COMPARISON BETWEEN THE HEAT TRANSFER CHARACTERISTICS OF SUPERCRITICAL PRESSURE WATER IN HORIZONTAL TUBES AND INCLINED TUBES

Shuiqing YU, Huixiong LI *, Xianliang LEI, Yifan ZHANG, Tingkuan CHEN
State Key Laboratory of Multiphase Flow in Power Engineering, Xi' an Jiaotong University,
Xi'an 710049, China Email：huixiong@mail.xjtu.edu.cn, Tel: +86-29-82665870

Abstract

This paper is devoted to elucidate the effect of flowing orientation on the flow and heat transfer characteristics of supercritical pressure water in the large specific heat region (LSHR) where significant thermo-physical property variations occur and may cause heat transfer enhancement or deterioration. In order to get insight into the mechanism governing heat transfer enhancement or heat transfer deterioration, experimental results of flow and heat transfer of supercritical pressure water in inclined upward smooth tube of Φ25×2.5mm and Φ32×3mm with an angle of $\alpha = 20°$ are compared to that in horizontal smooth tubes with a diameter of Φ32×3mm over a wide range of parameters such as pressures ranging from 23 to 28MPa, average heat fluxes up to 600kW/m^2, and mass fluxes in the range of 200 to 1000 kg/m^2·s, and emphasis is placed on the effect of flowing orientation on the flow and heat transfer characteristics of supercritical pressure water, especially in the LSHR. It is found that there exists distinct difference in heat transfer processes between the horizontal tubes and the inclined tubes, strikingly illustrated by the difference in both the temperature distribution and heat transfer coefficients distribution on the top and bottom surface of the tubes. In the enthalpy region which far away from the LSHR, the temperature on the top wall of the horizontal tube and the inclined tube slightly exceeds the temperature on the bottom wall of the corresponding tubes; while in the LSHR , there exist huge differences in temperature on the top wall and the bottom wall of the horizontal tubes under moderate and high heat fluxes, and the temperature difference between the top wall and bottom wall of the inclined tubes is small in comparison to that of the horizontal tubes. Difference in heat transfer coefficients between the horizontal tube and the inclined tube exhibits a trend similar to that of the wall temperature of the corresponding tubes. The reasons that cause such differences are analyzed. Results obtained in this study may be useful for the design of boilers and nuclear reactors operated at supercritical pressures.

Key words: flow and heat transfer, supercritical pressure water, horizontal tube, inclined tube, buoyancy force, the large specific heat region (LSHR)

1. Introduction

With the fast development of economy in the world and the successive progress in human society, there exist increasing demands for electricity, and supercritical water-cooled reactors (SCWRS) and supercritical (ultra-supercritical) pressure boilers may play more and more important roles in electricity supplying due to their distinct advantages, such as high efficiency, relatively low energy cost, low pollutant emission and the large capacity. As a result, the flow and heat transfer characteristics of supercritical pressure water flowing in passages with different cross sections and different orientations has become one of the most important research topics in the power and energy fields.

Early studies [1] on the heat transfer of supercritical water have shown that for supercritical water, there is a so-called large specific heat region (LSHR), which is generally defined as a region with the specific heat of water at constant pressure being greater than 8.4 kJ/(kg·K). Fig. 1 typically shows the variation of thermo-physical properties of water with temperature at pressures of 23MPa and 25MPa, respectively. It is seen from Figure 1 that although the supercritical pressure water does not experience any distinct phase change, its thermo-physical properties, including specific heat, density, dynamic viscosity, kinematic viscosity, volumetric expansivity, Prantal number and thermal conductivity etc., however exhibit drastic and fast changes with the temperatures in the LSHR. Such thermo-physical property changes are quite similar to, but obviously different from, that of the phase change of subcritical water, and may have great influence on the flow and heat transfer of supercritical pressure water, making the flow and heat transfer of supercritical pressure water substantially different from that at subcritical pressures.

