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Experimental study of supercritical water heat transfer deteriorations in different channels

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ABSTRACT

The experimental tests on heat transfer deterioration (HTD) of supercritical water flowing in 4 different kinds of channels, including tube, annular channel, and 2 × 2 bundle, have been carried out on the Supercritical WAter MUltiPurpose test loop (SWAMUP). The tube is made of Inconel alloy with different inner diameters; the annular channel consists of an Inconel alloy heated inner tube and a 304 stainless steel unheated outer tube. Two kinds of bundles were tested. The first kind of bundle consists of 4 Inconel-718 tubes with different Pitch-to-Diameter ratios, and the 2 × 2 bundle with grid spacers is installed into a square assembly box. The other kind of 2 × 2 bundle consists of 4 heater rods, and the rod bundle with wire wraps is also installed into a square assembly box. The heat transfer of supercritical water in simple channel like tube is stronger with larger cross-sectional flow area, but it is stronger with smaller cross-sectional flow area in complex channel like bundle. Two kinds of HTDs are observed in tube and annular channel, only the first kind of HTD is observed in bundle. The first kind of HTD occurs only at high ratio of heat flux to mass flow velocity in different channels, and the second kind of HTD is more likely to occur in simple channel which could be eliminated in bundle by the transverse turbulent flow. The effects of thermal–hydraulic and structural parameters on the second kind of HTD in tube are as follows: the HTD of supercritical water is severer with higher heat flux and the increment of wall temperature is much larger; the HTD occurs earlier and severer with lower mass flow velocity; the HTD delays and the wall temperature rises more slowly when the pressure rises; and the diameter has no evident effect on this kind of HTD. The heat transfer in bundles especially with wire wraps is qualitatively better and more stable than that in other tested channels. In order to avoid the first kind of HTD within the operating condition of SCWR, the low mass flow velocity condition and high heat flux condition should not occur at the same time during operation.

1. Introduction

As one of the six candidates of Generation IV (GEN-IV) innovational nuclear reactors recommended for further development, the supercritical water-cooled reactor (SCWR) is an once-through type water cooled reactor operating above the thermodynamic critical point of water (374.3 °C, 22.1 MPa) and supplying supercritical pressure steam with a high temperature for the turbine system (Oka and Koshizuka, 2000). The plant system is expected to achieve higher thermal efficiency, and more compact and simpler system than the existing nuclear power plants (Oka and Koshizuka, 2001). The design of SCWR is based on the proven light water reactor (LWR) technology and the experiences of supercritical fossil power plants. Several concepts of SCWRs have been studied in Japan, Europe, Canada and China in the last 10–20 years, examples are the Super Light Water Reactor and the Super Fast Reactor concepts studied by Oka et al. (2010), the High Performance Light Water Reactor documented by Schulenberg and Starflinger (2012), the Canadian SCWR outlined by Yetisir et al. (2013), or A Chinese SCWR concept presented by Li et al. (2013). For these SCWR concepts, the coolant is assumed to be operated well above the critical pressure at around 25 MPa, with a core inlet and outlet temperatures of about 280 °C and 500 °C to improve the thermal efficiency. The heat transfer of supercritical water is more complex than that of normal fluid because of the strong dependence of water thermo-physical property on temperature at supercritical pressure (Polyakov, 1991; Pioro and Duffey, 2005). One of the main features of supercritical water is the strong variation of its

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Nomenclature

C_p	Specific heat at constant pressure (J/kg °C)
D	Diameter (m)
D_n	Hydraulic diameter (m)
e	Error (–)
G	Mass flow velocity (kg/m^{2}s)
H	Specific enthalpy (J/kg)
I	Current (A)
k	Thermal conductivity W/(m°C)
L	Length (m)
Nu	Nusselt number (–)
M	Mass flow rate (kg/s)
P	Pressure (Pa)/Pitch (m)
Pr	Prandtl number (–)
q	Heat flux (W/m^2)
q_v	Volumetric heat flux (W/m^3)
R	Radius (m)
S	Perimeter (m)
T	temperature (°C)
U	Voltage (V)
W	Power (W)
Z	Axial location (m)
z	Ordinate (m)

Greek symbols

α	Heat transfer coefficient (W/m^2 °C)
δ	Thickness (m)
η	Heat efficiency (–)
μ	Average deviation (–)
π	Pi (–)
σ	Standard deviation (–)

