2014 Canada-China Conference on Advanced Reactor Development (CCCARD-2014)
Niagara Falls Marriott Fallsview Hotel & Spa, Niagara Falls, Ontario Canada, April 27-30, 2014.

CCCARD2014-011

FORCED CONVECTIVE HEAT TRANSFER EXPERIMENT OF SUPERCRITICAL WATER IN DIFFERENT DIAMETER OF TUBES

Chen Yuzhou, Yang Chunsheng, Zhao Minfu, Bi Kemin and Du Kaiwen
China Institute of Atomic Energy, Beijing, China

Abstract

Forced convective experiment of supercritical water was performed in Inconel-625 tubes of 4.62, 7.98 and 10.89 mm in diameters. The water flowed upward, covering the ranges of pressure of 23.6 – 26.1 MPa, mass flux of 92 – 3281 kg/m^{2}s, local bulk temperature of 102 -384℃, inner wall temperature of 148 – 669 ℃ and the heat flux of up to 2.41 MW/m^2. The results exhibited severe deteriorated and enhancement heat transfer. The experimental results can be calculated by the Jackson et al. correlation and the Bishop et al. correlation mostly. But some data with strong effects of the buoyancy force and the variations of flow regimes were not predicted properly.

Introduction

Since 1950's the development of supercritical pressure boiler has led to the studies of heat transfer of supercritical water significantly, and various correlations have been proposed in literature based on different conditions [1-5].

In recent years the concern of development of supercritical water cooled reactors as a candidate of 4th generation of nuclear power systems has promoted these studies further [6 - 13]. At supercritical pressure the properties vary substantially and they have great effect on the heat transfer. When the coolant temperature increases from a value of below the pseudo-critical point, T_{PC}, to beyond T_{PC} the flow regime varies, which is similar to the two-phase flow at subcritical pressure. So far, the existing correlations are the modified Dittus-Boelter ones. They have different forms and predict great different results for the same conditions.

In the authors previous experiments the heat transfer coefficient was measured in natural circulation of supercritical water with the test tubes of 4.62, 7.98 and 10.89 mm in diameter, covering wider ranges of conditions. The results exhibited the deterioration, the enhancement and the normal heat transfer modes [14, 15]. In the present experiment the heat transfer coefficients were obtained at forced convection condition and were compared with the typical existing correlations.

1. Experimental facility and test section

The experiment was performed in a test loop of supercritical water. The de-ioned water was supplied by a three-head piston pump with a maximum pressure of 45 MPa and a flow rate of 2.4 m^3/h. It passed a dumping tank, a preheater, and then flowed upward through the test section. After cooling by heat exchangers it flowed back to the pump.