Investigations on the flow and heat transfer characteristics of supercritical pressure fluids can be traced back to about seventy years ago [2], and has been carried out by scholars all over the world in order to find more and more applications of the supercritical pressure fluids in various industries and engineering [3]. Unfortunately, because of the complexity in flow and heat transfer of supercritical pressure fluids, the technical difficulties encountered in related experiments, and the expensive cost of sophisticated equipment and measuring techniques necessary for the related studies, the mechanism in flow and heat transfer of supercritical pressure fluids, especially in the so called LSHR has not been fully understood yet. For example, more than twenty correlations have been proposed to correlate the experimental data of flow and heat transfer of supercritical fluids[4-5] and to furthermore predict the heat transfer performance of facilities with supercritical pressure fluids as the working medium, but large discrepancies have been observed among the prediction results of these correlations, probably owing to the obvious fact that these correlations were obtained based on limited experimental data under different conditions. For the time being, an existing fact is that none of these correlations can give generally satisfactory results under different conditions. Because of the particularity and complexity of heat transfer of fluid at supercritical pressures, it is of great significance to thoroughly study the mechanism of heat transfer, especially the abnormal heat transfer characteristics of the supercritical water in the LSHR.

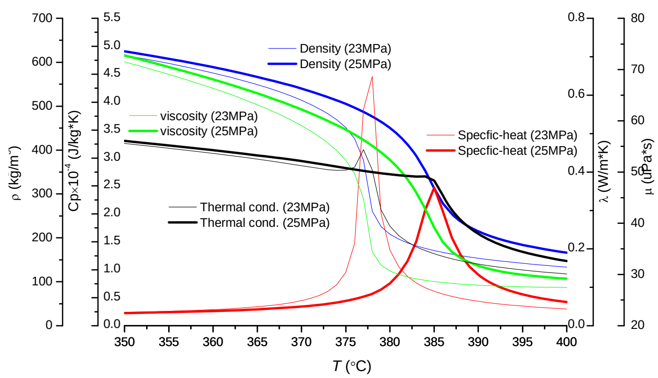


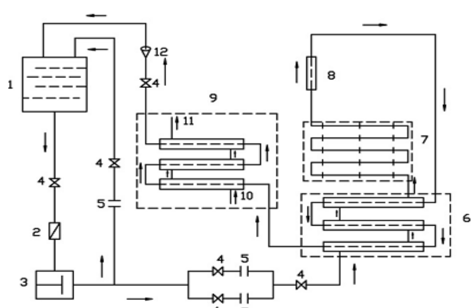
Fig. 1 Variations of properties of supercritical water with temperature at P=23, 25MPa

It should be noted that the previous work on this subject was mainly done in the former USSR and in the USA in the 1950s–1980s along with the development of supercritical pressure boilers in these countries. A review of the experimental studies was reported by Pioro and Duffey [6]. It should also be noted that most of the previous experimental studies focus on the heat transfer characteristics of supercritical pressure fluids flowing axi-symmetrically (e.g., upward flow and downward flow) in relatively small diameter tube, and only a few were carried out in large diameter tubes (horizontal tube or inclined tube) with little experimental data obtained. In order to understanding the effect of flowing orientations on the flow and heat transfer characteristics of supercritical pressure water, a series of experiments have been carried out by Xi'an Jiaotong University in Xi'an, China. Based on the experimental data obtained, a comparison of the heat transfer characteristics of supercritical pressures water in horizontal tubes is made to that in the inclined tubes which was done by Wang [7] and Li [8].

2. Experimental apparatus and procedure

Fig. 2 shows the schematic diagram of the test loop used to carry out the large scale test on heat transfer of supercritical water in Xi'an Jiaotong University, Xi'an, China. Deionized water is used as the working fluid and is pumped into the circulation system from a water tank by a high pressure piston pump. The water gains some heat by passing through a regenerative heat exchanger, and is then introduced to a pre-heater to reach the specific test conditions, and then flows into the test section. Both the pre-heater and test section are electrically heated by alternative currents of 0–10,000A with however low voltages. The whole tubes are thermally insulated by glass wool to minimize the heat loss. The water from the exit of the test section flows through the regenerator and the condenser, and then returns back to the feed water tank. A mass flow meter is used to measure the mass flux of water. The water temperature is measured at different locations by NiCr–NiSi armored thermocouples.

