EXPERIMENTAL RESEARCH ON HEAT TRANSFER OF SUPERCRITICAL WATER UPFLOWING IN VERTICAL TUBE

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Abstract

Heat transfer experiments in vertical tube were performed in Supercritical Water Thermal-hydraulic Mechanism Test (SCTM) Loop in Nuclear Power Institute of China. The test tube was 3.0 m long and the inner diameter of 6.0 mm. Experimental condition covered pressures of 23, 24 and 25MPa, mass flux of 600-1200 kg/m^2•s, heat flux of 600-1100kW/m^2, and bulk temperatures of 300-500℃. The experimental data were compared with several current correlations, respectively. It showed that these correlations could not predict heat transfer coefficient accurately in pseudo-critical area.

Keyword: Supercritical water, heat transfer, upward flowing, vertical tube

1. Introduction

The Supercritical Water Cooled Reactor (SCWR) belongs to the six reactor types currently being investigated within the framework of the Generation IV International Forum, which are expected to exceed the current nuclear reactors in reliability, safety, electricity generation costs and proliferation resistance [1]. The most visible advantages of the SCWR are the low construction costs because of size reduction of components and buildings compared to current PWR and the low electricity production costs due to high efficiency (approaching 44%)[2-3]. In China, SCWR is competitive and promising in Generation IV system not only for the low construction costs and the low electricity production costs, but also for successive technology of Chinese PWR roadmap and technology base of current supercritical-water-cooled fossil-fired power plants.

Supported by Chinese Government, Nuclear Power Institute of China (NPIC) started SCWR technology research in 2010, which aimed at the design and construction of first prototype SCWR in China. One of the important SCWR technologies is thermal hydraulic performance of the reactor system, which influences the SCWR safety, plant design and economics directly [4]. The supercritical water environment is unique and deficient data exist on the thermal hydraulic performance of water with complicated fuel assembly geometries under high heat flux (about megawatt per square meter level) in near-critical and pseudo-critical area [5].

This paper devoted to the experimental research of heat transfer in vertical bare tube with a length of 3.0m and an inner diameter of 6.0mm, which were performed in Supercritical Water Thermal-hydraulic Mechanism Test (SCTM) Loop. The Experimental condition covered pressures of 23, 24 and 25MPa, mass fluxes of 600-1200 kg/m^2•s, heat fluxes of 600-1100kW/m^2, and bulk temperatures of 300-500℃

2. Test Loop and experimental conditions

2.1 Description of the SCTM Loop

SCTM Loop was designed and constructed in NPIC for experimental research on SCW flow resistance and heat transfer with single/double pipe. The test loop not only supported supercritical water thermal-hydraulic test technology research, but also produced basic thermal hydraulic experimental data of supercritical water for CFD model and numerical research.

