# EXPERIMENTAL INVESTIGATION ON HEAT TRANSFER OF SUPERCRITICAL PRESSURE WATER IN ANNULAR CHANNEL

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## Abstract

This paper presents the experimental results of the heat transfer characteristics of water in vertical annulus. The experiments were carried out in the high pressure steam-water test loop in Xi'an Jiaotong University. Experiments were performed within the range of pressure from 23 to 28MPa, mass velocity from 700 to 2500 kg/(m$^2$.s), and heat flux from 200 to 1000kW/m$^2$. Based on the experimental results, the effects of mass flux, heat flux and pressure on heat transfer of supercritical pressure water in vertical annular channel were analyzed. The characteristics and mechanisms of heat transfer enhancement, and that of heat transfer deterioration, were also discussed.

## 1. Introduction

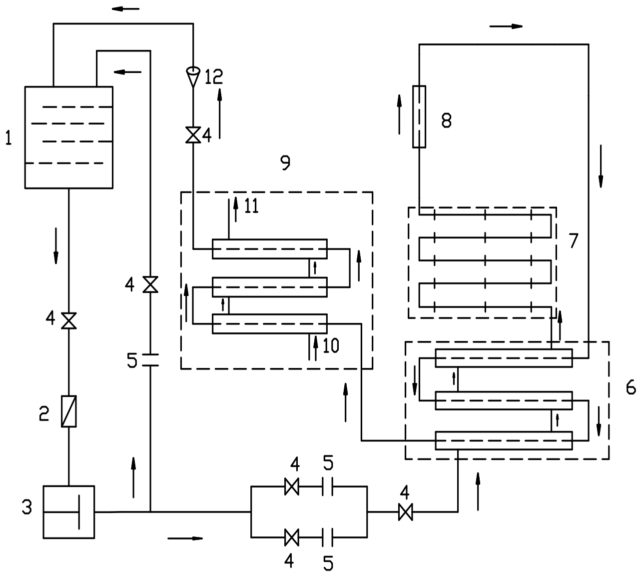
The supercritical pressure water-cooled reactor (SCWR) is one of the six reactor technologies selected for research and development under the Generation Ⅳ international Forum in 2002. It has the potential advantage of minimization of nuclear waste and low capital cost due to its high thermal efficiency and simplifications of the plant system. A SCWR power plant may achieve a high thermal efficiency (about 45% vs. about 35% efficiency for advanced LWR). It is operated above the critical pressure of water, where the reactor coolant experiences no phase change. Because of this, the SCWR plant system can be kept simply as the need for many of the traditional LWR components such as the coolant recirculation pumps, pressurizer, steam generator, and steam separator and dryer is eliminated. One of the main features of supercritical water is the strong variation of its thermal-physical properties in the vicinity of the pseudo-critical line. Although operation above the critical pressure eliminates coolants boiling, and the coolants remains single-phase throughout the system, the large variation of thermal-physical properties may result in unusual heat transfer which demands further investigations.