Fig. 3 shows a schematic diagram of the layout of wall temperature measuring points installed on the outer surface of the horizontal and inclined tubes. Two smooth tubes are used in the present study, with the parameter of one of them being Φ32×3mm and the parameter of another one being Φ25×2.5mm. Each test section is connected with an unheated tube with a length of 1.5 m to allow for the fully-developed flow in the tube. Totally 76 NiCr–NiSi K-type thermocouples (Φ0.3 mm) are welded on the outer surface of each tested tube to measure the outside wall temperatures. A series of Φ3 mm NiCr–NiSi armored thermocouples are protruded into the inlet and outlet of the test section to measure the bulk temperature. The fluid pressure at the inlet of the test section is measured by a Rosemount 3051 capacitance-type pressure transmitter, while the pressure drop of the test section is measured by a 3051 capacitance-type differential pressure transducer.



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

Fig. 2. Schematic diagram of the test loop.

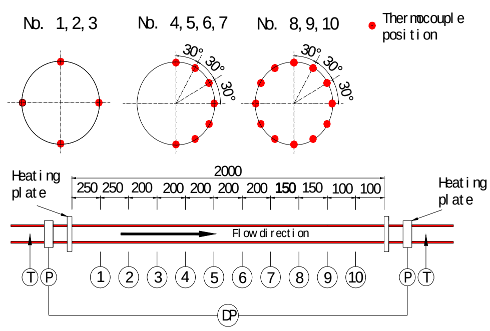


Fig. 3. Structure of the test section and placement of measurement points

In the present study, the pressure P at the inlet of the test section ranges from 23.0 to 28.0MPa, and the mass flux G is from 400 to 1000 kg/(m^2 s), and the average internal wall heat flux q varies from 200 to 600 kW/m^2.

3. Experimental results and analysis

Table 1 gives the starting enthalpy and end enthalpy of the large specific heat region (LSHR) of water at different pressures. Generally, the LSHR of supercritical water covers an enthalpy range from roughly 1700 kJ/kg to 2750 kJ/kg (IFC-67). In the present study, in order to simplify the analysis of the experimental results and to place the emphasis on the LSHR, the test section is divided into three parts according to the variation of enthalpy of water along the flowing direction, i.e., (1) the low enthalpy range (LER) (1000-1700kJ/kg), (2) the large specific heat region (LSHR) or Medium enthalpy range (1700-2750 kJ/kg), and (3) the high enthalpy range (HER) (>2750 kJ/kg).

Table 1 The large specific heat region corresponding different supercritical pressure

P(MPa)	Starting temperature (℃)	Starting enthalpy kJ/kg	Corresponding c_p kJ/(kg/℃)	End temperature (℃)	End enthalpy kJ/kg	Corresponding c_p kJ/(kg/℃)
23	358.6	1702.161276	8.399646	404.1	2728.474229	8.400625
25	363.9	1732.506697	8.393465	414.1	2727.437081	8.392556
28	369.8	1760.187330	8.399276	427.4	2721.883728	8.409070

Fig.4a and Fig.4b show the typical results obtained in the present study. It can be seen from Fig.4a and Fig.4b that both heat transfer enhancement and heat transfer deterioration are observed under different conditions. Based on the experimental data, three heat transfer modes can be defined for supercritical pressure water, i.e. (1) normal heat transfer; (2) deteriorated heat transfer, with low values of the heat transfer coefficient (HTC) in some part of the test section, and (3) enhanced heat transfer, with high values of the HTC in comparison to the normal heat transfer. It should point out that it is difficult to provide exact definitions of the boundaries among the different heat transfer modes. Fig.5 shows a comparison of the HTC value predicted by the Dittus-Boelter correlation to the average HTC value obtained in experiments at different heat fluxes. As shown in the Fig.5 that the HTC values predicted by the Dittus-Boelter correlation are in very good agreement with the average HTC values obtained in the experiments at different heat fluxes in the low enthalpy range, with the HTC being a roughly constant of 7~9 kW/(m2 K), and this kind of heat transfer is considered as in the normal heat transfer mode in the present study. The HTC value of 7~9 kW/(m2 K) may be considered as the boundary of heat transfer deterioration, i.e., once the HTC value is lower than 7~9 kW/(m2 K), the heat transfer deterioration is considered to occur. It is also seen from Fig.5 that the HTC values predicted by the Dittus-Boelter correlation deviates greatly from the experimental data in the LSHR and the high enthalpy region.

