ASSESSMENT OF MIXED CONVECTION HEAT TRANSFER CORRELATIONS AT SUPERCRITICAL PRESSURES

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Abstract

Despite the numerous supercritical heat transfer correlations have been proposed in the past several decades, the predictions by using those correlations showed wide discrepancies each other and were not satisfactory. Especially, in a mixed convection heat transfer regime, no correlation was successful in producing accurate predictions. Under a strong buoyancy influence, boundary layer structure is known to deform significantly at a wall temperature close to the pseudocritical temperature. Recently, several correlations have been proposed for the prediction of heat transfer coefficient in both a mixed convection and a forced convection. In this paper, the applicability of those correlations was assessed against the data for CO_2 and water.

1. Introduction

In the development of an SCWR concept, heat transfer at supercritical pressures is one of the most demanding research areas. Despite the numerous supercritical heat transfer correlations that have been suggested in the past several decades, a search for a reliable and accurate correlation continues, because the predictions of heat transfer rate by using those correlations showed wide discrepancies each other. Especially, in the regime of strong buoyancy, no correlation was successful in producing accurate predictions. The boundary layer structure is known to deform significantly in an upward flow, as the wall temperature approaches the pseudo-critical temperature at a sufficiently low mass flow rate. The heat transfer deterioration may be caused by local flow properties but also by upstream flow history as well.

Watts and Chou [1] reported the results of a mixed convection heat transfer test using a supercritical pressure water at 25 MPa, flowing either vertically upwards or downwards in two test sections, respectively 2000 mm long x 25 mm bore and 2000 mm long x 32.2 mm bore. In their experiment, a regime of deteriorated heat transfer was found in a vertical upward flow, commencing at the buoyancy parameter, $\overline{Gr}_b \Big/ \left(Re_b^{2.7} \overline{Pr}_b^{0.5} \right)$ was increased above 10^{-5}; heat transfer reached a minimum at a value of the buoyancy parameter of 4.5×10^{-5} and then recovered steadily into the free convection region. In formulating correlations, they treated the deterioration and normal regime separately and proposed correlations for each regime. As a result, the suggested correlations returned two values for certain flow conditions. It should be noted that their experiments were carried out with relatively large diameter tubes.

Komita et al. [2] slightly modified the Watt and Chou's correlation based on a test with HCFC22, and have similar disadvantage to the Watts and Chou's. Mori et al. [3,4] reported comparisons of the test results between a tube, a single rod (annular channel), and a sub-bundle channel having a hydraulic diameter of 4.4 mm, using HCFC22. Their test results showed a suppression of heat transfer deterioration in a sub-bundle channel compared to a single tube and a single rod compared to a tube. In a single tube, the deterioration was also suppressed in downward flow. At a high flow rate in downward flow in a sub-bundle channel, they reported an observation of oscillation of heat transfer in the region of the enthalpy higher than the pseudo-critical point. A similar phenomenon was observed in the KAERI's experiment concerning a downward flow in an annulus channel, although the phenomena were not exactly similar to each other. Their test geometry was nearly the same as that presented in this paper.

Pis'menny et al. [5] experimentally studied heat transfer to upward and downward flows of water in a circular tubes with inner diameters of 6.28 and 9.5 mm. Their test data indicated a clear dependency on the non-dimensional buoyancy parameter, Gr/Re^2 . However, they did not attempt to formulate a correlation covering a deterioration regime.

Bae and Kim [6] developed a set of correlations and evaluated against published data for water and HCFC22. A fairly good agreement between the predictions and the data was shown, even though it was developed from an experiment using CO_2 as a medium. The proposed correlation produced reasonably accurate heat transfer rate in water and HCFC22 results, even in the range of strong buoyancy. Bae [7] also assessed several correlations including the one in reference [6] against the KAERI's test data. As expected, Bishop [8] and Jackson and Hall [9] correlations completely failed to predict the heat transfer rate in a mixed convection regime. The correlations proposed by Watts and Chou [1] and Bae and Kim [6] reproduced the test data with a reasonable accuracy. However, the accuracy of Watts and Chou was little bit low, and it probably was due to the difference in the test medium. The onset of deterioration is known to depend on test medium [10,11]. However, it is expected that the dependency of the criterion on the medium will diminish, if not completely, if it were based on a proper non-dimensional parameter.

An analytical approach has been suggested by Fewster and Jackson [12] and Jackson [13]. They developed a recursive equation of Nusselt number, which needed an iteration to get a correct Nusselt number or heat transfer rate. It successfully predicted heat transfer in an air flow through a large bore pipe, but its applicability should be confirmed by comparing the predictions with experimental data on heat transfer to water in a narrow tube.

