COMPARISON OF THE HEAT TRANSFER CHARACTERISTICS OF SUPERCRITICAL PRESSURE WATER TO THAT OF SUBCRITICAL PRESSURE WATER IN VERTICALLY-UPWARD TUBES

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Abstract

A systematic comparison was made between the forced convection heat transfer characteristics of the supercritical pressure water and that of the subcritical pressure water in vertically-upward tubes. It was found that, severe heat transfer deterioration did not occur in the vertically-upward internally-ribbed tube at supercritical pressures, and the variations in the inside-wall-temperature with the bulk fluid enthalpy experienced three stages, namely, the monotonically increasing stage, the fast changing stage and another monotonically increasing stage at the supercritical pressures; however, at subcritical pressures, there existed at least four stages for the variation of the internal tube wall temperature, i.e., the monotonically increasing stage, the basically unchanging stage, the sharply rising stage and another monotonically increasing stage. The heat transfer coefficients (HTC) in the subcritical two-phase region, in which the heat transfer deterioration did not occur, were much greater than that in the heat transfer enhancement region of supercritical pressure water. In the large specific heat region of supercritical pressure water, the lower the heat flux, the more obvious the heat transfer enhancement would be; however, in the subcritical two-phase region, the higher the heat flux, the greater the heat transfer coefficient would be. It was also found that the heat transfer deterioration of supercritical pressure water was similar in mechanism to the DNB (departure from nucleate boiling) at subcritical pressures.

1. Introduction

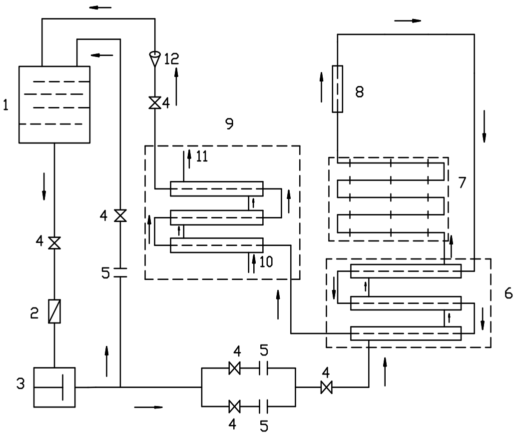
With the fast development of supercritical (ultra-supercritical) pressure boilers in China, and especially, with the supercritical water-cooled reactors (SCWR) being accepted as one of the six most promising reactor concepts considered in the Generation IV International Forum (GIF), heat transfer and flow of supercritical pressure water in channels have been attracting much more and more attentions from all over the world [1], because a thorough understanding of heat transfer characteristics of supercritical pressure water is crucial to the optimal design and safe operation of systems operating at supercritical pressures. Early studies on the heat transfer of supercritical media include that of supercritical water, Freon and CO_2 as well. It has been shown that there exists a so-called large specific heat region for supercritical pressure water, which is defined as a region where the specific heat of water at constant pressure is greater than 8.4 kJ/(kg K) [2]. Generally, such large specific heat region is just in the neighborhood of the so-called pseudocritical temperature, t_{pc}, and in this region, the thermophysical properties of the supercritical pressure water exhibit drastic changes with temperatures [2]. It is anticipated that at some stages of the flow of the supercritical pressure water in channels, the bulk fluid temperature t_b is lower than the pseudocritical temperature t_{pc} but the inner wall temperature of the tube may be higher than t_{pc}, and the heat transfer of supercritical pressure water flowing inside the tube may be quite peculiar, owing to rapid change in the thermophysical properties of supercritical pressure water along the tube radius. Existing investigations [3-5] has showed that, in the large specific heat region, the heat transfer enhancement might some time occur at low heat fluxes as the pseudocritical temperature is approached, however, as the heat flux is increased to a certain value, a remarkable deterioration of heat transfer might possibly take place, and the higher the heat flux is, the more severe the heat transfer deterioration will be. From an engineering point of view, heat transfer deterioration should be avoided all the time in power plants, including both the supercritical pressure water reactors and the supercritical pressure boilers. Unfortunately, the mechanism of the heat transfer deterioration or enhancement of supercritical pressure water has not been understood thoroughly due to the complexity of heat transfer of supercritical pressure water in the large specific heat region [6].