3.1 Effect of Heat Fluxes

Fig. 4a shows the variation of the wall temperature of the test sections with the increasing of fluid enthalpy at various heat fluxes when the pressure is kept 25MPa and mass flux is 600kg/(m^2 s). As seen in Fig. 4a, regardless of the difference in test section arrangements (horizontal tube, or inclined tube), the top surface temperature of the test section is always higher than that of the bottom surface temperature, and both the top surface temperature and the bottom surface temperature rise with the increasing of heat fluxes. It is seen in Fig.4a that heat transfer deterioration occurs on the top surface of horizontal tubes in the low enthalpy region (LER), and the top surface temperature of the horizontal tubes reaches a peak value at the early stage of the LSHR region, with the corresponding enthalpy being about 1700-1900 kJ/kg, and this peak value of the top surface temperature increases with the heat flux. Under the conditions of a heat flux of 300kW/m^2, the peak value of the top wall temperature is about 476°C occurring at a position with a corresponding water enthalpy 1865 kJ/kg, while the peak value of the top wall temperature is about 620 °C with a corresponding enthalpy 1779 kJ/kg when the heat flux is 400kW/m^2.

As mentioned above in this paper, a HTC value of roughly 7~9 kW/(m^2 K) is considered as the boundary between the normal heat transfer mode and the deteriorated heat transfer mode. It is seen from Fig.4a that the heat transfer on the bottom surface of both the horizontal tube and the inclined tube is deteriorated in the cases with heat flux of 300~400kW/m^2, and, an obvious decrease in HTC is observed even on the bottom surface of the horizontal tube even in the low enthalpy region (LER) with the increasing in heat fluxes, indicating the heat transfer deterioration becoming worse. The reason of this phenomenon can be explained as follows.

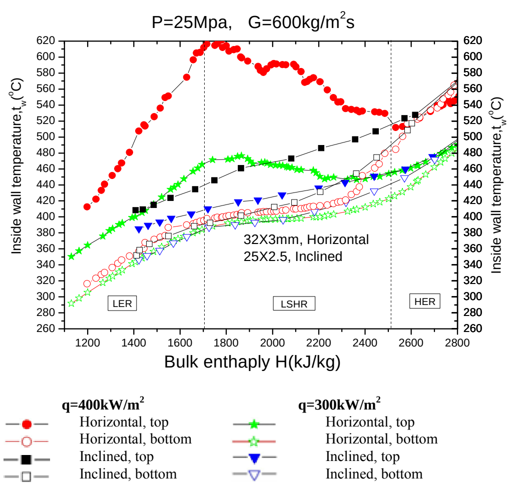


Fig.4a. Variation of the inner wall temperature with fluid enthalpy at different heat fluxes

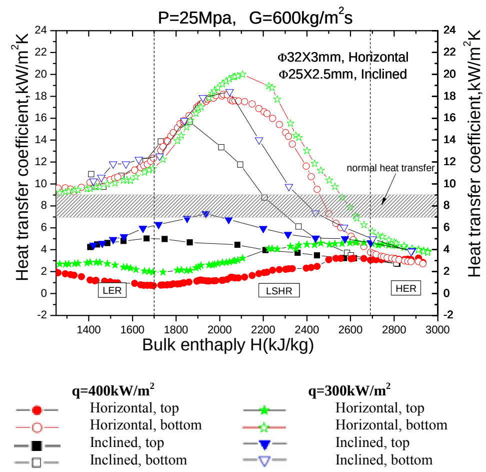


Fig.4b. Variation of the heat transfer coefficient with fluid enthalpy at different heat fluxes

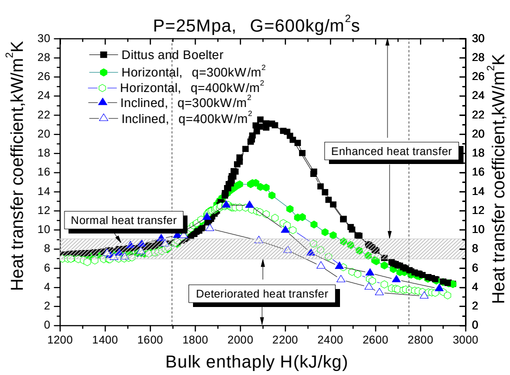


Fig. 5 Comparison of the prediction of Dittus-Boelter with HTC experiment obtained from this study at different heat fluxes