There are various design proposals of an SCWR core, the University of Tokyo has studied such reactors in detail since about 1990. Some results have been summarized, e.g. by Oka and Koshizuka (2000) [1-2]. In Europe, the common program High Performance Light Water Reactor (HPLWR), first announced by Heusener et al [3] (2000), has been launched with the main objective to assess the technical and economic feasibility of a high efficiency LWR operating at supercritical pressure. One of the emphases for SCWR is the thermal-hydraulics behavior, especially the heat transfer characteristics of water at supercritical conditions, which differ strongly from that at sub-critical conditions, due to a rapid variation of the thermal-physical properties in the vicinity of the pseudo-critical line. Heat transfer deterioration would occur at high heat fluxes, and low mass fluxes, which leads to a strong reduction in the heat transfer coefficient. Therefore, a profound knowledge of heat transfer characteristics at reactor relevant conditions is necessary for the design work of SCWR. In the 1950s, using supercritical steam-water became an attractive idea for steam generators to increase the thermal efficiency of fossil-fired power plants. Intensive work was done on this subject from 1950's till now. Swenson et al (1965) [4] found that heat transfer coefficients (HTC) has a peak when the film temperature is within the pseudo-critical temperature range, and this peak in HTC decreases with increase in pressure and heat flux. Shiralkar and Geiffith[5] determined the limits for safe operation in terms of maximum heat flux for a particular mass flux with the coolant of supercritical carbon dioxide, they found that the deteriorated heat transfer occurred at a high heat flux relative to the mass flux. Yamagata [6] et al. (1972) found that the HTC increases significantly in the pseudo-critical region for water in vertical and horizontal tubes. He indicated that the heat transfer deterioration was decided by heat flux and mass flux, and gave the limit value of heat flux: $q_c = 0.2G^{1.2}$ for vertical upward tube with an inner diameter of 10mm. Yashida and Mori(2000) [7] stated that the enhancement and deterioration phenomena of heat transfer in the great specific heat region is caused by drastic variations of physical properties with temperature change across the coolant. However, the flow geometries used in previous experiments were mainly restricted to circular tubes. There are few publications devoted to heat transfer in bundle and annuli cooled with water at supercritical pressure. This paper presents the experimental results of the heat transfer characteristics of water in vertical annulus. Experiments were performed within the range of pressure from 23 to 28MPa, mass flux from 700 to 2500 kg/(m$^2$.s), and heat flux from 200 to 1000kW/m$^2$. Based on the experimental results, the effects of mass flux, heat flux and pressure on heat transfer of supercritical pressure water in vertical annular channel were analyzed. The characteristics and mechanisms of heat transfer enhancement, and that of heat transfer deterioration, were also discussed.

## 2. Experimental facility and methods

The experiments were carried out in the High Pressure Steam-water Test Loop in Xi'an Jiaotong University. The schematic diagram of the test loop is shown in Fig.1. Distilled and de-ionized feed water from the water tank is driven through a filter by a high pressure plunger-type pump which is cable of operating at up to 40 MPa. The feed water is pre-heated in a heat exchanger and a main pre-heater before flowing into the test section. The pre-heater and the test section are electrically heated by alternating current power supply with maximum heating capacities of 1.0MW and 0.5 MW, respectively. Therefore, we can adjust the test section inlet bulk temperature and heat flux simply by controlling the alternating current power supply. The heat of feed water flowing from the test section was removed by a regenerative heat exchanger and a condenser, and then flowed back to the water tank. The pressure and the mass flux in test section are controlled by adjusting the main valve and bypass valve, respectively.

The annular test section geometry is a $\Phi 8 \times 1.5$mm stainless steel (1Cr18Ni9Ti) circular pipe within a $\Phi$20x2.0mm circular pipe, with the gap of 4.0mm and the hydraulic diameter of 8mm. The electrically-heated length of the test sections is 2 m. The inner pipe and outer piper are thermally insulated to minimize the heat loss. As illustrated in Fig.2. The sealing structure is used on the both ends of the test section to guarantee the electric insulation between the inner and outer pipes as well as the test section's hermetic capability under the pressure of 25MPa. Double Sealing structure is used of the test section: flange 2 and outer pipe are wielded together and flat seal structure is adopted between flange 1 and flange 2 with gasket seal. There is a stuffing box between flange 1 and inner pipe and packing seal could be achieved through the gland's squeeze to stuffing, graphite.