It has been well known that two types of heat transfer deterioration exist in subcritical pressure power system, one of which is the DNB (departure from nucleate boiling) occurring in the subcooled or low steam quality region, and another one is the dry out occurring in the high steam quality region [7]. The mechanism of these two types of heat transfer deterioration is clear. For flowing systems operated at supercritical pressures, there still remain some open questions, such as: Is the heat transfer deterioration at supercritical pressures completely different from the two-phase heat transfer deterioration at subcritical pressures in mechanism and characteristics? What are the similarities or differences between the heat transfer characteristics of supercritical pressure water and that of subcritical pressure water? In order to answer these questions, it is quite necessary to make a systematic comparison between the heat transfer characteristics of supercritical pressure water and that of subcritical pressure water, so as to get a deep insight of the heat transfer characteristics of supercritical pressure water. In the present paper, a systematic comparison is made based on the experimental data obtained at Xi'an Jiaotong University, Xi'an, China, between the heat transfer characteristics of the supercritical pressure water and that of the subcritical pressure water, and it is believed that the investigation may be helpful for the development of SCWR.

2. Test Loop and Experimental Conditions

The experiments were carried out on the high-pressure steam-water two-phase flow test loop established at Xi'an Jiaotong University, Xi'an, China. The schematic diagram of the loop is shown in Fig. 1. Deionized water was used as the flowing media and was pumped by a high pressure plunge-type pump, which can provide a maximum pressure of 40MPa. Part of the water was returned to the water tank through a bypass, and the rest part of the water flowed through measuring orifices and adjusting valves into a heat exchanger to absorb the heat of the hot fluid coming from the test section, and then was heated to a specific state in a pre-heater installed just upstream the test section. The test section was electrically heated by alternating currents of 0~10000 Amperes with low voltages. The fluid flowing out from the test section was cooled first by the above-mentioned heat exchanger and then by a condenser, and finally flowed into the water tank. The mass flow rate was measured with the orifice meters calibrated by weighing method.

Three kinds of tubes were used in the present experiments. The first kind of tubes was a six-head internally-ribbed tube with an outer diameter of 31.8 mm and a wall thickness of 6 mm and the second kind of tubes was a smooth tube with a diameter of Ø31.8×6 mm, both of which were made of SA-213T12 steel. The third kind of tubes was a four-head internally-ribbed tube with an outer diameter of 28.6 mm and a wall thickness of 5.8 mm, which was made of SA-213T2 steel. The mean inner diameter of the six-head internally-ribbed tube was measured to be 17.63 mm and that of the four-head internally-ribbed tube was 15.24 mm. The test sections were all installed vertically upwards. The electrically-heated length of all the test sections was 2000 mm.



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

Figure 1 Schematic diagram of the test loop

Figure 2 schematically shows the structure of the test section and the placement of measurement points. The fluid temperatures were measured by 10 pairs of Ø3 mm NiCr-NiSi sheathed thermocouples installed in the pre-heater and the test section. The fluid pressure at the inlet of the test section was measured by Rosemount 3051 capacitance-type pressure transmitter. A 3051 capacitance-type differential pressure transducer was used to measure the pressure drop of the test section. Total 26 thermocouples were welded on the tube outer surface to measure the outside wall temperatures. The electrically-heated power was defined as a product of effective value of the voltage and the current. All the data were monitored and collected by a computer equipped with an IMP3595 distributed data acquisition board connected with all the sensors used in the experiments.