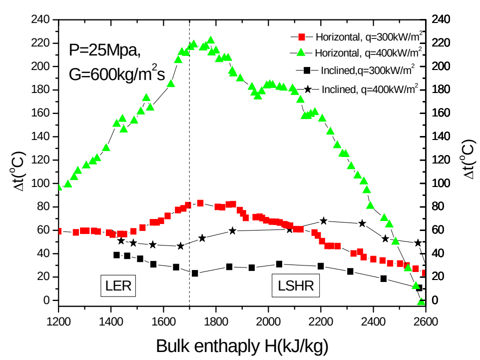


Fig. 6 Variation of the temperature difference with fluid enthalpy at different heat fluxes

As seen in Fig.1, there is a drastic and fast variation of the thermo-physical properties of water with the increasing of enthalpy in the LSHR region. Before entering into the LSHR region, i.e., in the LER region, the fluid near the top surface of the horizontal tube may first reach its pseudo-critical temperature, i.e., t_{pc}, due to heating from the tube surface, and its temperature may then become much higher than t_{pc}, but at the same time, the temperature of the fluid in the center of the tube may be still much lower than t_{pc}. In this case, differences in thermo-physical properties between the fluid near the heating surface and the fluid in the center of the tube may be very large, and buoyancy effect may become significant, resulting in gathering of the low density fluid in the upper half of the tube. Meanwhile, the thermal conductivity of the near wall layer of fluid decreases rapidly due to on the one hand the fast variation of thermo-physical properties of water (see Fig.1) and on the other hand the gathering of low density fluid, leading to increased thermal resistance and weakened heat transfer in this layer. With the development of this process along the tube, the increasing in top wall temperature augments the density difference between the fluid near the top wall and the fluid in the tube center, causing an upward acceleration and inducing the secondary flow [1-2]. One of the characteristics of heat transfer deterioration of horizontal tube in the LER region is that the temperature difference between the top surface and the bottom surface, i.e., Δt_{hor}, keeps increasing with the increase of the fluid bulk enthalpy, and reaches a maximum when the top surface temperature reaches to the peak value. The maximum of Δt_{hor} is 83°C when the heat flux is 300kW/m^2, while it is 221 °C when the heat flux is 400 kW/m^2, as shown in Fig.6.

It can be seen from Fig. 4b that there are significant differences in HTC between the top surface and bottom surface of the horizontal tubes in the LER region and the LSHR region, and similar phenomenon is observed in the inclined test sections. As shown in Fig.4b that the HTC at the bottom surface are much higher than that at the top surface, and heat transfer deterioration appears on the top surface, but the heat transfer is generally enhanced on the bottom surface in the LSHR region. Difference in HTC between the bottom surface and top surface in horizontal tubes is much larger than that in inclined tubes. The maximum value of the HTC corresponds to a bulk fluid enthalpy of 2105kJ/kg, which is slightly less than the pseudocritical bulk fluid enthalpy. This phenomenon is similar to the results of Yamagata et al [11].

Under identical test conditions in the present study, in the LER and LSHR region, the distribution of HTC on the bottom surface of the horizontal tubes is generally similar to that of the inclined tube, but the magnitude of the HTC on the bottom surface of the horizontal tube is however larger than that of the inclined tube. On the contrary, the HTC on the top surface of the horizontal tubes is smaller than that of the inclined tube. Difference in HTC between the horizontal tube and the incline tube diminishes in the HER region.

3.2 Effect of Pressures

Fig. 7a and Fig. 7b shows the variation of the wall temperature and HTC with the increasing of fluid enthalpy at different pressures when heat flux is 300 kW/m^2 and mass flux is 600 kg/(m^2·s). It is seen from Fig. 7a that in the LSHR region, temperature on the top surface of both the horizontal tube and the inclined tube rises with the increasing in pressure. As shown in Fig.7a and Fig.7b, heat transfer deterioration occurs at both 23Mpa and 25MPa pressures on the top surface of the horizontal tube in the LER (nearby the large specific heat region). When the pressure is 23Mpa, the peak temperature value on the top surface of the horizontal tube is 476℃ at a axial position corresponding to a bulk enthalpy of 1865.4KJ/Kg, while when the pressure is 25Mpa, the peak wall temperature value on the top surface of the horizontal tube is 467.91°C at a axial position corresponding to a bulk enthalpy of 1731.3KJ/Kg, indicating generally slight effect of pressure on the peak wall temperature value on the top surface of the horizontal tube.