1: Water tank; 2: Filter; 3: Water pump; 4: Valve; 5: Orifice;
6: Heat exchanger; 7: Preheater; 8: Test section; 9: Condenser;
10: Cooling water inlet; 11: Cooling water outlet; 12: Rotor flow meter

Fig.1 Schematic diagram of the test loop

The annular test section geometry is a Φ8 × 1.5mm stainless steel (1Cr18Ni9Ti) circular pipe within a Φ20x2.0mm circular pipe, with the gap of 4.0mm and the hydraulic diameter of 8mm. The electrically-heated length of the test sections is 2 m. The inner pipe and outer piper are thermally insulated to minimize the heat loss. As illustrated in Fig.2. The sealing structure is used on the both ends of the test section to guarantee the electric insulation between the inner and outer pipes as well as the test section's hermetic capability under the pressure of 25MPa. Double Sealing structure is used of the test section: flange 2 and outer pipe are wielded together and flat seal structure is adopted between flange 1 and flange 2 with gasket seal. There is a stuffing box between flange 1 and inner pipe and packing seal could be achieved through the gland's squeeze to stuffing, graphite.

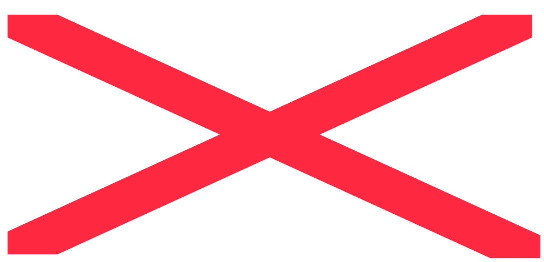


Fig.2 Structure of the test section

The inner pipe of test section is heated through directly supplying power (Low Voltage and High Current) and can achieve the heating condition of variable Heat Flux Density. Heat transfer experiment is carried out via the heavy-current transformer connected to the copper heat sink which is well-matched to the outer diameter of both ends of the inner pipe. When the current passes the inner pipe, it produces Joule Heat and heats the inner pipe as well as the water inside it.

Since the temperature of inner pipe is higher than outer pipe, the axial expansion of inner pipe is consequently larger than that of outer pipe. When the bulk temperature is up to 400℃, the inner pipe is flexible and thus likely to be twisty and oscillate. So, it was found necessary to add spacers along the annular channel to hold the inner pipe in the center of the annular geometry and to prevent oscillations. Thus, the following two methods were adopted:

- The sealing structure ensures that the inner pipe has certain free dilatability in axial direction.
- Set three support points(spacer) along the axial of the test section. Each point is composed of three ceramic sticks which are uniformly distributed in circumferential direction on the cross section. As shown in Fig.3.

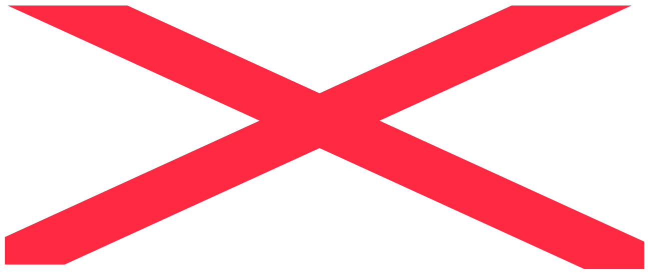


Fig.3 Structure of the spacer

The inner pipe is heated through directly supplying power (Low Voltage and High Current) and can achieve the heating condition of variable Heat Flux Density. Heat transfer experiment is carried out via the heavy-current transformer connected to the copper heat sink which is well-matched to the outer diameter of both ends of the inner pipe. When the current passes the inner pipe, it produces Joule Heat and heats the inner pipe as well as the water inside it.

When it is electrified, the overheating in non-cooling area on both ends will exert an unfavorable influence on sealing structure. So, the method of plating silver on both ends of the inner pipe is used to lower partial thermal resistance, so as to reduce remarkably the partial heat.

The experiment was performed at steady state experimental conditions close to operating conditions of an SCWR. The pressures are of 23, 25 and 28MPa, the mass flux is from 400 to 2500 kg/($m^2$ s), and the heat flux varies from 200 to 800 kW/$m^2$.

The experiment was carried out as follows: adjusted the mass flux, system pressure and the heat flux of the test section to given values, while increasing the heating power of the pre-heater step by step, so the bulk enthalpy of the test section increased correspondingly. The test was finished once the wall temperature was over 700℃ due to heat transfer deterioration or the heating power reached the maximum. Then adjusted the mass flux, system pressure and the heat flux of the test section to another given values and began the next test.