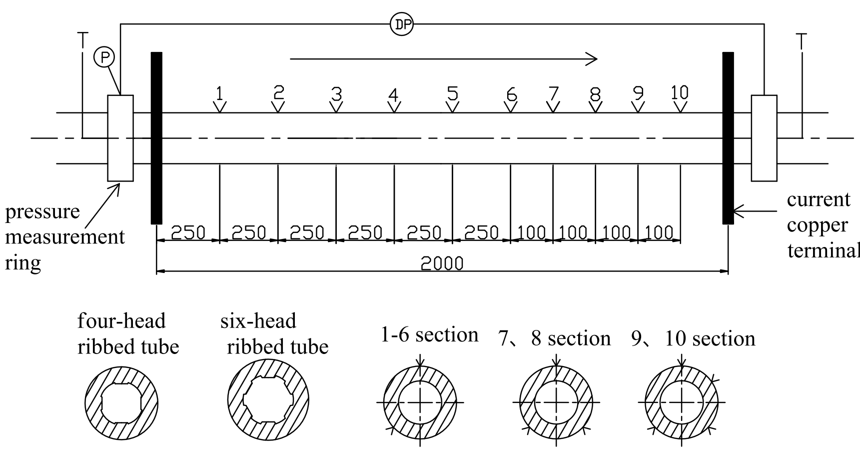


Figure 2 Structure of the test section and placement of measurement points

The experimental parameters are as follows. For experiment with the six-head internally-ribbed tube and the smooth tube, the pressures p at the inlet of the test section are 12.6, 15.4, 25.0 and 29.0MPa, respectively and the mass flux G is from 600 to 1200 kg/(m^2 s), and the inside wall heat flux q varies from 150 to 650 kW/m^2. For experiment with the four-head internally-ribbed tube, the pressures p at the inlet of the test section are 14.2, 17.0, 25.0 and 29.0MPa, respectively and the mass flux G is from 600 to 1250 kg/(m^2 s), and the inside wall heat flux q varies from 150 to 600 kW/m^2.

In each of the test, the mass flux and pressure were firstly adjusted to given values, and then, kept the heat flux of the heat transfer test section constant, but raised the heating power of the pre-heater to increase the fluid enthalpy at the inlet of the heat transfer test section. Once the wall temperature of the heat transfer test section was over 700℃ due to heat transfer deterioration or the heating power reached the maximum, the test was over.

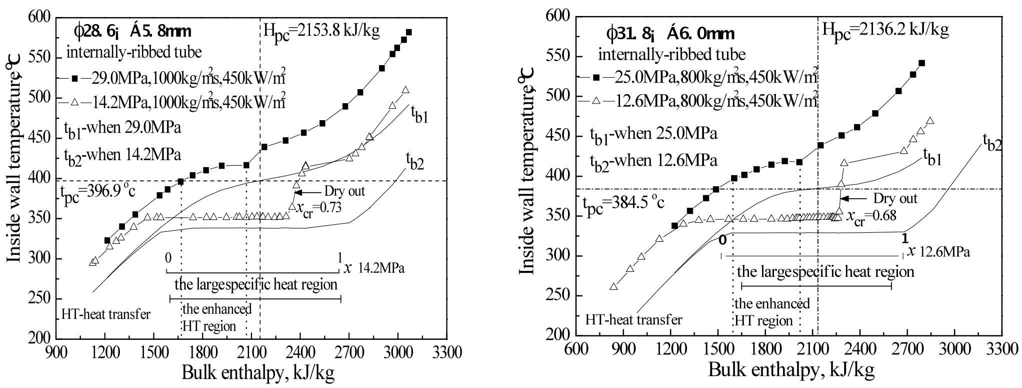
3. Comparison of the Wall Temperature Characteristics

Figure 3 gives a comparison of the wall temperature distributions at supercritical pressures to those at subcritical pressures in the vertically-upward internally-ribbed tubes. It can be seen from Fig. 3a or Fig. 3b that the variations in the inside-wall-temperature with the bulk fluid enthalpy at supercritical pressures are different from those at subcritical pressures, though the two experimental conditions are the same except pressure. As seen from Fig. 3a, when the bulk fluid enthalpy is lower than 1669 kJ/kg, the inside wall temperatures of the internally-ribbed tube with a diameter of Ø28.6×5.8mm increase monotonically with the bulk fluid enthalpy at a pressure of 29.0 MPa, and the temperature differences between the inside wall of the tube and the bulk fluid are basically unchanged and are about 40℃, and as a result, the heat transfer Coefficients are also generally unchanged at a fixed heat flux. This is the so-called normal heat transfer mode for supercritical pressure water.