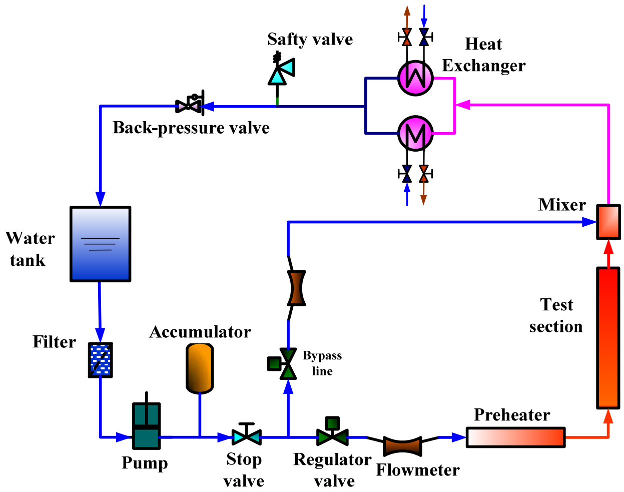
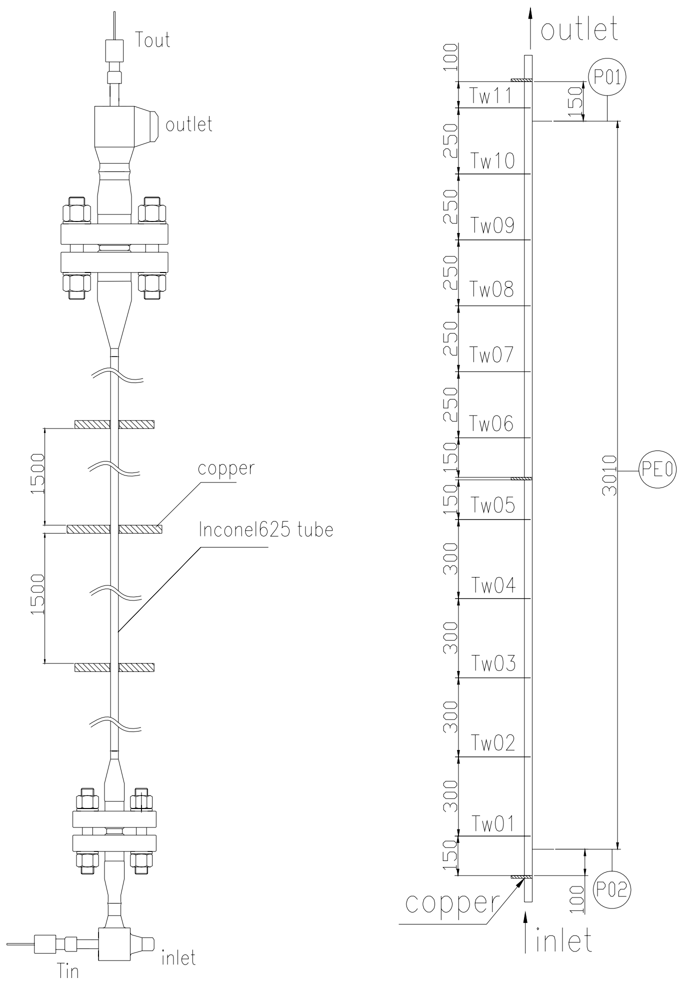


Fig.1 Schematic diagram of SCTM loop

The schematic diagram of SCTM Loop was shown in Fig.1. Distilled and de-ionized water from water tank was driven through a filter by a high pressure plunger pump which had a capacity of operating at up to 32MPa and mass flow rate supply up to 0.5t/h, an accumulator was used to control the loop pressure. The mass flow rate of test section was controlled and measured by regulator valves and flow meters in the test line and bypass line. Before flowing into the test section, water was preheated to the demanded temperature in the pre-heater which heated directly by a 240kVA AC power supply. The heat flux of the test section was controlled by a 600kW DC power supply. Water from test section outlet of temperature up to 550℃ mixed with water from bypass line of room temperature in the mixer and then flowed into two heat exchangers. The heat exchangers cooled down the water from the mixer to room temperature with circulating cooling water. Passing by the back-pressure valve, the water's pressure decreased to atmospheric pressure from supercritical pressure and then it flowed back to the water tank. The loop was controlled and measured with a control and data acquisition system which hardware provided by NI Company and Solartron Mobrey Company.

2.2 Test section

Fig.2a showed detailed structure of the single tube test section. The test tube was made of Inconel 625, which inner diameter of 6mm, thickness of 2.0mm and active heated length of 300cm. The tube was shunt-wound heated through three copper by a 600kW DC power supply. Besides 2 N-type thermocouples to measure the temperature of test section inlet and outlet, there were 11 outer wall temperature measure sections along the test tube and 2 N-type thermocouples fixed in every section. Also there was 1 pressure drop measure area with differential pressure transmitter to measure the total pressure drop. Fig.2b showed the detailed temperature and pressure drop measuring points distributing along the tube. Tab.1 showed the uncertainties of measured parameters.