It is seen from Fig. 7b that the distribution curves of HTC on the bottom surface of the two above-mentioned tubes (horizontal tube and inclined tube) are quite similar at different pressures except in the LSHR region, where the magnitude of the HTC on the bottom surface of the horizontal tube is however larger than that of the inclined tube. At a pressure of 25.0MPa, the peak of HTC on the bottom of the horizontal tube is about 20 kW/(m^2 K), but that of the inclined tube is about 18.4 kW/(m^2 K). It is seen in Fig.7 that with the pressure increasing, the peak HTCs on the bottom surface of both the two tubes decrease, and the bulk fluid enthalpy corresponding to the peak HTC value however increases.

It is also seen from Fig.7b that heat transfer deterioration occurs on the top surface of the horizontal tube and inclined tubes in the LSHR region. With the increasing of pressure, heat transfer improvement on the top surface of the horizontal tube appears even late on the tube and in a even little magnitude.

Fig. 8 shows the variation of Δt, i.e. the temperature difference between the top surface and bottom surface of each tube. It is seen in Fig.8 that in the LSHR, the Δt_{hor} of the horizontal tube at pressure of 25MPa is generally higher, but varies slower, than that at pressure of 23MPa.

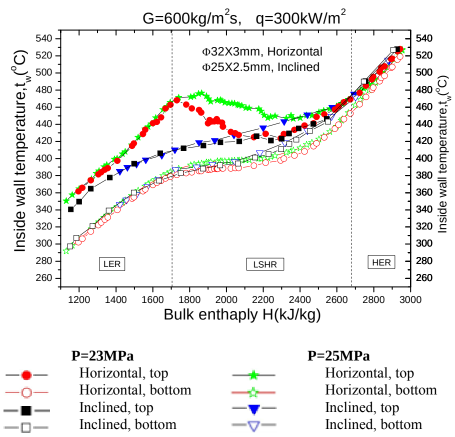


Fig. 7a. Variation of the inner wall temperature with fluid enthalpy at different pressures

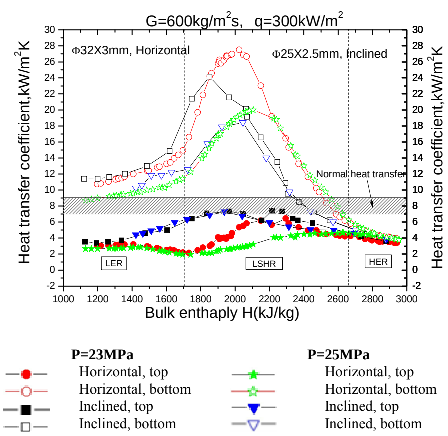


Fig. 7b. Variation of the heat transfer coefficient with fluid enthalpy at different pressures

3.3. Effect of Mass Fluxes

Fig. 9a and Fig. 9b shows the variations of the wall temperature and HTC of the tubes with the bulk enthalpy at different mass fluxes at a pressure of 26 MPa and an inner wall heat flux of 400kW/m^2. It is shown in Fig.9a and Fig.9b that the increasing in mass fluxes can improve the heat transfer on both the top and the bottom surface of the tube (horizontal tube and inclined tube). It is seen from Fig.9a and Fig.9b that when the mass flux is 700kW/m^2, heat transfer deterioration occurs on the top surface of the horizontal tube, but does not occur on the top surface of the inclined tube.

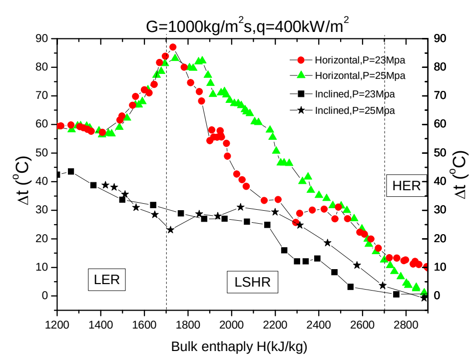


Fig. 8 Variation of the temperature difference with fluid enthalpy at different pressures

When the mass flux is increased to 1000 kW/m^2, heat transfer enhancement occurs on the top and bottom surface of both two tubes. The reason for this result is that when the mass flux is increased, the turbulent diffusivity of the bulk fluid is enhanced and effect of the buoyancy force on the heat transfer is mitigated.