It is seen in Fig. 3a that when the bulk fluid enthalpy is greater than 1669 kJ/kg but lower than the pseudocritical enthalpy 2153.8 kJ/kg, the fluid is in the large specific heat region of the supercritical pressure water. In this area, the inside wall temperatures change fast, but gently, and the temperature differences between the tube wall and the bulk fluid became smaller and smaller gradually and reach a minimum value of about 22℃ with the increase in bulk fluid enthalpy. That is to say, the heat transfer coefficients become higher gradually with the increase in fluid enthalpy and approaches a peak value, which means that the heat transfer enhancement occurs in this area. With the further increase in bulk fluid enthalpy, i.e., in an area where the bulk fluid enthalpy is greater than the pseudocritical enthalpy 2153.8 kJ/kg, the inside wall temperatures of the tube increase monotonically again with the bulk fluid enthalpy, as shown in Fig. 3a.

Thus, it is seen from Fig. 3a that at the supercritical pressures, the variations in the inside-wall-temperature with the bulk fluid enthalpy generally experienced three stages, namely, the first monotonically increasing stage, the fast changing stage and the second monotonically increasing stage.

However, in contrast, at a pressure of 14.2 MPa, when the bulk fluid enthalpy is lower than 1426 kJ/kg, the inside-wall-temperature increases monotonically with the bulk fluid enthalpy, which is similar, or, to some extent, identical to that at supercritical pressures. When the bulk fluid enthalpy is greater than 1426 kJ/kg but lower than 2309 kJ/kg, the fluid enters into the two-phase region of subcritical pressure fluid, and the inside wall temperature of the internally-ribbed tube is basically unchanged with an increase in the bulk fluid enthalpy. When the steam quality exceeds a certain critical value, which is 0.73 in Fig. 3a, corresponding to an enthalpy of 2350 kJ/kg for the subcritical pressure fluid, the inside wall temperature increases sharply due to the occurrence of heat transfer deterioration. In the superheated steam region, the inside wall temperature increase monotonically. Therefore, it can be seen from Fig. 3a that the variations in the inside-wall-temperature with the bulk fluid enthalpy experienced at least four stages, namely, the monotonically increasing stage, the basically unchanging stage, the sharply rising stage and another monotonically increasing stage at the subcritical pressures. In the superheated steam region, the inside wall temperature increases monotonically, but still keeps at a level much lower than the inside tube wall temperature of the corresponding supercritical fluid case. Therefore, it can be seen from Fig. 3a that for the subcritical pressure fluid, the variations in the inside-wall-temperature with the bulk fluid enthalpy experience at least four stages, namely, the first monotonically increasing stage, the basically unchanging stage, the sharply rising stage and the second monotonically increasing stage.



(a) (b)

Figure 3 Comparison between the inside wall temperatures at supercritical pressures and those at subcritical pressures

From the above analysis, it can be seen in Fig. 3 that for the supercritical pressure water, there are two different heat transfer modes in the experimental conditions, one of which is the normal heat transfer mode, and another is the enhanced heat transfer mode. The normal heat transfer of supercritical pressure water can be defined here as a process in which the inside tube wall temperatures increase monotonically with the increasing bulk fluid enthalpy, while the enhanced heat transfer of supercritical pressure water can be defined as a process in which the inside tube wall temperatures change fast, but gently, with the increase in the bulk fluid enthalpy. However, for the subcritical pressure fluid, there are three different heat transfer modes at the experimental conditions as shown in Fig. 3, namely, the normal heat transfer (i.e., forced convection heat transfer of single-phase water and superheated steam), forced convection boiling heat transfer and the heat transfer deterioration, which has been made quite clear in the past studies. Considering the fact that the heat transfer coefficients of the convection boiling (two-phase) is much greater than those of the single-phase forced convection heat transfer, the forced two-phase convection boiling heat transfer can be considered as the enhanced heat transfer mode. Therefore, it can be said that there are three different heat transfer modes at subcritical pressures as shown in Fig. 3, i.e., the normal heat transfer, the enhanced heat transfer and the deteriorated heat transfer. This is the first big difference of the heat transfer of subcritical pressure water to that of supercritical pressure water.

It should be mentioned that the mechanism of heat transfer enhancement of supercritical pressure water is completely different from that of subcritical pressure water. Some researchers [3, 8-9] suggested that the drastic change in thermophysical properties near the pseudocritical point resulted in the heat transfer enhancement in the large specific heat region of supercritical pressure water. This principle view was supported in the present paper. However, as well known, it is the nucleate boiling phenomenon that results in the big increase in the heat transfer coefficients at subcritical pressures.