## 3. Experimental results and discussions

### 3.1 The effect of mass flux on wall temperature and heat transfer coefficients (HTC)

Fig.4 (a)~(f) show the examples of wall temperature and HTC plotted against bulk enthalpy, respectively, for the vertical annular channel of a heat flux as 600 kW/m$^2$ at three different mass flux of 400,700,1000 kg/(m$^2$s) and the pressure of 23,25,28MPa. .

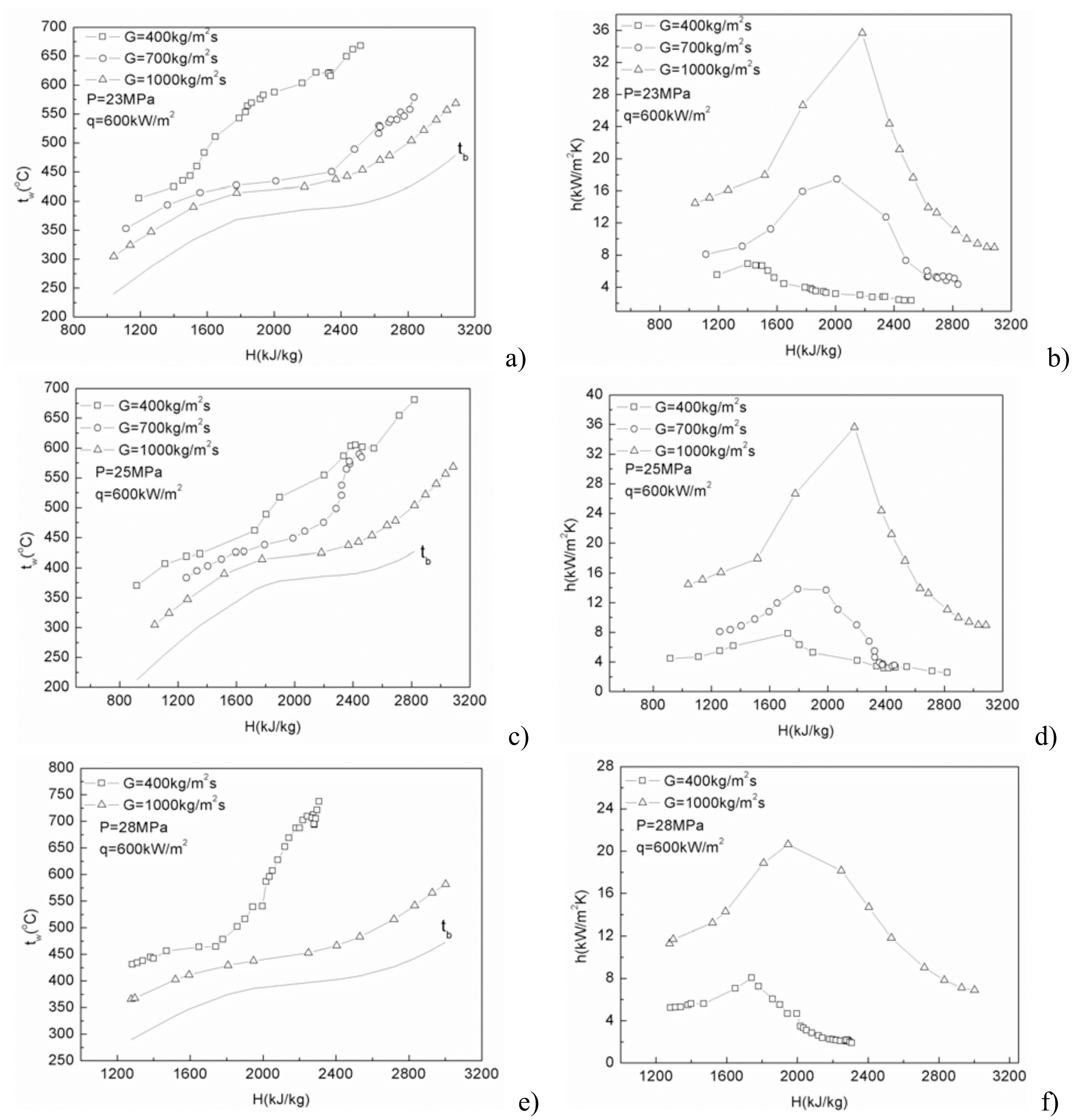



Fig.4 Comparison of the wall temperatures and HTC at different mass fluxes

The heat transfer to supercritical water flowing in tube was found to be roughly classified into two different regimes according to the heat flux relative to the mass flux. At a relatively high mass flux of 1000 kg/(m$^2$s), when the bulk temperature becomes closer to the pseudo-critical temperature, the HTC increases abruptly, and takes a maximum at a bulk temperature which is close to the pseudo-critical temperature. However, the heat transfer enhancement is diminished at a relatively low mass flux of 400 kg/ ($m^2$s). Deterioration of heat transfer occurs when the mass flux reduces from 1000 to 400 kg/ ($m^2$s) at the pressure of 23, 25 and 28MPa. The HTC depends strongly upon the mass flux, especially in the pseudo-critical region, and its maximum value increases with increase of mass flux.

### 3.2 The effect of heat flux on wall temperature and heat transfer coefficients (HTC)

Fig.5 (a)~(f) show the examples of wall temperature and HTC plotted against bulk enthalpy, respectively, for the vertical annular channel of a mass flux as 400 kg/($m^2$s) at three different heat flux of 200,400,600 kW/$m^2$ and the pressure of 23,25,28MPa.