Subscripts and superscripts

Ave	Average
I	Test section I
II	Test section II
III	Test section III
IV	Test section IV
b	Bulk
c	Calculated value
cr	Critical
e	Experiment data
i, j	Index
in	inner wall of the heating tube
inlet	Inlet
o	Outer wall of the heating tube/heater rod
out	Outlet
pc	Pseudo-critical
v	Volume
w	Wall

thermal-physical properties across the pseudo-critical point. This large variation of thermal-physical properties results in an unusual flow and heat transfer behavior. Operation across the pseudo-critical point should be carefully considered for it might cause a temporary boiling crisis with significantly variation of the thermal-physical properties of supercritical water. So the reliable knowledge of the thermal-hydraulic behavior at the relevant conditions of the SCWR is very important for the design of the reactor core.

Studies of thermal–hydraulic behavior of supercritical fluids have been performed since 1950s. The existing experimental and theoretical studies on heat transfer at supercritical pressure conditions were reviewed and published by several authors. Exhaustive literature search, carried out by Cheng and Schulenberg (2001) and Pioro and Duffey (2005), showed that the majority of experimental data were obtained in vertical tubes and some in annular channels, while experimental investigations devoted to heat transfer in bundles cooled with supercritical fluid are very limited in open literature. Bae and Kim (2009) carried out the supercritical flow heat transfer experiment in vertical tube and annular channel using CO_2. The heat transfer coefficient (HTC) and Nusselt number were obtained from the experiment and a heat transfer correlation was derived which can well estimate the HTC for supercritical water. Li et al. (2012) carried out the supercritical heat transfer experiment in tube using water, and the effects of thermal-hydraulic parameters on flow and heat transfer of supercritical water were researched. Bae et al. (2011) carried out heat transfer experiment of supercritical CO_2 flowing through annular channel with helical wires, they found out that heat transfer with wire wraps was enhanced several times compared with that without wire wraps. Wang et al. (2012) investigated heat transfer characteristics of supercritical water flowing in annular channel with wire wraps, they found that the affected distance of wire wraps depends strongly on flow condition and spiral interval. The wire wrap eliminates the phenomenon of heat transfer deterioration (HTD), which may occur at high ratio of heat flux to mass flow velocity. Razumovskiy et al. experimentally investigated the mean heat transfer of supercritical water in vertical 7-rod bundles (Razumovskiy, 2008) and 3-rod bundles (Razumovskiy, 2009). Li et al. carried out experiments on the heat transfer of supercritical water in 2 × 2 bundles with grid spacers (Li et al., 2015) and wire wraps (Li et al., 2017a) separately, the heat transfer enhancement caused by the grid spacers and a non-uniform circumferential wall temperature distribution were observed, the wire wraps used in the test could even the temperature nonuniformity on a certain degree. Wang et al. (2014) performed heat transfer experiments with supercritical pressure water flowing upward in a 2 × 2 bundle without spacing device. They assessed eight selected correlations against the experimental data, and found that the correlations of Jackson (Jackson and Hall, 1979; Jackson, 2002) and Ornatsky et al. (1970) provided the best prediction accuracies. However, all these heat transfer researches mentioned above didn't focus on the transient heat transfer which may occur during the SCWR operation.

The special characteristic of fluid near the thermodynamic critical point, which is also stated as pseudo-critical point, is that their thermodynamic properties vary rapidly with temperature and pressure. Some experimental studies have been carried out on the transient heat transfer near the thermodynamic critical point. Li et al. (2017b) and Li et al. (2017c) carried out transient heat transfer in 2 × 2 bundle with wire wraps across the critical pressure, boiling crisis occurs and the wall temperature rises significantly during both pressurization and depressurization which indicates the heat transfer is unstable near the thermodynamic critical point. A similar large variation in the fluid properties exists at the pseudo-critical point in the supercritical pressure region which might also cause boiling crisis. Therefore, it is essential to investigate on the thermal hydraulic characteristics of supercritical fluids for the operation across the pseudo-critical point at supercritical conditions of the SCWRs. Only a few researches have been published which focused on the boiling crisis. Vikhrev et al. (1967) mainly studied the HTD of supercritical water in upright tube in