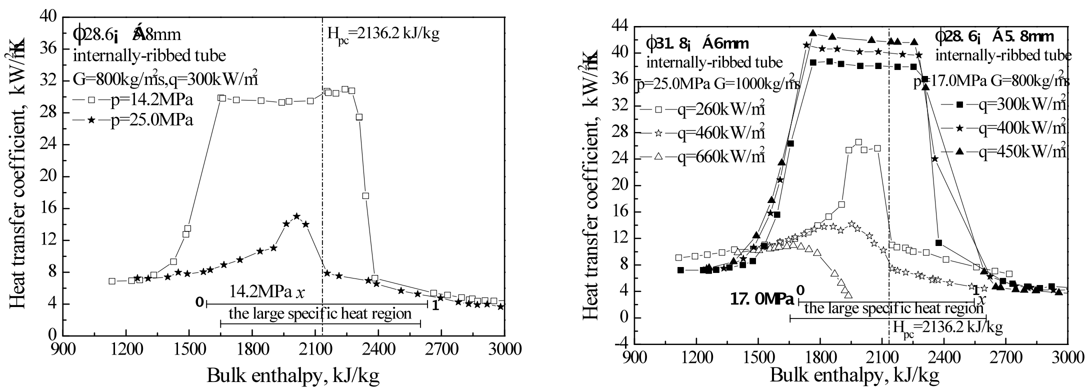
Fig 3b shows another comparison of the wall temperature distributions at a different supercritical pressure to that at a subcritical pressure in another vertically-upward internally-ribbed tube. It can be seen from Fig. 3b that, in the region where the bulk fluid enthalpy is less than 1300 kJ/kg, the inside wall temperatures of the tube in the case at 25.0 MPa are about equal to that in the case at 12.6 MPa, with the two experimental conditions are the same except pressure. However, with the continuous increase in bulk fluid enthalpy, the inside wall temperatures of the tube at 25.0 MPa is higher than that at 12.6 MPa, as seen clearly from Fig. 3b. As well known, there is no constant-temperature evaporation region for supercritical pressure water, and it is understandable that the temperatures of supercritical pressure water increase continuously with continuous heat absorption, and the inside wall temperatures, which is higher than the temperatures of supercritical pressure water, also increase continuously. However, the nucleate-boiling heat transfer at subcritical pressures is very drastic due to phase change, and there exist small temperature differences between the inside tube wall and bulk fluid, and moreover, the inside wall temperatures of the tube will more or less stay the same, and as a result, with the continuous increase in bulk enthalpy, the increasing in inside-tube-wall temperatures at supercritical pressures will be higher than those at subcritical pressures.

It also can be seen from Fig.3 that the variations in temperature differences between the inside-tube-wall and the bulk fluid with bulk fluid enthalpy at supercritical pressures are different from those at subcritical pressures.

As shown in Fig. 3a, in the low enthalpy region where the bulk fluid enthalpy is less than 1426 kJ/kg and in the high enthalpy region where the bulk fluid enthalpy is greater than 2700 kJ/kg, the temperature differences between the inside-tube-wall and the bulk fluid at supercritical pressures are nearly equal to those at subcritical pressures, and remain unchanged with the increase in the bulk fluid enthalpy. In the heat transfer enhancement region of supercritical pressure water, with the increase in the bulk fluid enthalpy, the temperature differences between supercritical pressure fluid and the inside tube wall become smaller and smaller and reach a minimum value; however, in the two-phase region of the subcritical pressure water even with the bulk fluid enthalpy the same as that of the supercritical pressure water, the temperature differences between the fluid and inside-tube-wall remain unchanged at roughly 13℃. Therefore, it can be said that from the viewpoint of temperature differences between the bulk fluid and the inside-tube-wall, the normal heat transfer of supercritical pressure water is characterized by the basically unchanged temperature differences, while the enhanced heat transfer is characterized by a low temperature difference in comparison to the normal heat transfer.