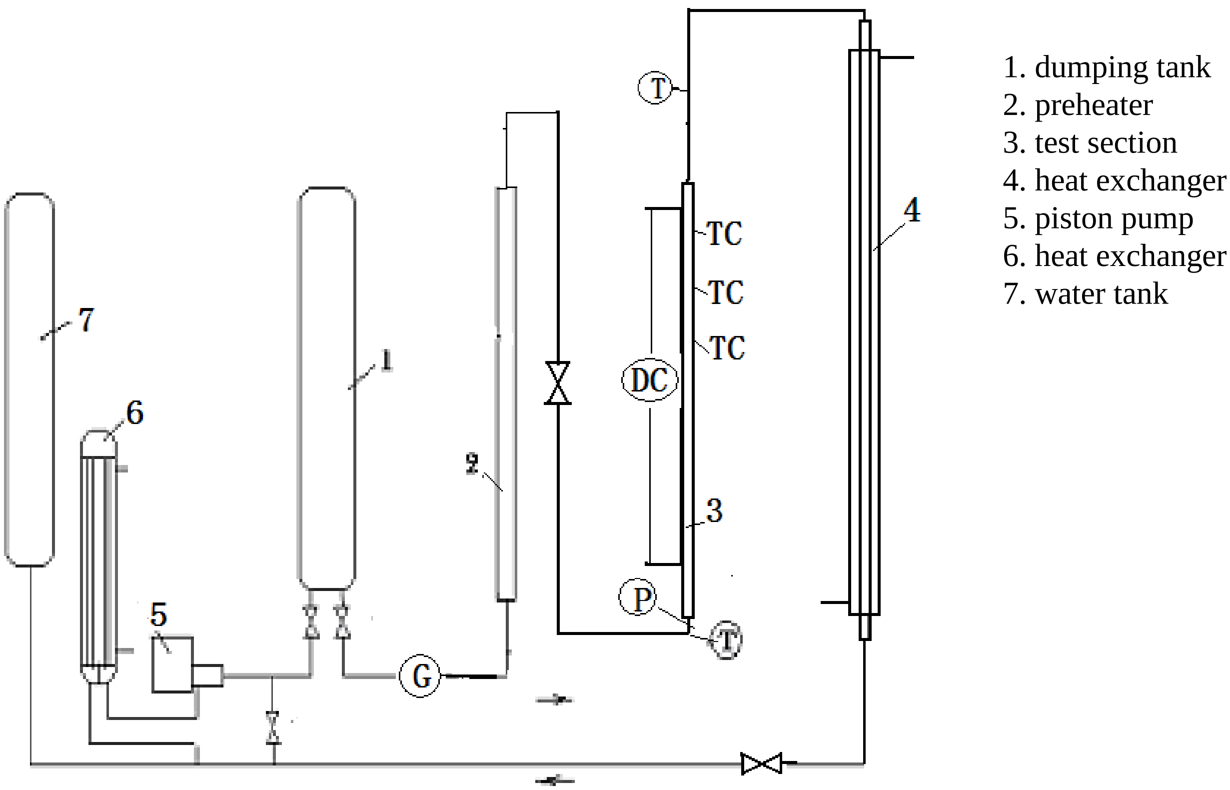


Figure 1 Schematic diagram of the supercritical water test loop

The heated power was supplied by a DC with capacity of 70V×6750A, and the preheater was supplied by a AC with capacity of 60 kW.

The test sections were the Inconel-625 tubes of D_i/D_o of 4.62/6.5, 7.98/9.6 and 10.89/12.7 mm. The heated lengths were 1.30 to 1.36 m. The test sections were thermally insulated by glass-fiber. Eight to twelve sheathed thermocouples with 0.5 or 1 mm in diameter were installed on the outer surface of test section to measure the wall temperatures at 2 to 4 locations. At each location there are three or four thermocouples with 120℃ each to other and one on the insulation layer. An electric heating wire was wrapped in the insulation layer for compensation of heat loss, which was achieved by adjusting the current to keep the temperature in the insulation close to the wall temperature.

The major measurements are: the inlet and outlet water temperatures and the outer wall temperatures by Ni-Cr/Ni-Si sheathed thermocouples, the flow rate by the turbine flowmeters with diameter of 4 or 6 mm, the inlet pressure by the pressure transducer (Rosemound 1151) and the voltage and current to the test section. All the readings were recorded by a data acquisition system with frequency of 1 s.

2. Experimental results

The experiment is performed in Inconel-625 tubes of 4.62, 7.98 and 10.89 mm in diameter. It covers the rangers of pressure of 23.6 – 26.1 MPa, mass flux of 92 – 3281 kg/m^2s, local bulk temperature of 102 -384℃, inner wall temperature of 148 – 669 ℃ and the heat flux of up to 2.41 MW/m^2. The deviations of heat balances are within 0.02 mostly and 0.035 for maximum. The experimental conditions for three diameters are listed in Table 1.

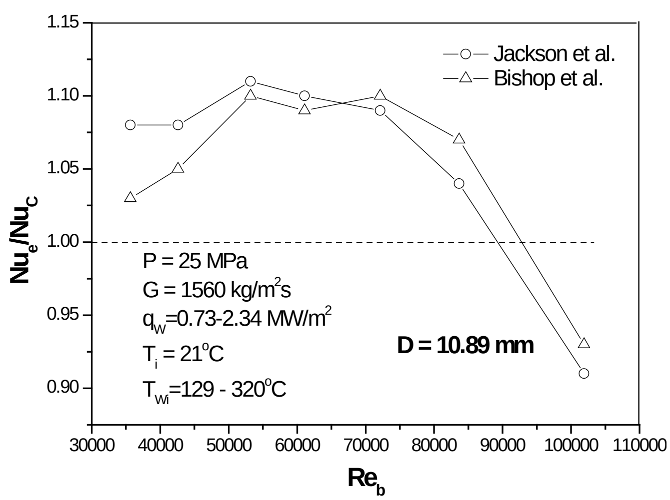
Di (mm)	P (MPa)	G (kg/m^2s)	T_b (℃)	T_{wi} (℃)	q_W (MW/m^2)
4.62	23.9 – 25.8	1098 - 3281	102 - 371	148 - 509	0.51 – 2.41
7.98	24.3 – 25.5	240- 730	109 - 384	217 - 669	0.23 – 1.4
10.89	23.6 – 26.1	92 - 2236	102 - 373	179 - 661	0.23 – 2.34

Table 1 Experimental conditions for three diameters of tubes

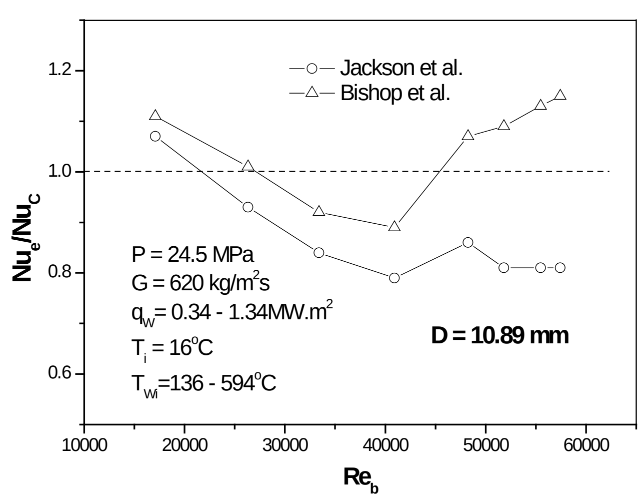
For supercritical condition the heat transfer is affected by the great variations of properties and thus exhibits both the deterioration and enhancement. So far various correlations have been proposed, based on different experimental conditions. They are the correlations by the Jackson et al. [12], the Bishop et al. [3], the Yamagata et al. [5], the Swenson et al. [4], the Watts et al. [9], the Cheng et al. [10] and so on. All they are the modified Dittus-Boelter correlations. In the present study the experimental results are compared with the Jackson et al. correlation and the Bishop et al. correlation.

