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Experimental study on heat transfer of supercritical water flowing upward and downward in 2 × 2 rod bundle with wrapped wire

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ABSTRACT

Heat transfer to supercritical water flowing upward and downward in a 2 × 2 rod bundle with wrapped wire was experimentally investigated. The rod bundle consists of four heating rods within out-diameter of 10 mm. The rods are arranged in a 2 × 2 square array and the pitch-to-diameter ratio is 1.18. The bundle is inserted into a square assembly box with round corners. The water as coolant flows upward or downward in the channel between the rod bundle and the assembly box. The pressure ranges from 23 to 26 MPa, mass flux ranges from 450 to 1200 kg/(m^2 s), heat flux ranges from 200 to 1000 kW/m^2, and the fluid temperature ranges from 200 to 450 °C. The effects of system parameters including mass flux, heat flux and pressure on the heat transfer are presented, respectively. The heat transfer deterioration occurs at a low G/q ratio in the upward flow, but does not appear in the downward flow. Watts-Chou correlation and Bishop correlation give the best predictions when evaluated against the experimental data both in the upward and downward flow. The experimental data are compared with the bare rod bundle. The comparison indicates that the swirl flow of wrapped wire promotes the heat transfer in the rod bundle.

1. Introduction

The supercritical water-cooled reactor (SCWR) is identified by Generation-IV International Forum (GIF) as one of six advanced concept reactors. The supercritical water has a high heat capacity in the pseudo-critical area, so the coolant flow rate in the SCWR is much less than a conventional reactor. Moreover, without a steam generator, the size of the SCWR is reduced with simplified facilities. There is no phase transition in supercritical water, and the burning phenomenon will not occur in the reactor core. Its economy and security are expected to be greatly improved. The properties of supercritical water near the pseudo-critical region exhibit rapid variations, leading to particular heat transfer characteristics. These characteristics are distinguishing in various flow channels with different spacers, which include grid spacer (Dobashi et al., 1998; Squarer et al., 2003) and wrapped wire (Bae et al., 2004; Schulenberg et al., 2008). Therefore, the heat transfer behavior in supercritical pressure fluids is the focus of SCWR research.

The heat transfer characteristics of supercritical fluids have been studied widely by scholars (Swenson et al., 1965; Yamagata et al., 1972; Gang et al., 2011). Cheng and Schulenberg (2001), Pioro and Duffey (2005), Jackson (2013) made detailed summery reports. CO_2 (Krasnoshchekov and Protopopov, 1959; Dong and Kim, 2011; Bae et al., 2011), Freon (Richards et al., 2012; Zhang et al., 2014), and water (Zhao et al., 2013; Wang et al., 2014; Gu et al., 2015, 2016; Razumovskiy et al., 2016) were used as the working medium by most of testers. Due to the technical limitation, the supercritical research in rod bundle was scarcer than circular and annular channels. Recently, Shanghai Jiao Tong University and Xi'an Jiao Tong University carried out a series of experimental studies on heat transfer of supercritical water in 2 × 2 rod bundle. Zhao et al. (2013) conducted an experiment on heat transfer of supercritical water in 2 × 2 rod bundle with spacers. The pitch-to-diameter ratios (P/D) were 1.18 and 1.3, respectively. They reported that the spacer enhanced the downstream heat transfer. The heat transfer deterioration was not observed in the fully developed region. Gu et al. (2015) performed an experiment on heat transfer of supercritical water in 2 × 2 bare rod bundle. They found the non-uniformity of circumferential wall temperature distribution in heater rods. The effects of heat flux, mass flux, and pressure on heat transfer in bundle were similar to tube and annuli. The high heat flux would lead to a low heat

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Nomenclature

Cp	specific heat at constant pressure (J/(kg °C)
D	diameter (m)
e	error (–)
G	mass flux (kg/m^2 s)
H	specific enthalpy (J/kg)
L	length (m)
N	total number of data points (–)
Nu	Nusselt number (–)
M	mass flow rate (kg/s)
P	pressure (MPa)
Pr	Prandtl number (–)
$\bar{P}_r$	average Prandtl number (–)
q	heat flux (W/m^2)
R	radius (m)
T	temperature (°C)
x	axial location along the heated length (m)
z	axial location (m)
Greek symbols	
α	heat transfer coefficient (W/(m^2·°C))
β	volumetric expansion coefficient (/°C)
λ	thermal conductivity (W/(m·°C))
ρ	density (kg/m^3)
μ	average deviation (-)
σ	standard deviation (-)
Subscripts and superscripts	
b	bulk
cal	calculated value
exp	experiment data
in	inlet
out	outlet
pc	pseudo-critical
v	volume
w	wall
Acronyms	
AC	alternating current
DC	direct current
GIF	generation-IV International Forum
HTC	heat transfer coefficient
HTD	heat transfer deterioration
OD	out diameter
P/D	pitch-to-diameter
SCWR	supercritical water-cooled reactor