Fig. 10 shows the variation of Δt, i.e. the temperature difference between the top surface and bottom surface of each tube with the increasing of fluid enthalpy at different mass fluxes. As shown in Fig. 10, when the mass flux is 700 kW/m^2, the maximum of Δt_{hor} is 104℃ and maximum of Δt_{inc} is 52℃, but when mass flux is increased to 1000kW/m^2, the maximum of Δt_{hor} decreases to 33℃ and maximum of Δt_{inc} is reduced to 35℃. In general, at low heat fluxes, HTC at both the top and bottom surfaces is effectively improved by increasing in mass fluxes.

It is worth noting that as shown in Fig. 9b, the value of HTC of both the horizontal tube and the inclined tube rises obviously with the increasing of mass fluxes. For example, when the mass flux is increased from 700 to 1000 kg/(m2 s), the maximum HTC on the bottom surface of the horizontal tube raises from 29.5 to 41.7 kW/(m2 K), while the corresponding HTC for inclined tube raises from 28.9 to 41.6 kW/(m2 K). Obviously, the difference in HTC between the horizontal tube and inclined tube tends to diminish with the increasing in mass fluxes.

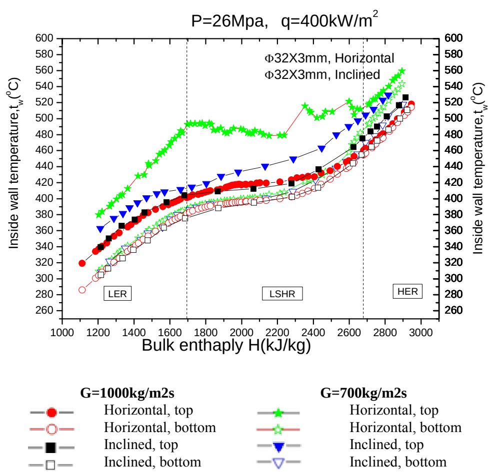


Fig. 9a. Variation of the inner wall temperature with fluid enthalpy at different mass fluxes

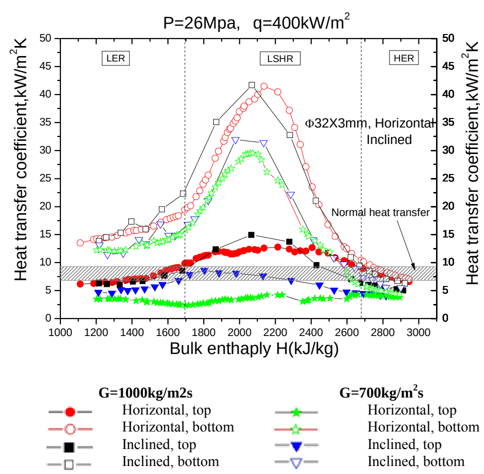


Fig. 9b. Variation of the heat transfer coefficient with fluid enthalpy at different mass fluxes

4. Conclusions

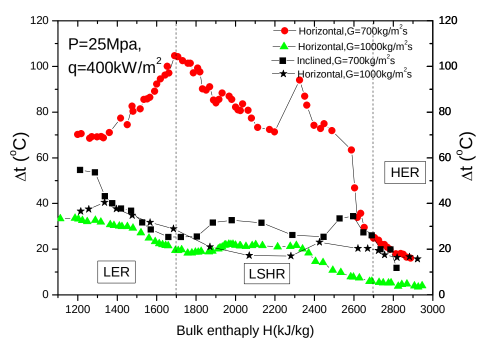


Fig. 10 Variation of the temperature difference with fluid enthalpy at different mass fluxes

1) There exist big difference in the wall temperature and also the HTC between the top surface and the bottom surface of the tube in the LER and the LSHR region of supercritical water.

2) In the LSHR region, the temperature distribution and HTC distribution on the surface of the horizontal tube are greatly different from that of the inclined tube. Heat transfer deterioration easily occurs on the top surface of the horizontal tube in the LER region, and the enthalpy corresponding to the peak wall temperature on the top surface of horizontal tube is

roughly in a region of 1700-1900kJ/kg.