2.1 Experimental results for different mass fluxes

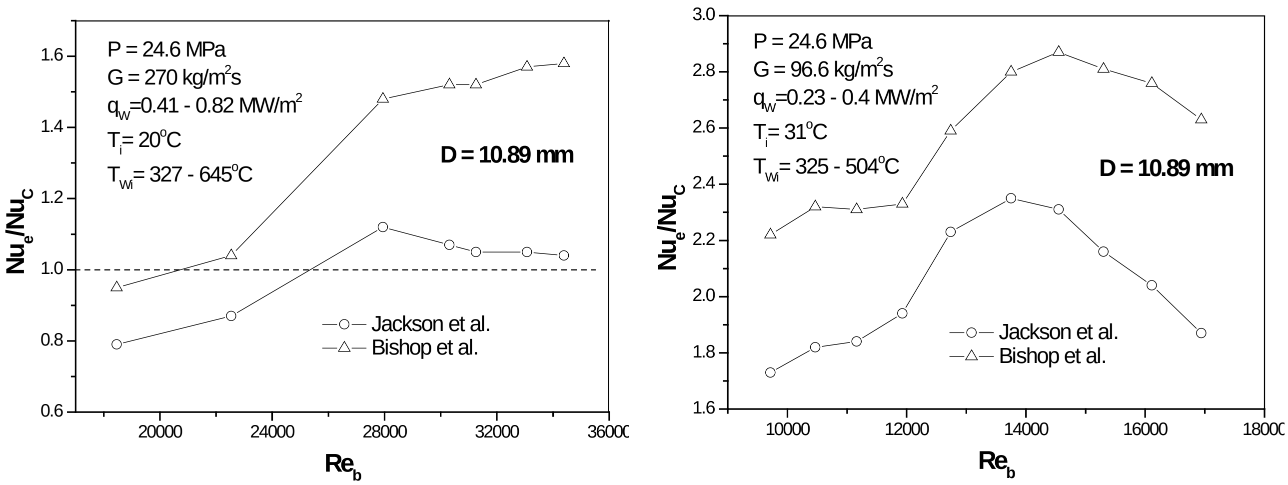
In figure 2 and 3 the experimental results are compared with the predictions of Jackson et al. correlation and Bishop et al. correlation at mass fluxes of 96 – 1560 kg/m^2s for D = 10.89 mm and at 1320 – 3220 kg/m^2s for D = 4.62 mm, respectively. As seen, for the mass flux of 500 - 1600 kg/m^2s the majority of experimental results are calculated by two correlations within ±15%. For G > 3000 kg/m^2s the results are



(a)

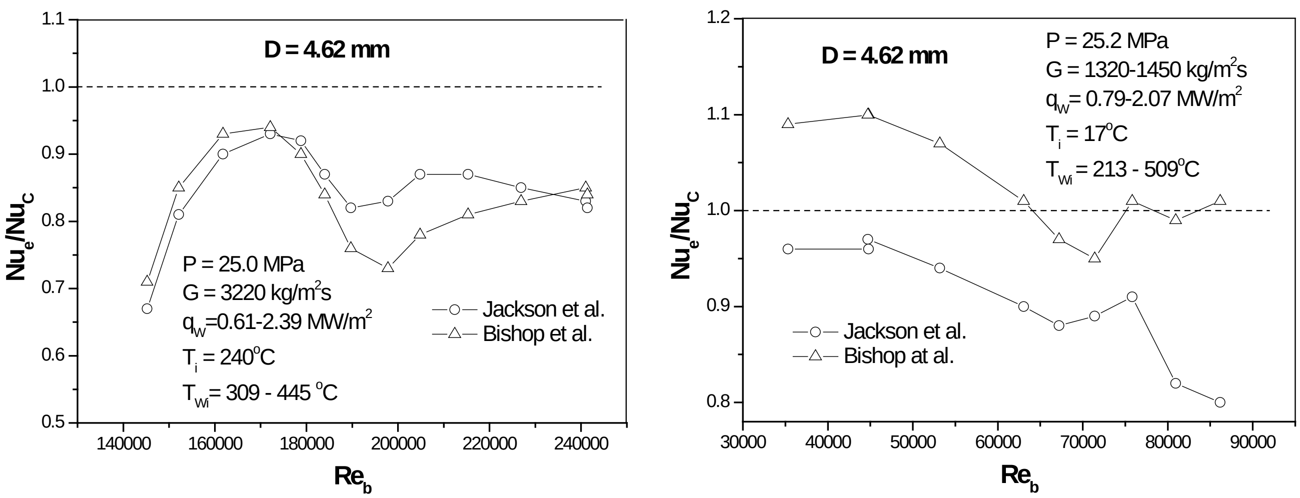


(b)