transfer coefficient. Wang et al. (2014) carried out a heat transfer experiment in 2 × 2 rod bundle without spacers. At the surface of the heater rods, the high temperature appeared at the direction of corner subchannel while the low temperature was close to the center subchannel. They analyzed the effects of the thermal-hydraulic parameters and did not experience heat transfer deterioration in their working conditions. Gu et al. (2016) carried out an experiment on heat transfer of supercritical water in 2 × 2 rod bundle with wrapped wire and two paths. The ratio of heat transfer from the second path to the first path was less than 0.14 under their test cases. They reported that the heat transfer deterioration occurred and the wrapped wire could strengthen the heat transfer.

According to the latest open literature, all supercritical water experiments in rod bundle were performed flowing upward. The heat transfer data of supercritical water flowing downward in rod bundle is lacking. In this paper, the experimental studies on heat transfer of supercritical water flowing upward and downward in a 2 × 2 rod bundle with wrapped wire are presented.

2. Experimental process

2.1. Experimental facility

The experiment has been performed at the SWAMUP-II test facility in Shanghai Jiao Tong University. The scheme of the facility is shown in Fig. 1. The main loop consists of two plunger pumps, a pre-heater, a re-heater, a mixing chamber, a heat exchanger, a water tank and a test section. It is designed for pressure up to 35 MPa, temperature up to 550 °C, and mass flow rate up to 2.8 kg/s. The deionized water in the tank is driven by the plunger pump. Main flow goes through the re-heater to absorb the heat of the hot fluid coming from the outlet of the test section. It passes the pre-heater to be heated up to a pre-defined temperature and enters the test section. Then hot fluid leaving the test section releases the heat at the re-heater. The cooled water leaving the re-heater is mixed with the cold flow from the bypass line before it enters the heat exchanger. After fully cooled by the heat exchanger, the flow goes back to the water tank.

The pre-heater is directly heated by AC power with a maximum heating capability of 600 kW. The test section is heated by DC power with a maximum heating capacity of 900 kW. Two Venturi flow meters with different ranges are installed in parallel in the main flow path to measure the mass flow rate of the water entering the test section. The pressure at the inlet of the test section is controlled by adjusting the pressure regulator valve at the exit of the main loop and measured by a Yokogawa EJA-150A capacitance-type pressure transducer. The pressure drop over the test section is obtained using a Yokogawa EJA-130A capacitance-type differential pressure transducer. Fluid temperatures at the inlet and the outlet of the test section are measured by two sheathed N-type thermocouples with sheath of outer diameters of 0.5 mm. All data are collected and recorded using a National Instrument data acquisition system.

2.2. Test section

The structure of the test section is shown in Fig. 2. A square assembly box with round corners is installed in a stainless tube with an inner diameter of 38 mm as the pressure vessel. Four rods with an outer diameter of 10 mm arranged in a 2 × 2 square array with a P/D = 1.18 are inserted into the assembly box. The rods are fixed by a grid spacer at inlet direction of upward flow as shown in Fig. 2(c) and wrapped by wires along the whole bundle. The diameter and axial pitch of the wrapped wire on each heater rod are 1.65 mm and 250 mm, respectively. Cross-sectional geometry of the test section is shown in Fig. 2(d). Each heater rod is uniformly heated by DC power and the available heated length is 750 mm from the starting point at the axial position of Z = 0 which is 33 mm above the grid spacer.

Eight thermocouples (0.5 mm OD, sheathed N-type) are fixed on each heater rod surface at eight axial positions from Z1 to Z8. Thus, there are four thermocouples fixed at each axial cross section in the 2 × 2 rod bundle. The wires rotate clockwise viewing in flow direction from bottom to top around the four heater rods starting from the cross section Z = 0 mm. The Arrangements of thermocouples and wires at the eight cross sections are listed in Table 1.