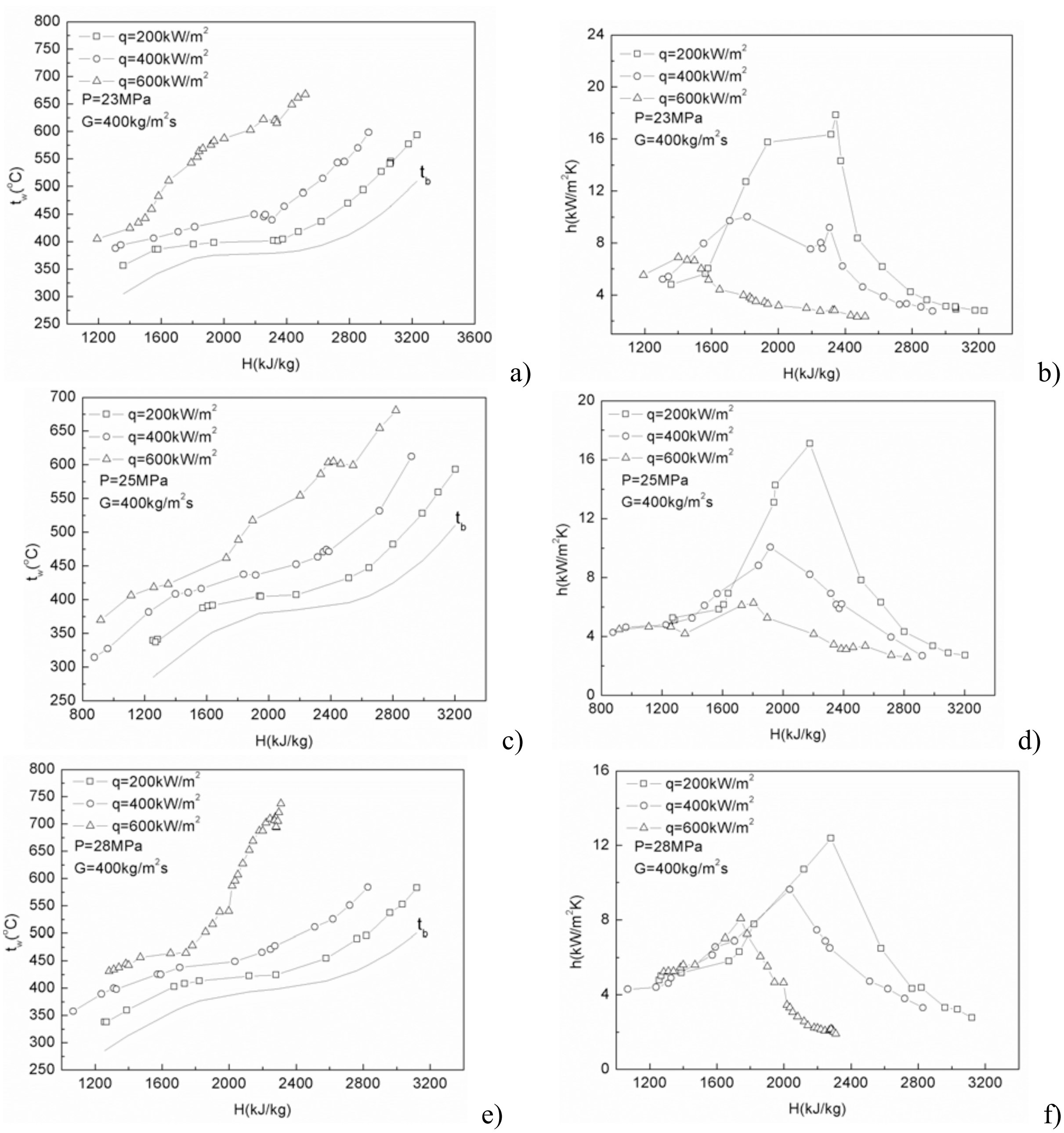



Fig.5 Comparison of the wall temperatures and HTC at different heat fluxes

Fig.5 (a)~(f) show that at a relatively low heat flux, the HTC takes a maximum at a bulk temperature which is close to the pseudo-critical temperature, and its maximum value decreases with increase of heat flux. In the pseudo-critical region, the heat flux has a significant influence on the heat transfer regime. When the heat flux is relatively low (200 kW/m$^2$), the heat transfer is enhanced significantly. While as the heat flux is relatively high (600 kW/m$^2$), heat transfer deterioration occurs.

### 3.3 The effect of pressure on wall temperature and heat transfer coefficients (HTC)

Fig.6 (a) and (b) show the examples of wall temperature and HTC plotted against bulk enthalpy for the vertical annular channel of a relatively high ratio of q/G and a relatively low ratio of q/G at different pressures, respectively.