(c) (d)

Figure 2 Comparison of experimental results with two correlations for different mass fluxes in the tube of D = 10.89 mm and L = 1.2 m



(a) (b)

Figure 3 Comparison of experimental results with two correlations for different mass fluxes in the tube of D = 4.62 mm and L = 1.2 m

lower than the calculations slightly. For G = 270 kg/m^{2}s the results also agree with the Jackson et al. correlation properly, but they are more than 40% over the Bishop et al. correlation at higher bulk temperatures (T_b = 264 – 316℃). At G =96.6 kg/m^{2}s (T_b= 272 - 364℃) the results are severely higher than the calculations, especially for the Bishop et al. correlation.

This comparison indicates that the experimental results of mass flux of 500 – 1600 kg/m^{2}s are calculated better by two correlations, but they are uncerpredicted at low flow and are overpredicted at high flow.

2.2 Effect of buoyancy on the heat transfer coefficient

The effect of buoyancy is generally accounted by the buoyancy parameter, Bo, defined by

$$Bo = \frac{Gr}{\mathrm{Re}_b^{3.425}\,\mathrm{Pr}_b^{0.8}} \qquad \text{with} \qquad Gr = \frac{g\beta q D^4}{k\nu^2}$$

Figure 4 shows the variations of ratio of measured Nusselt number to the calculation by Dittus-Boelter correlation, Nu_e/Nu_{D-B}, with Bo for D = 10.89 mm at $T_{Wi} < T_{PC}$ and $Re_b > 10000$. At these conditions the coolant is pure liquid-like and the ratio of Nu_e/Nu_{D-B} reflects the effect of buoyancy force. As can be seen, at Bo of 4×10^{-7} to 1×10^{-5} the ratio of Nu_e/Nu_{D-B} decreases to around 0.6. This is thought to be the deteriorated heat transfer caused by buoyancy force. When the Bo > 1×10^{-4} (G of around 100 kg/m^{2}s) the ratio is more than 1.7, indicating the enhancement in heat transfer. In the region of $T_{Wi} > T_{PC}$ the Nu_e/Nu_{D-B} could be decreased to less than 0.2. This deteriorated heat transfer is caused by both the buoyancy and the variation of flow regimes.

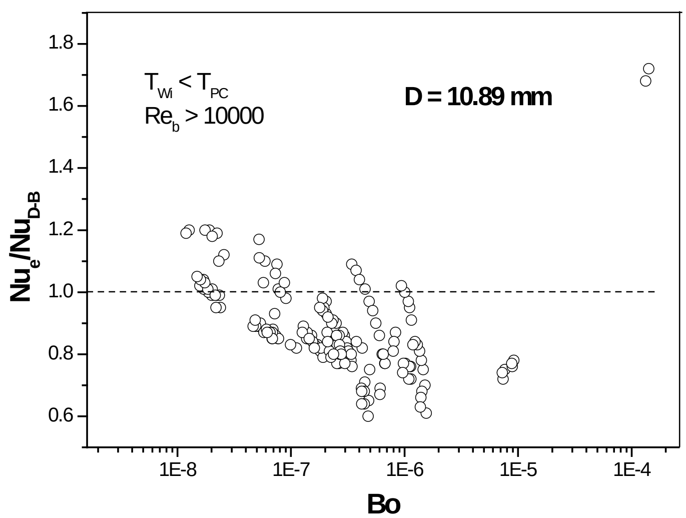
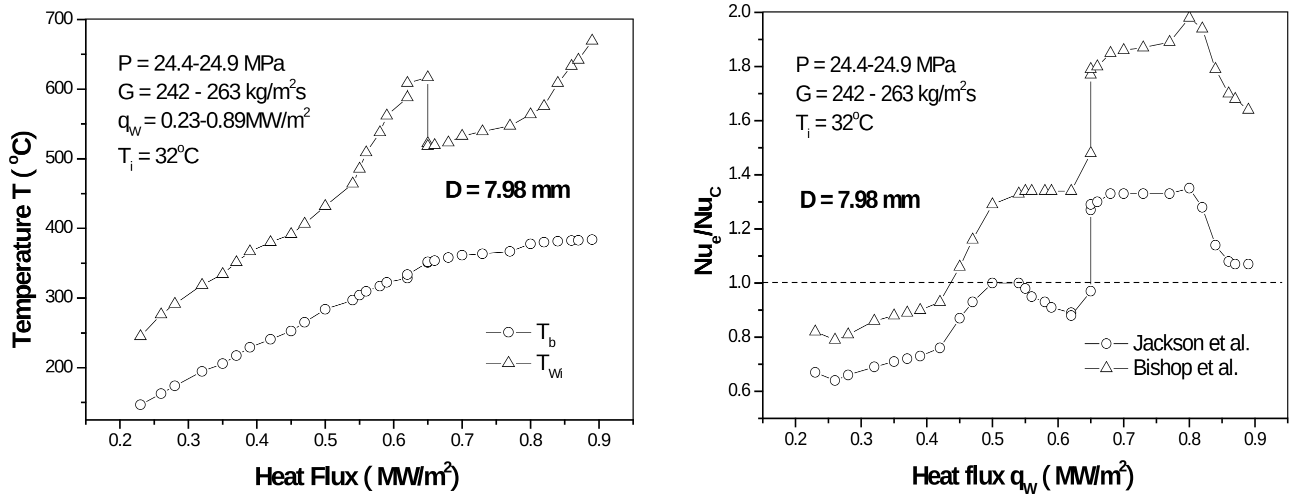