(a) detailed drawing of test section (b) measuring points distributing of test section

Fig.2 Test section

Tab.1 Uncertainties of measured parameters

Parameter	Maximum uncertainties
Temperature	±1.3℃
Mass flowrate	±0.77%
Pressure	±0.75%
Pressure difference	±0.63%
Heated power	±1.12%

2.3 Experimental condition

Experiments were performed changing pressure and heat flux at given mass flow rate. The pressure selected were 23, 24 and 25MPa, the mass flux changed from 600 kg/m^2•s to 1200 kg/m^2•s, the heat flux ranged from 600kW/m^2 to 1100kW/m^2. Tab.2 showed the detailed parameters of the experiment conditions.

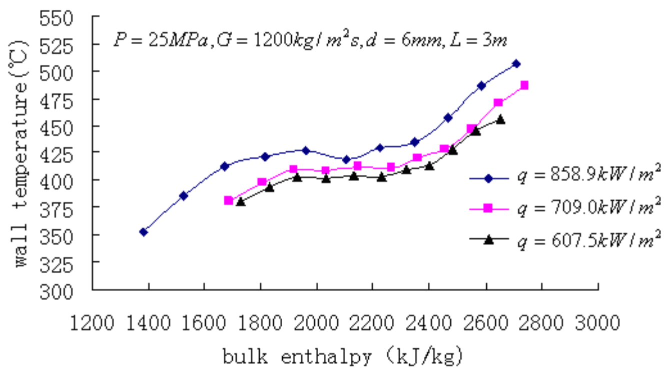
Tab.2 Experimental condition

Parameter	Range
Pressure(MPa)	23,24,25
Mass flux (kg/m^2•s)	600～1200
Heat flux(kW/m^2)	600～1100
Bulk temperature（℃）	300～500

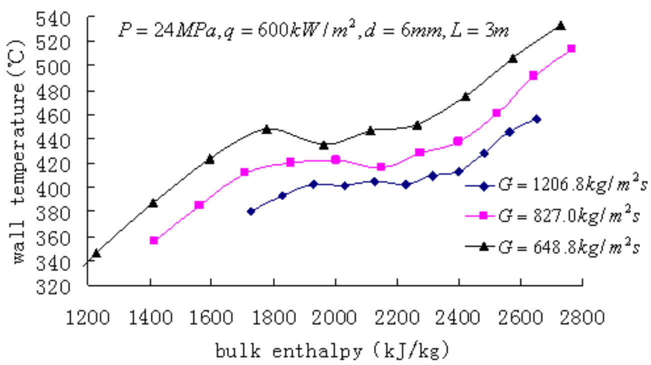
3. Results and discussion

3.1 The effect of mass flux, heat flux and pressure to heat transfer

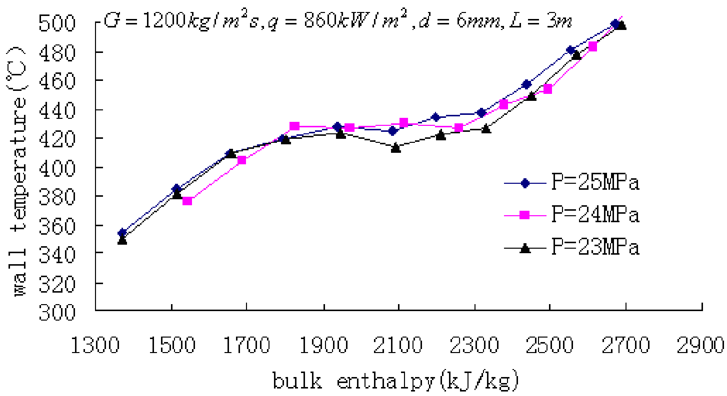
Fig.3 showed the effect of mass flux, heat flux and pressure to wall temperature. At pressure of 25 MPa and the mass flux of 1200 kg/m^2•s, wall temperature of the test section increased entirely as the heat flux increasing from 607.5 to 858.9 kW/m^2. Also at the same pressure of 24MPa and low heat flux of 600 kW/m^2, the tube wall temperature changed dramatically when the mass flux decreasing from 1206.8 to 648.8 kg/m^2•s. At normal heat transfer condition, experimental pressure affected the inner wall temperature of the tube unobvious.