3) The temperature on the top surface of the tube will increase with increasing in heat flux, but heat flux has relatively small effect on the temperature on the bottom surface of the tube. Increasing in heat flux has greater influence on the non-uniform distributions of temperature and HTC on the horizontal tube than that on the inclined tube.

4) With the increasing in pressure, the peak HTCs on the bottom surface of both the two tubes decrease, and pressure has generally slight effect on the peak wall temperature on the top surface of the horizontal tube.

5) Increasing in mass fluxes may greatly reduce and even diminish the difference in the surface temperature distributions and HTC distributions between the horizontal tube and the inclined tube.

Nomenclature

P	pressure/ MPa	C_p	Specific heat at constant pressure/ kJ·kg^{-1}
T	temperature/ °C	h	Heat transfer coefficient/ kW·m^{-2}·K^{-1}
G	Mass flux/ kg·m^{-2}·s^{-1}	q	Heat flux/ kW·m^{-2}

Greek letters

λ	Thermal conductivity/ W·m^{-1}·K^{-1}	μ	viscosity/ μPa*s
ρ	density/ kg·m^{-3}	α	Inclined angle/°

Subscripts

Hor,	Horizontal tube	Inc.	Inclined tube
pc	pseudocritical		

Abbreviation

LER	Low enthalpy range	HER	High enthalpy range
LSHR	Large specific heat range	SCWRS	Supercritical water-cooled reactors
Δt	Temperature difference between the top and bottom surfaces		

Acknowledgements

The authors acknowledge the support of the National Basic Research Program of China (973 Program) (grant No. 2009CB219805) and the National Natural Science Foundation of China (grant No. 50876090).

5. References

[1] Lin, Z.H., Chen, L.X., 1990. Inter-boiler Process. Xi’an Jiaotong University Press, Xi’an, China, pp. 203–205 (in Chinese).

[2] Schmidt, E., Eckert, E., Grigull, V., April 1946. Heat Transfer by Liquids Near the Critical State, AFF Translation, No. 527. Air Materials Command, Wright Field, Dayton, OH, USA.

[3] Majid Bazargan, Daniel Fraser, Vijay Chatoorgan, Effect of Buoyancy on Heat Transfer in Supercritical Water Flow in a Horizontal Round Tube, Journal of Heat Transfer, ASME 2005 (897-902)

[4] Igor L. Pioro, Hussam F. Khartabil, Romney B. Duffey. Heat transfer to supercritical fluids flowing in channels—empirical correlations (survey). Nuclear Engineering and Design, 230 (2004) 69–91

[5] Bazargan, M., and Fraser, D. W., 2000, "Forced Convection Heat Transfer toTurbulent Flow of Water at Supercritical Pressure," 2000 National Heat Transfer Conf., Pittsburgh, Aug. 20-22.

[6] Pioro, I.L., Duffey, R.B., 2005. Experimental heat transfer in supercritical water flowing inside channels (Survey). Nucl. Eng. Des., 235, 2407–2430.

[7] WANG W.S., CHEN T.K., LUO Y.S., etc., Experimental Research on Wall Temperature Distribution and Heat Transfer Characteristics of the Tilted Smooth Riser Tubes in the Supercritical Pressure Region. Power Engineering Vol.25, No.5(2005) (in Chinese)

[8] Li, H.X., Sun, S.W., Guo, B., et al., 2008. Experimental investigation on the circumferential ununiformity in heat transfer of water in inclined smooth upward tubes at supercritical pressures. J. Eng. Thermophys. 29 (2), 241–245 (in Chinese).

[9] Jackson, J.D., Hall,W.B., 1979a. Forced convection heat transfer to fluids at supercritical pressure. Turbulent Forced Convection in Channels and Bundles. Hemisphere Publishing Corporation, pp. 563–611.

[10] Jackson, J.D., Hall, W.B., 1979b. Influences of buoyancy on heat transfer to fluids flowing in vertical tubes under turbulent conditions. Turbulent Forced Convection in Channels and Bundles. Hemisphere Publishing Corporation, pp. 613–640.

[11] Yamagata K., Nishikawa K., and Hasegawa S. et al.. Forced convection heat transfer to supercritical water flowing in tubes [J]. Int. J. Heat Mass Transfer. 15(12): 2575-2593 (1972)