Figure 4 Variations of Nu_e/Nu_{D-B} with Bo for three diameters at $T_{Wi} < T_{PC}$

2.3 Effect of flow regime on the heat transfer coefficient

As the bulk temperature increases with the heat flux the wall temperature increases from a temperature below T_{PC} to beyond T_{PC}, and the flow regime varies from a pure liquid-like to a pseudo-inverted annular and then to a pure gas-like. For the pseudo-inverted annular regime the gas film will be transited from the laminar flow to turbulent flow. These variations of the flow regimes could cause a strong effect on the heat transfer coefficient.

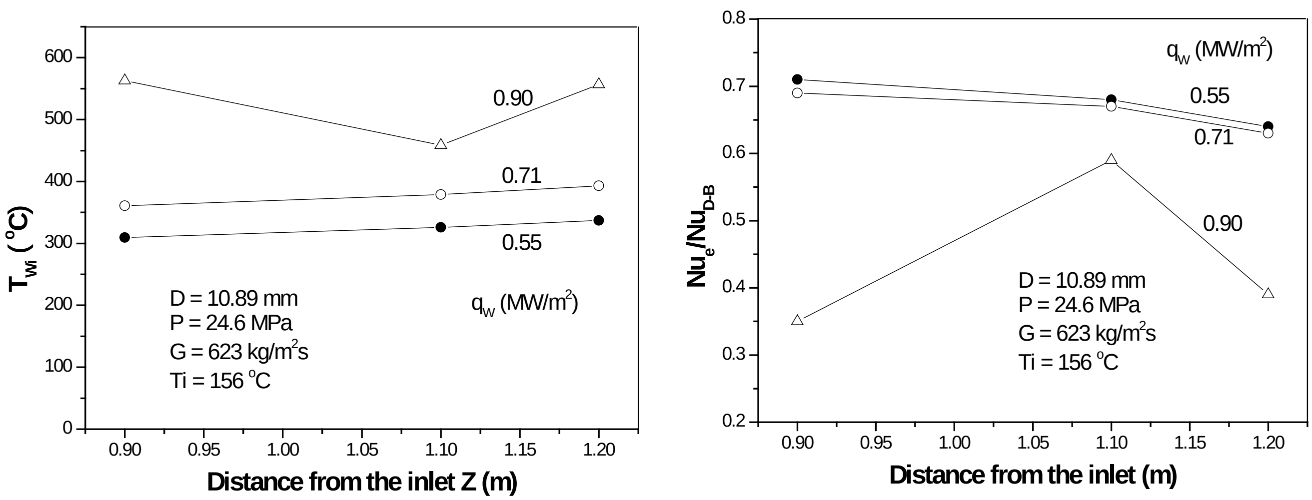
As shown in figure 5 for D = 7.98 mm, at $T_{Wi} = T_{PC}$ the T_b is 250℃and q_w is 0.42 MW/m^2, and the ratios of Nu_e/Nu_J and Nu_e/Nu_B are 0.76 and 0.93, respectively. As the power increases further the regime is pseudo-inverted annular, and boundary layer is laminar gas first and then transits to turbulent, associated with the wall temperature decreases sharply. At these conditions the ratios of Nu_e/Nu_J and Nu_e/Nu_B increase to nearly 1.33 and 2.0, respectively.



(a) (b)

Figure 5 Experimental results of D = 7.98 mm at different heat fluxes with G = 242-263 kg/m^{2}s

Figure 6 exemplifies the variations of $Nu_e/Nu_{D\text{-}B}$ of D = 10.89 mm at different heat fluxes for the inlet temperature of 156℃. It is noted that when the heat flux reaches 0.9 MW/m^2 the inner wall temperature at Z = 0.9 m is much higher than that at Z = 1.1 m. This is understandable, because at this condition the flow is the pseudo-inverted annular regime and the gas film is laminar firstly and then transits to turbulent, resulting in a decrease in the wall temperature. This phenomenon was also observed in the author's experiment of natural circulation heat transfer [15].



