) and Jackson (2006) showed that a remarkable

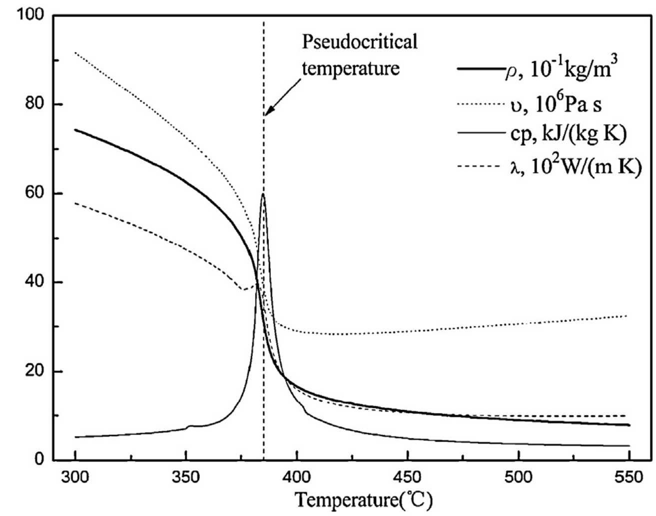

Fig. 1. Thermophysical property variation of water at 25 MPa.

heat transfer deterioration might take place when the heat flux is increased to a certain value. Shiralkar and Griffith (1970) determined the limits for safe operation in terms of the maximum heat flux for a given mass flux with the coolant of supercritical carbon dioxide. They found that the deteriorated heat transfer occurs at a high heat flux relative to mass flux. Koshizuka et al. (1995) conducted numerical analysis on the heat transfer deterioration phenomenon of supercritical water and derived an empirical correlation for predicting heat transfer coefficient. Based on the dimensional analysis of mixed convection heat transfer, Jackson and Hall (1979a) proposed a criterion of $Gr/Re^{2.7} < 1 \times 10^{-5}$ for negligible buoyancy effect in tube flow. Research of Zhang et al. (2010) showed that this criterion is satisfying for vertical upward flow, except in the pseudo-critical enthalpy region. On the other hand, the criterion of Jackson and Hall (Jackson and Hall, 1979a) was found inapplicable for horizontal flow by Bazargan et al. (2005). Recently, a lot of new empirical correlations have been developed to predict heat transfer at supercritical pressures. Mokry et al. (2011) summarized some widely-used heat transfer correlations nowadays. Since most of the correlations were developed in early stage, they believe that these correlations need update against new set of heat-transfer data. Based on dimensional analysis and a large number of data base, a new heat transfer correlation was developed. Cheng et al. (2009) believed that heat transfer at supercritical pressures was influenced by acceleration effect, buoyancy effect as well as property variation near the pseudo-critical temperature. They put forward three dimensionless numbers to account for these effects. A new correlation was developed covering both of the normal and deteriorated heat transfer modes.

Exhaustive literature reviews on heat transfer of supercritical water were summarized in the paper of Pioro and Duffey (Pioro and Duffey, 2005). Although much work has been conducted, the heat transfer characteristics of supercritical water have not been completely understood due to the complexity of variable-property flow in the pseudo-critical region. Moreover, geometries used in previous experiments were mainly restricted to circular pipes, little research has been done in annulus or bundle channel with supercritical pressure water. To accumulate fundamental experimental data for the design of SCWR fuel bundle, Xi'an Jiaotong University carried out experiments on heat transfer of supercritical water in annuli over a wide range of flow parameter. The objective of the present paper is to systematically analyze the heat transfer characteristics of supercritical water in 4 mm and 6 mm annular flow channels.