4. Comparison of Heat Transfer Coefficients

Figure 4 shows a comparison of heat transfer coefficients (HTC) of water at supercritical pressures to those at subcritical pressures in vertically-upward internally-ribbed tubes. As seen clearly from Fig. 4a, in the region where the bulk fluid enthalpy is less than 1300 kJ/kg and in the region where the bulk fluid enthalpy is greater than 2700 kJ/kg, the variations in heat transfer coefficients with bulk fluid enthalpy at supercritical pressures are nearly the same as those at subcritical pressures, and the values of heat transfer coefficients of water at supercritical pressures are, basically, equal to those at subcritical pressures. However, the variations in heat transfer coefficients with the bulk fluid enthalpy in the large specific heat region of water at supercritical pressures are totally different from those in the two-phase region of water at subcritical pressures. One of the characteristics of heat transfer enhancement in the large specific heat region of supercritical pressure water is that a peak value exists for the heat transfer coefficients in this region, and for example, the maximum value of the HTC is about 15 kW/(m^2 K) at 25.0 MPa, which is however much lower than the HTC value of water at a subcritical pressure of 14.2 MPa. In the present study, the heat transfer enhancement is believed to have occurred in the large specific heat region of supercritical pressure water, because the HTC value in the most part of this region is greater than 12 kW/(m^2 K), and is much higher than that of the supercritical water in its normal heat transfer region, which is in the range from 8 to 12 kW/(m^2 K), as seen clearly from Fig. 4a.



(a) (b)

Figure 4 Comparison between the heat transfer coefficients at supercritical pressures and those at subcritical pressures in vertically-upward internally-ribbed tubes

However, it is clearly seen in Fig. 4a that the HTC remains unchanged in the two-phase region at 14.2 MPa and the value of the HTC is about 29.5 kW/(m^2 K), which is much larger than that at supercritical pressures.

In the two-phase flowing boiling region of water at subcritical pressures, the bulk fluid temperature is generally kept at a constant, which is equal to the local water saturation temperature t_s, and the inside wall temperature of the tube, t_w, is also nearly a constant, and thus the temperature difference, t_w-t_s, is a constant, and consequently, the heat transfer coefficient in this region is a constant under conditions with a fixed heat flux. The possible reason for the heat transfer coefficients in subcritical two-phase flowing boiling region being much larger than those in the heat transfer enhancement region at supercritical pressures is believed to be as follows. In the two-phase boiling region at subcritical pressures, the heat transfer is mainly fulfilled by phase change of the liquid, and the macro-convection of bulk fluid and the micro-convection caused by the boiling near the tube wall together make the heat transfer coefficients very large. In more detail, the formation, growth and departure of bubbles not only take away latent heat but also push the superheated liquid near the tube wall into the bulk fluid, and at the same time, the cold bulk liquid supplements the vacancy generated by the departure of bubbles. However, for the supercritical pressure water, even in the enhanced heat transfer region, heat transfer is carried out only by the variable-property single-phase convection, and the contributions from micro-convection near the tube wall in this case might be much smaller than the liquid boiling at subcritical pressures. The drastic changes in thermophysical properties near the pseudocritical points, especially the sudden rise in the specific heat of water at supercritical pressures, contributes, but within a limited content, to the local heat transfer promotion.

It can be seen from Fig. 4b that in the large specific heat region of supercritical pressure water, both the magnitude of the HTC peak, and the range covered by heat transfer enhancement in terms of fluid enthalpy, and, as well, the value of the bulk fluid enthalpy corresponding to the HTC peaks decrease with the increasing heat flux, indicating the diminishing of the heat transfer enhancement with increasing heat fluxes, and even, the occurrence of heat transfer deterioration at high heat fluxes.

As shown in Fig. 4b, obvious heat transfer deterioration occurs in the low-bulk-fluid-enthalpy region when the heat flux is 660kW/m^2 at a pressure of 25.0MPa in the vertically-upward internally-ribbed tube, and heat transfer deterioration also occurs in the high-bulk-fluid-enthalpy when the heat flux is 460kW/m^2 in this tube at the same pressure of 25.0MPa. One of the characteristics of heat transfer deterioration is that there is a sudden decrease in HTC and in the present study, the heat transfer deterioration is considered to occur when the HTC is less than 8 kW/(m^2 K).