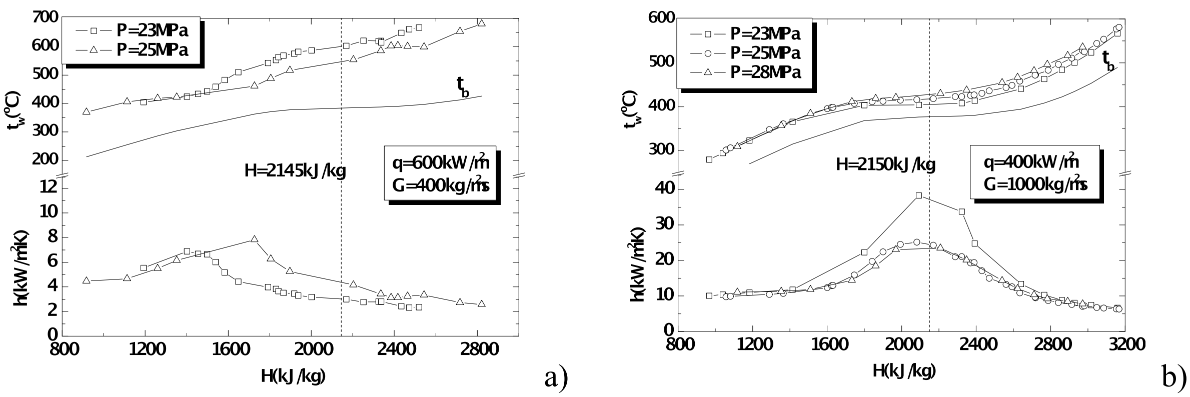



Fig.6 Comparison of the wall temperatures and HTC at different pressure

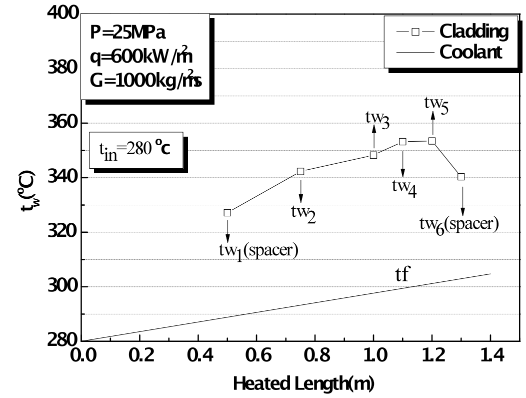
Fig.6 (b) shows results for a relatively low ratio of q/G. It is evident in this figure that the HTC in the pseudo-critical region becomes higher as the pressure down from 28MPa to 23MPa, which is close to the critical pressure of 22.064MPa. That is, the closer the pressure to the critical point is, the higher the HTC will be. This tendency of the HTC is similar to that of the specific heat in relation to the pressure and temperature.

Fig.6 (a) shows results for a relatively high ratio of q/G. When the pressure approaches down from 25MPa to 23 MPa, the HTC in the pseudo-critical region becomes lower and the wall temperature increases accordingly with a value of about 50℃. This result indicates that increase of pressure helps to restrain the heat transfer deterioration in the pseudo-critical region.

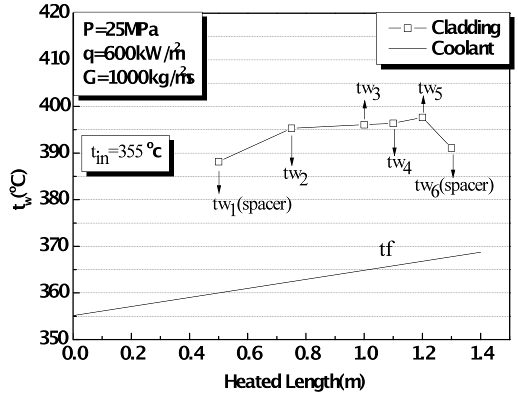
Fig.6 shows that the enhancement and deterioration of HTC mainly occur in the pseudo-critical region. When the parameters go beyond this region, the enhancement and deterioration of HTC disappear accordingly. This phenomenon may attribute to the drastic change of thermo-physical property in the pseudo-critical region.

### 3.4 The effect of spacers and wall temperature distribution

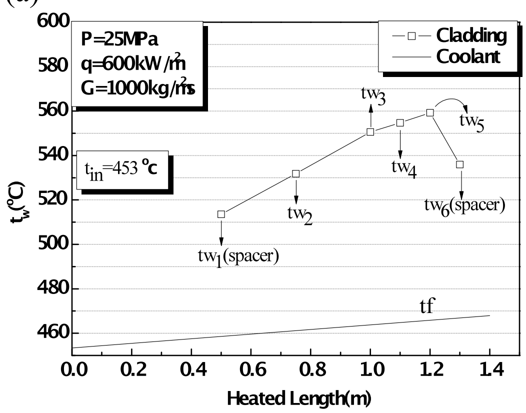
Fig.7 (a) to (c) show typical results of the cladding and coolant temperatures for a heat flux of 600 kW/m$^2$ and an average mass flux of 1000kg /(m$^2$s) at different preheat temperatures of 280℃, 355 ℃and 453℃, simulating the inlet, a mid section and a top section of a core.