(a) (b)

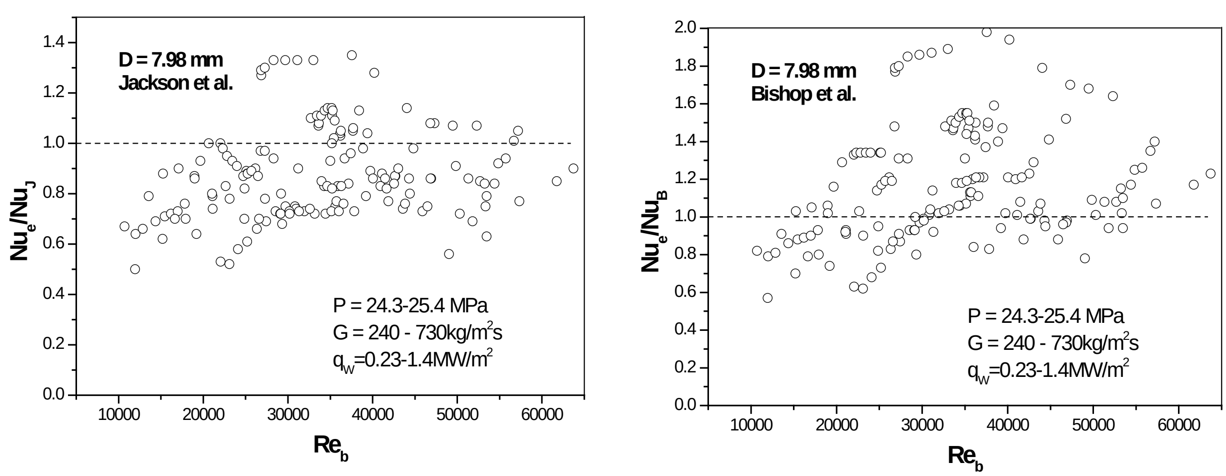
Figure 6 Experimental results of D = 10.89 mm at different heat fluxes with G = 623 kg/m^{2}s

3. Comparison of the experimental results with the predictions of Jackson et al correlation and Bishop et al. correlation

All the present experimental results are compared with the calculations by the Jackson et al. correlation and the Bishop et al. correlation for three diameters by plotting the Nu_e/Nu_J and Nu_e/Nu_B versus Re_b. As shown in figure 7 for D = 7.98 mm, the low values of the ratios of Nusselt numbers (about 0.5) are obtained at the buoyancy parameter Bo of around 1×10^{-6}, where the deterioration is thought to be most significant [13]. The high values of the ratios of Nusselt numbers (1.3 to 1.33 and 1.8 to 2.0 for the Jackson et al. and the Bishop et al. correlation, respectively) are obtained at the transition of flow regime from laminar to turbulent. Except for these conditions the experimental data are calculated by the Jackson et al. correlation mostly within -30% to +20%. They are slightly larger by the Bishop et al. correlation.

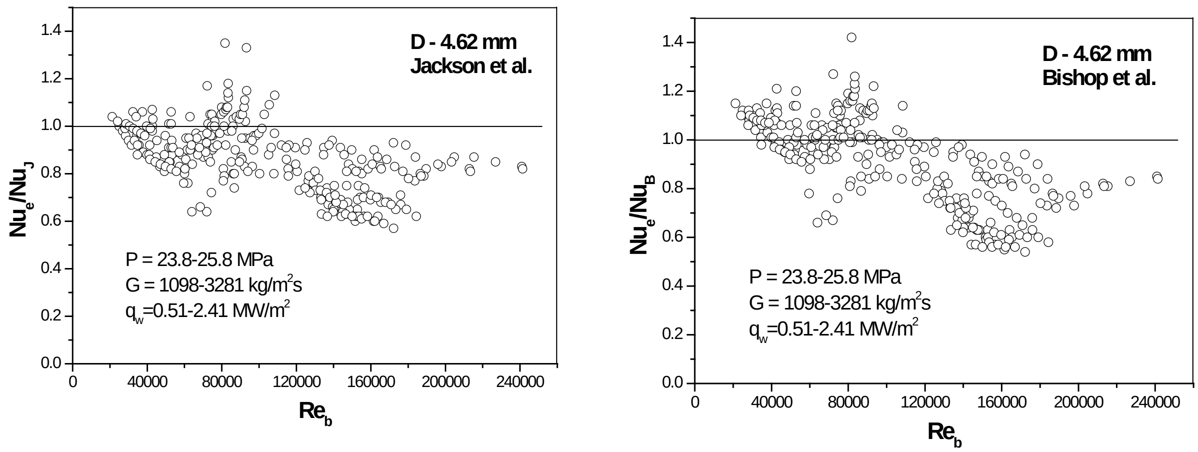
Figure 8 shows the comparison of experimental data of D = 4.62 mm with the calculations by these two correlations. The majority of the data points agree with the calculations within −30% to +20%. In general, for D = 4.62 mm the Bishop et al. correlation appears better than the Jackson et al. correlation.