(a) Wall temperature at 25MPa, 1200 kg/m^2•s with different heat flux



(b) Wall temperature at 24MPa, 600 kg/m^2•s with different mass flux



(c) Wall temperature at 860 kW/m^2, 1200 kg/m^2•s with different pressure

Fig.3 Effect of mass flux, heat flux and pressure to heat transfer

There were several heat transfer correlations developed to calculate heat transfer coefficient (HTC) in forced convection of SCW. Majority of the correlations were based on D-B correlation with various modified factors. The correlations used in this paper to predict the wall temperature and HTC were showed in Tab.3.

Tab.3 Heat transfer correlations for comparison

Author	Correlation
Bishop(1964)[6]	$Nu_B = 0.0069 \cdot \mathrm{Re}_B^{0.90} \cdot \overline{\mathrm{Pr}}_B^{0.66} \cdot \left(\frac{\rho_w}{\rho_b}\right)^{0.43} \cdot \left(1 + \frac{2.4 \cdot D}{L}\right)$ $\overline{\mathrm{Pr}}_B = (\bar{C}_p \cdot \mu_B / \lambda_B)$ $\bar{C}_p = \frac{h_w - h_b}{T_w - T_b}$
Swenson(1965)	$\frac{hD}{k_W} = 0.00459 \cdot \left(\frac{DG}{\mu_W}\right)^{0.923} \cdot \left(\frac{H_W - H_b}{T_W - T_b}\frac{\mu_W}{k_W}\right)^{0.613} \cdot \left(\frac{\rho_W}{\rho_b}\right)^{0.231}$
Jackson(2002)	$Nu = 0.0183\mathrm{Re}_b^{0.82}\mathrm{Pr}_b^{0.5}\left(\frac{\rho_w}{\rho_b}\right)^{0.3}\left(\frac{\bar{c}_p}{c_{pb}}\right)^n$ $n = \begin{cases} 0.4 & T_b < T_w < T_{pc} \text{ and } 1.2T_{pc} < T_b < T_w \\ 0.4 + 0.2(\frac{T_w}{T_{pc}} - 1) & T_b < T_{pc} < T_w \\ 0.4 + 0.2(\frac{T_w}{T_{pc}} - 1)\left[1 - 5(\frac{T_b}{T_{pc}} - 1)\right] & T_{pc} < T_b < 1.2T_{pc} \end{cases}$
Watts（1982）	$Nu = Nu_{\mathrm{var}P}\left[1 - \frac{3000\overline{Gr}_b}{\mathrm{Re}_b^{2.7} \cdot \overline{\mathrm{Pr}}_b^{0.5}}\right]^{0.295}$ $\quad \frac{\overline{Gr}_b}{\mathrm{Re}_b^{2.7} \cdot \overline{\mathrm{Pr}}_b^{0.5}} < 10^{-4}$

	$Nu = Nu_{\text{var}\,P}\left[\dfrac{7000\overline{Gr_b}}{\text{Re}_b^{2.7}\cdot\overline{\text{Pr}_b}^{0.5}}\right]^{0.295}$	$\dfrac{\overline{Gr_b}}{\text{Re}_b^{2.7}\cdot\overline{\text{Pr}_b}^{0.5}} > 10^{-4}$
	$Nu_{\text{var}\,P} = 0.021\text{Re}_b^{0.8}\cdot\overline{\text{Pr}_b}^{0.55}\left(\dfrac{\rho_w}{\rho_b}\right)^{0.35}$	

Fig.4 showed the comparison between experimental data and results calculated by 4 correlations. It was found that the wall temperature and HTC agree well between experimental data and correlations calculated results apart from pseudo-critical area. In pseudo-critical area there were a peak of HTC in both of experimental data and correlations calculated results. However, values of the HTC peek were quite different, and the experimental data was lower than the results of Bishop(1964), Jackson(2002) and Watts（1982）correlations.