(a)

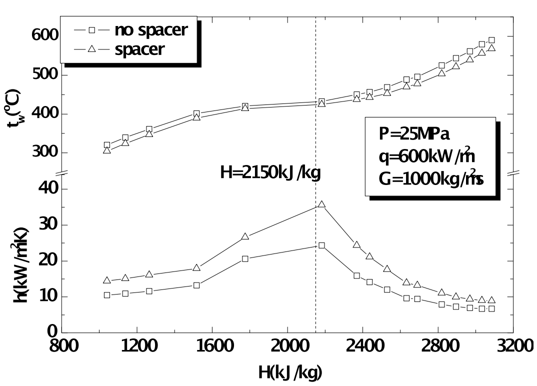



(b)

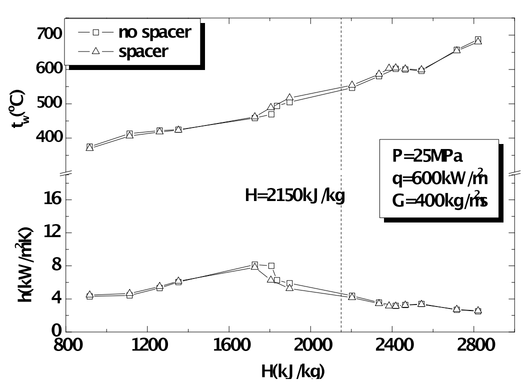



(c)

Fig.7 Wall temperature distribute along the heater length




(a) q/G=0.6




(b) q/G=1.5

Fig.8 Comparison of the wall temperatures and HTC with and without spacer

Fig.7 (a) to (c) indicate that the wall temperatures increase step by step along the heated length except the section of $tw_1$ and $tw_2$, where the spacer was located. We learn from these figures that the spacer has an obvious effect on heat transfer enhancement, this attributes to the additional mixture of local coolant made by spacer. Fig.8 show the Comparison of the wall temperatures and HTC with and without spacer at two different flow conditions: q/G=0.6 and q/G=1.5. We learn from these figures that when the mass flux decreases, the heat transfer enhancement made by spacer is restrained. Previous investigations also show that heat transfer enhancement and the propagation length of the spacer effect depend strongly on the flow conditions (Cheng et al., 2001) [8].

## 4. Conclusions

(1) The heat transfer to supercritical water flowing in vertical annular channel was found to be roughly classified into two different regimes according to the heat flux relative to the mass flux. At a relatively high mass flux, when the bulk temperature becomes closer to the pseudo-critical temperature, the HTC increases abruptly, and takes a maximum at a bulk temperature which is close to the pseudo-critical temperature. However, the heat transfer enhancement is diminished at a relatively low mass flux. Deterioration of heat transfer occurs for a relatively high ratio of q/G=1.5 at the pressure of 23, 25 and 28MPa. The HTC depends strongly upon the mass flux, especially in the pseudo-critical region, and its maximum value increases with the increase of mass flux.

(2) At a relatively low heat flux, the HTC takes a maximum at a bulk temperature which is close to the pseudo-critical temperature, and its maximum value decreases with the increase of heat flux. In the pseudo-critical region, the heat flux has a significant influence on the heat transfer regime. When the heat flux is relatively low, the heat transfer is enhanced significantly. At high heat flux relatively to the mass flux, heat transfer deterioration occurs in the pseudo-critical region.

(3) For a relatively low ratio of q/G, the HTC in the pseudo-critical region becomes higher as the pressure approaches down to the critical pressure. For a relatively high ratio of q/G, when the pressure approaches down from 25MPa to 23 MPa, the HTC in the pseudo-critical region becomes lower and the wall temperature increases accordingly with a value of about 50℃. This result indicates that increase of pressure helps to restrain the heat transfer deterioration in the pseudo-critical region.

(4) Heat transfer enhancement and the propagation length of the spacer effect depend strongly on the flow conditions. At a relatively high mass flux, the spacer has an obvious effect on heat transfer enhancement. When the mass flux decreases to a certain extent, the heat transfer enhancement made by spacer is restrained.

## 5. References

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