From the viewpoint of heat transfer coefficients, the normal heat transfer of supercritical pressure water is characterized with the basically unchanged heat transfer coefficients, and the enhanced heat transfer is characterized with the high heat transfer coefficients in comparison to the normal heat transfer, and the deteriorated heat transfer is characterized with a sudden decrease in, and the low value of heat transfer coefficients in comparison to the normal heat transfer.

5. Comparison of Heat Transfer Deterioration

Usually, the heat transfer deterioration is defined as phenomena with sudden decrease in the heat transfer coefficient on the wall for a constant-wall-temperature system or a sharp increase in the wall temperature for a constant-heat-flux system. As mentioned before, there are two kinds of heat transfer deterioration at subcritical pressures, one of which is the DNB, and another one is the dry out. According to the literatures [2, 6-7, 11], there are also two kinds of heat transfer deterioration at supercritical pressures in vertically-upward tubes. The first type of deteriorated heat transfer observed in supercritical pressure liquid was due to the change in flow structure in the entrance region of the tube, and can occur at any bulk fluid enthalpy up to the pseudocritical enthalpy [11]. The second type of deteriorated heat transfer may occur in supercritical pressure fluids when the wall temperature exceeds the pseudocritical temperature t_{pc} but the bulk fluid temperature is still less than t_{pc} [5]. According to Belyakov (Беляков) [11], the first type of deteriorated heat transfer at supercritical pressures was related to the formation of boundary layer within the entrance region of the tube. Belyakov believed that, when the flow direction of the natural convection was same as that of the forced convection, the boundary layer of fluid would be in a state of laminar flow, which eventually resulted in the occurrence of heat transfer deterioration, and the first type of deteriorated heat transfer may not occur at all in the supercritical pressure boilers. In the present study, no such so-called first type of deteriorated heat transfer was observed.

According to open literatures, Ackerman (1970) [12] was the first person who has compared the heat transfer deterioration of supercritical pressure water with film boiling at subcritical pressures. Ackerman believed that a pseudo-film boiling phenomenon could occur at supercritical pressures, and the pseudo-film boiling phenomenon at supercritical pressures was analogous to the film boiling at subcritical pressures in mechanism. Figure 5 gives a comparison of the heat transfer deterioration of water at supercritical pressures and the DNB at subcritical pressures. As demonstrated in Fig. 5, the heat transfer deterioration at supercritical pressures and the DNB at subcritical pressures both occurs in a region with low fluid enthalpy, and the wall temperature curve at 26.0 MPa closely resembles the DNB curve at 15.4 MPa, suggesting that the heat transfer deterioration at supercritical pressures may be similar to the DNB at subcritical pressures. Another similarity of the heat transfer deterioration at supercritical pressures to the DNB at subcritical pressures is that both the heat transfer deterioration at supercritical pressures and the DNB at subcritical pressures are caused by the covering of the heat transfer surface by low density fluids. However, the fluids covering the heat transfer surface in the DNB case at subcritical pressures are vapor films produced from the violent water boiling, while the fluids covering the surface with deteriorated heat transfer at supercritical pressures are single-phase fluids.

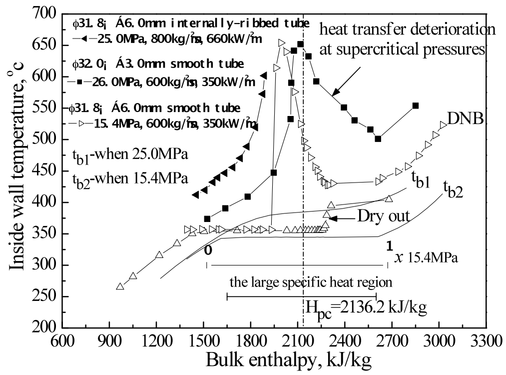


Figure 5 Comparison between the heat transfer deterioration at supercritical pressures and the DNB at subcritical pressures