In figure 9 the experimental data of D = 10.89 mm are compared with the calculations by these two correlations. As explained in the last paragraph, the lowest point of Nu_e/Nu_J (0.49) is thought to be caused by the laminar gas film at Z = 0.9 m, and it recovers to 0.75 at Z = 1.1 m. At this condition the ratio of Nu_e/Nu_B is 0.67 and 0.89 for Z = 0.9 and 1.1 m, respectively. In the region of Re_b of 10000 – 20000 (G of around 100 kg/m^{2}s) a strong enhancement heat transfer is obtained. This is out of the ranges for two correlations. Except for these conditions the agreements for the majority of data points are within ±20%.



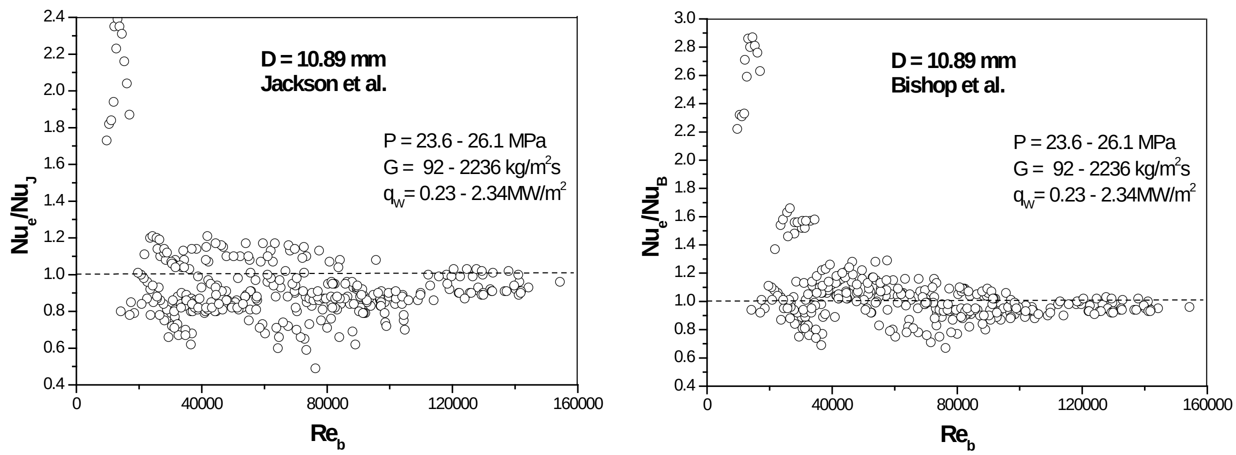
(a) (b)

Figure 7 Comparison of the experimental data with existing correlations for D = 7.98 mm



(a) (b)

Figure 8 Comparison of the experimental data with existing correlations for D = 4.62 mm



(a) (b)

Figure 9 Comparison of the experimental data with existing correlations for D = 10.89 mm

4. Conclusions

Forced convection experiment of supercritical water was performed in Inconel-625 tubes of Di = 4.62, 7.98 and 10.89 mm, covering the ranges of pressure of 23.6 – 26.1 MPa, mass flux of 92 – 3281 kg/m^{2}s, local bulk temperature of 102 -384℃, inner wall temperature of 148 – 669 ℃ and heat flux of up to 2.41 MW/m^2. The heat transfer coefficients exhibit the normal, deteriorated and enhancement behavior. The buoyancy causes severe deteriorated and enhancement heat transfer at different range of parameters. The transition of flow regimes also causes a strong effect on the heat transfer. The experiment data are compared with the predictions by Jackson et al. correlation and Bishop et al. correlation, and the agreements are reasonable mostly, except for the above conditions.

5. Acknowledgmemt

The present experiment was supported by the International Science and Technology Cooperation Program of China (Grand No, 2012DFG61030).

6. References

[1] R.C HENDRICKS, R. J. SIMONEAU and S R.V. MITH, "Survey of heat transfer to near critical fluids", NASA Technical Memorandum NASA TM X-S 2612, 1969

[2] J.D. JACKSON, W.B. HALL, J. FEWSTER, A. WATSON and M.J. WATTS, "Review of heat transfer to supercritical pressure fluids", H.T.F.S. Design Report No. 34, A.E.R.E. Harwell, 1975.

[3] A, Bishop, R, Sandberg L Tong, "Forced convection heat transfer to water at near-critical temperatures and supercritical pressures", *WCAP-2056*, (1964).

[4] H.S. SWENSON, J.R. CARVER, and C.R. KAKARALA, "Heat transfer to supercritical water in smooth-bore tubes", *A.S.M.E. Journal of Heat Transfer*, 1965.

[5] K. Yamagata, K. Nishigawa, S. Hasegawa, T. Fuju and S. Yoshida, "Forced convective heat transfer to supercritical water flowing in tubes". International Journal of Heat *and* Mass Transfer, , **15**(12): 2575–2593 (1972)

[6] H. ZAHLAN, D.C. GROENEVELD, S. TAVOULARIS, S. MOKRY and I. PIORO, "Assessment of supercritical heat transfer prediction methods", the 5th Int. Sym. SCWR (ISSCWR-5), Vancouver, British Columbia, Canada, March 13-16, 2011, 20 pages.