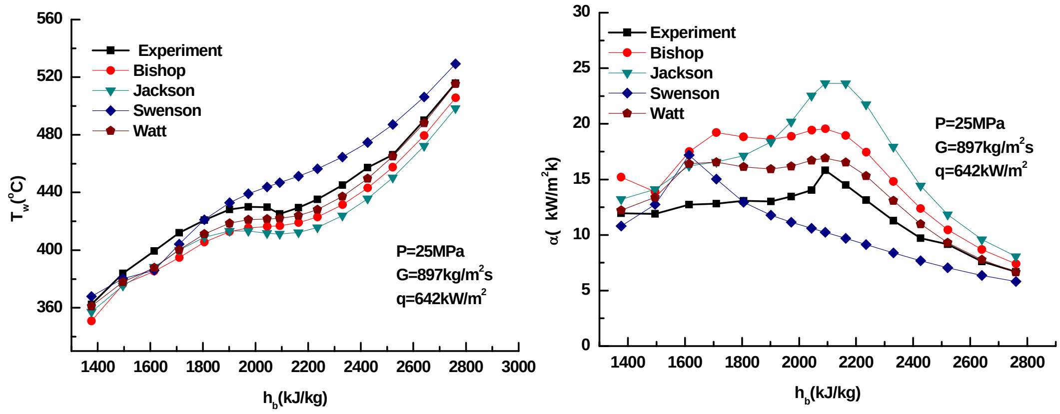


Fig.4 Comparison between experimental data and results calculated by correlations

3.2 Heat transfer deterioration phenomenon

During the experiment, it was also found heat transfer deterioration phenomenon at different pressure and mass flux. Fig.5 showed the wall temperature of the test tube at 25, 23MPa with different heat flux. When the flow flux was fixed, a peak and trough of the wall temperature arose clearly in pseudo-critical area during the increasing of heat flux. And the peak was nearly 50℃ higher than the following trough when the ratio between heat flux and mass flux approach 1.

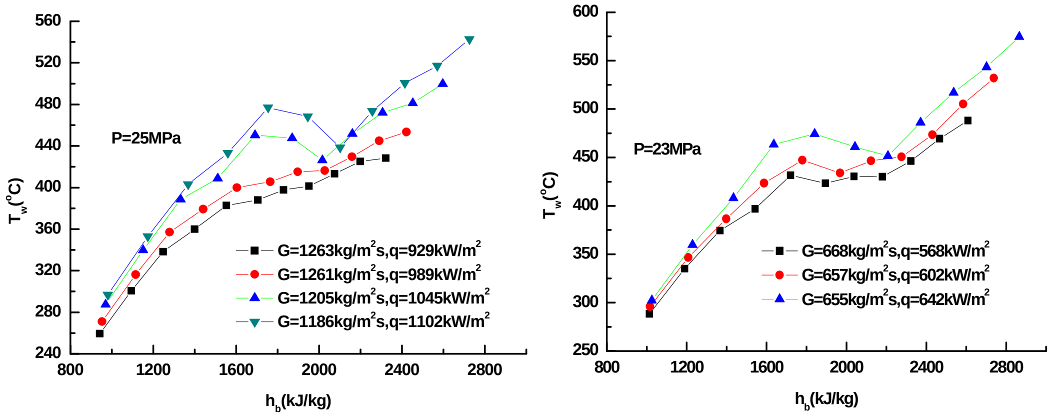


Fig.5 Heat transfer deterioration phenomenon in 25 and 23MPa

4. Conclusions

Heat transfer experimental research of SCW upward flowing in vertical bare tube was carried out in SCTM Loop of NPIC. At normal heat transfer condition, experimental pressure affected the inner wall temperature of the tube unobvious, but mass flux and heat flux influenced evidently. The experimental data were compared with Bishop(1964), Swenson(1965), Jackson(2002) and Watts（1982）correlations, respectively. It showed that these correlations could not predict heat transfer coefficient accurately in pseudo-critical area. Heat transfer deterioration phenomenon at different pressure and mass flux was observed as the heat flux increasing gradually.

5. References

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