A possible reason for the occurrence of heat transfer deterioration in the vertically-upward tubes at supercritical pressures is that when heat flux increases to a certain value, there exists a large radial gradient in fluid temperature, and as a result, a thin layer of fluid directly contacting the inside tube wall absorbs heat easily and becomes hot enough and firstly "enter" into the large specific heat region with its density and thermal conductivity dropping dramatically and rapidly, while the properties of the bulk fluid in the center region of the tube remains unchanged. On the one hand, the dramatic reduction in viscosity of the fluid in the near-wall hot layer may make the boundary layer of fluid change to a state of laminar flow, and at the same time, the buoyancy effects duo to a large and rapid decrease in fluid density with temperature might make the boundary layer of fluid be in a state of laminar flow too. The above-mentioned factors eventually make the heat transfer surface of the tube covered by light and hot fluids, and the effect on heat transfer is similar to that of the vapor films on subcooled boiling at subcritical pressures, and the heat transfer deterioration may occur, resulting the sharply increasing in the wall temperature. Such a mechanism in deteriorated heat transfer at supercritical pressures has been reported in the literature [13], and this mechanism is applicable in the present study. Of course, because of the particularity and complexity of supercritical fluid heat transfer, a further in-depth study on the mechanism in heat transfer deterioration of supercritical pressure water is necessary.

Conventionally, the critical heat flux, q_{cr}, was used to describe the DNB, i.e., the first type of deteriorated heat transfer and the critical steam quality, x_{cr}, was used to describe the Dry out, i.e., the second type of deteriorated heat transfer at subcritical pressures. There remains an open question, that is, which parameter can be used to properly describe the deteriorated heat transfer at supercritical pressures? According to literatures, there were two methods for determining the starting point of deteriorated heat transfer at supercritical pressures. One is to determine the critical heat flux, at which deteriorated heat transfer occurs, for example, a correlation $q_{cr}=0.2G^{1.2}$, proposed by Yamagata et al [4]. Another method is to determine the critical length of the tube, within which deteriorated heat transfer did not occur [14-15]. However, according to the literature [7], the method used to determine the critical length of the tube was complex.

Moreover, from the viewpoint of wall temperature, the deteriorated heat transfer is characterized with sharp increase in wall temperature.

In short, it was found that the heat transfer characteristics of supercritical pressure water were greatly different from not only that of the vapor-water two-phase flow at subcritical pressures, but also that of the single-phase subcritical pressure water. There existed three different heat transfer modes for supercritical pressure water: 1) the normal heat transfer, 2) the deteriorated heat transfer, with low HTC but high tube wall temperatures and large temperature differences between the inside wall and the bulk fluid, and 3) the enhanced heat transfer with high HTC and low wall temperatures and small temperature differences between the inside wall and the bulk fluid. It should be pointed out here that such categorization does not mean that the three heat transfer modes for supercritical pressure water will be included in one experimental condition. In general, with increasing bulk enthalpy, two modes may appear: the normal heat transfer and the heat transfer enhancement at low heat fluxes, e.g., in experimental conditions shown in Fig. 3, and at conditions of high heat fluxes, the normal heat transfer and the heat transfer deterioration may appear as shown in Fig. 5.

6. Conclusions

(1) It was found that, severe heat transfer deterioration did not occur in the vertically-upward internally-ribbed tube at supercritical pressures, and the variations in the inside-wall-temperature with the bulk fluid enthalpy experienced three stages, namely, the monotonically increasing stage, the fast changing stage and another monotonically increasing stage at the supercritical pressures; however, at subcritical pressures, there existed at least four stages for the variation of the internal tube wall temperature, i.e., the monotonically increasing stage, the basically unchanging stage, the sharply rising stage and another monotonically increasing stage.

(2) The heat transfer coefficients in the subcritical two-phase region, in which the heat transfer deterioration did not occur, were much greater than that in the heat transfer enhancement region of supercritical pressure water. In the large specific heat region of supercritical pressure water, the lower the heat flux is, the more obvious the heat transfer enhancement would be; however, in the subcritical two-phase region, the higher the heat flux is, the greater the heat transfer coefficient would be.

(3) There existed three different heat transfer modes for supercritical pressure water: 1) the normal heat transfer, 2) the deteriorated heat transfer, and 3) the enhanced heat transfer. It was also found that the heat transfer deterioration of supercritical pressure water was similar in mechanism to the DNB at subcritical pressures.

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