[7] S. MOKRY, Y.E. GOSPODINOV, I. PIORO, and P. Kirillov, "Supercritical water heat-transfer correlation for vertical bare tubes", Proceedings of the 17th International Conference on Nuclear Engineering ICONE-17, Brussels, Belgium, July 12-16, Paper # 76010, 2009, 8 pages.

[8] I. PIORO, and S. MOKRY, "Heat transfer to fluids at supercritical pressures", Chapter in Heat Transfer – Theoretical Analysis, Experimental Investigations and Industrial Systems, Edited by A. Belmiloudi INTECH, Rijeka, Croatia, pp481-504, 2011

[9] M.J. WATTS and C.T. CHOU, "Mixed convection heat transfer to supercritical pressure water", Proc. 7th International Heat Transfer Conference, Munich, Paper MC16, Vol. 3, 495-500, 1982.

10] X. CHENG, Y.H. YANG and S.F. HUANG, "A simple heat transfer correlation for SC fluid flow in circular tubes", NURETH-13, Kanazawa City, Ishikawa Prefecture, Japan, September 27-October 2, 2009.

[11] Y. Y. BAE, and H. Y. KIM, "Convective heat transfer to CO_2 at a supercritical pressure flowing vertically upward in tubes and an annular channel", Exp. Therm. Fluid Sci. Vol. 33, No. 2, pp. 329-339, 2009.

[12] J D. Jackson, "Consideration of the heat transfer properties of supercritical pressure water in convection with the cooling of advanced nuclear reactors". In: Proceedings of *the 13th Pacific Basin Nuclear Conference*, Shenzhen, China, (2002).

[13] J.D. Jackson, and W.B. Hall, "Influences of buoyancy on heat transfer to fluids flowing in vertical tubes under turbulent conditions". Turbulent Forced Convection in Channels and Bundles (eds. S. Kakac, and D.B. Spalding, Hemisphere Publishing Corporation, USA), pp 613-640, 1979.

[14] Chen Yuzhou Zhao Minfu, Yang Chunsheng, Bi Keming, Du Kaiwen, "An Experimental Study of Heat Transfer in Natural Circulation of Supercritical Water", Proc. of *NUTHOS-9*, N9P0049, Taiwan, (2012)

[15] Chen Yuzhou Zhao Minfu, Yang Chunsheng, Bi Keming, Du Kaiwen, "Natural Circulation Experiment of Heat Transfer coefficients for Supercritical Water in different diameters of tubes", IHTC-15, Kyoto, Japan (2014)

7. Appendix

(1) Dittus-Boelter correlation

$$Nu = 0.023\,\mathrm{Re}_b^{0.8}\,\mathrm{Pr}_b^{0.4}$$

where the Re_b and Pr_b are based on the bulk temperature.

(2) Jackson correlation [12]

$$Nu_b = 0.0183\,\mathrm{Re}_b^{0.82}\,\mathrm{Pr}_b^{0.5}\left(\frac{\rho_w}{\rho_b}\right)^{0.3}\left(\frac{\overline{C_p}}{C_{pb}}\right)^n$$

with

$$n = \begin{cases} 0.4 & T_w/T_{pc} \le 1, or T_b/T_{pc} \ge 1.2 \\ 0.4 + 0.2(T_w/T_{pc} - 1) & T_b < T_{pc} < T_w \\ 0.4 + 0.2(T_w/T_{pc} - 1)\left[\,1 - 5(T_b/T_{pc} - 1)\,\right] & 1 \le T_b/T_{pc} \le 1.2 \end{cases}$$

and

$$\overline{C_p} = \frac{h_w - h_b}{T_w - T_b}$$

(3) Bishop's correlation [3]

$$Nu_b = 0.0069\,\mathrm{Re}_b^{0.9}\,\overline{\mathrm{Pr}}^{0.66}\left(\frac{\rho_w}{\rho_b}\right)^{0.43}\left(1 + \frac{2.4D}{x}\right)$$

where

$$\overline{\mathrm{Pr}} = \frac{h_w - h_b}{T_w - T_b}\frac{\mu_b}{\kappa_b}$$

(4) Yamagata et al. correlation [5]

$$Nu_b = 0.0135\,\mathrm{Re}_b^{0.85}\,\mathrm{Pr}_b^{0.8}\,Fc$$

where

$$Fc = \begin{cases} 1.0 & E > 1 \\ 0.67\,\mathrm{Pr}_{pc}^{-0.05}\left(\dfrac{\overline{C_p}}{C_{pb}}\right)^{n_1} & 0 \le E \le 1 \\ \left(\dfrac{\overline{C_p}}{C_{pb}}\right)^{n_2} & E < 0 \end{cases}$$

where

$$n_1 = -0.77\left(1 + \frac{1}{\mathrm{Pr}_{pc}}\right) + 1.49$$

and

$$n_2 = 1.44\left(1 + \frac{1}{\mathrm{Pr}_{pc}}\right) - 0.53$$

with

$$E = \frac{T_{pc} - T_b}{T_w - T_b}$$