Cheng et al. [14] derived a simple heat transfer correlation based on phenomenological assessment of heat transfer behavior and a thorough evaluation of the test data base. A dimensionless number, the acceleration number, $\pi_A = \beta q / (c_p G)$, was introduced to correct the deviation of heat transfer from its conventional behavior. The new correlation structure excluded direct dependence of heat transfer coefficient on the wall surface temperature, and eliminated possible numerical instability. They claimed that the correlation could be applied to both normal and deteriorated heat transfer conditions.

In this paper, the assessment of correlation will be focused on mixed convection heat transfer. In this regards, only the correlations, which claimed to be applied to both normal and deteriorated heat transfer conditions, will be evaluated against the test data for CO_2 and water.

2. Correlations and test data

The correlations suggested by Bae and Kim [6], Jackson [13], Cheng et al. [14], and a newly proposed correlation, which is a slightly modified version of the one suggested in reference [7], will be evaluated in this paper. The correlations are summarized in Table 1. It should be noted that in the Bae and Kim's correlation, the constant in the equation of Nu_f was changed from 0.021 to 0.0183 for better correlation. The newly introduced correlation designated as Bae was based on the test data obtained for upward flow in a tube with the inner diameter of 4.57 mm at a pressure of 7.75 MPa; and it was formulated as simple as possible for easy use. For a convenience, the correlations will be referred to as acronyms such as BK (Bae and Kim), JK (Jackson), CH (Cheng et al.), and BA (present), respectively. JK was a semi-empirical correlation, which was derived from a sound theoretical analysis together with empirical equations. CH was claimed that it used only fluid propertied at bulk temperature in order to avoid the iteration, which was inevitable, since the wall temperature and the Nusselt number were inter-related.

In Figure 1, the experimental Nusselt numbers normalized by the forced convection correlation Nu_f and the predictions by using BA (solid line) were plotted against the non-dimensional buoyancy parameter, $Bu = \overline{Gr}_b / Re_b^{2.7}$.

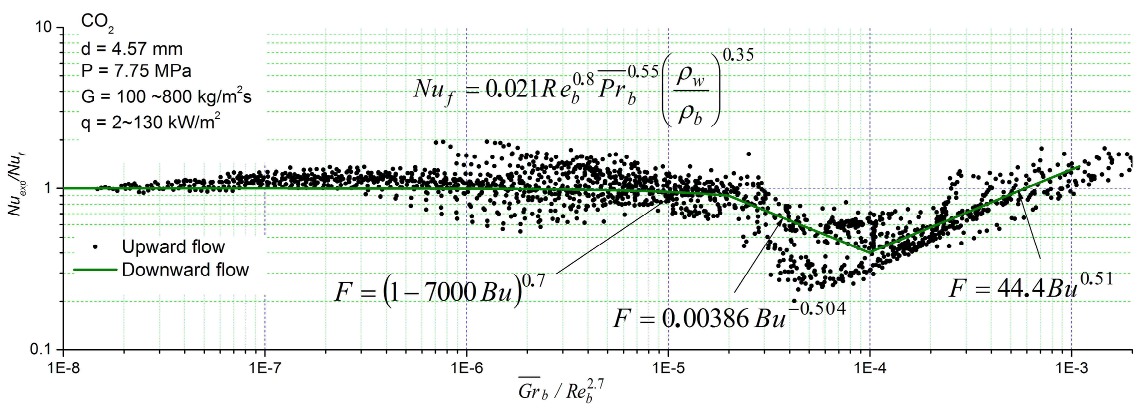


Figure 1 Experimental Nusselt number normalized by forced convection correlation versus non-dimensional buoyancy parameter.

Table 1 Correlations evaluated in this paper

Author(s)	Correlations
Bae and Kim [6]: slightly modified	$Nu = Nu_f f(Bu)$ $f(Bu) = \left(1+1.0\times10^{8} Bu\right)^{-0.032}$ for $5.0\times10^{-8} < Bu < 7.0\times10^{-7}$ $f(Bu) = 0.00185\times Bu^{-0.43465}$ for $7.0\times10^{-7} < Bu < 1.0\times10^{-6}$ $f(Bu) = 0.75$ for $1.0\times10^{-6} < Bu < 1.0\times10^{-5}$ $f(Bu) = 0.0119\times Bu^{-0.36}$ for $1.0\times10^{-5} < Bu < 3.0\times10^{-5}$ $f(Bu) = 32.4\times Bu^{0.40}$ for $3.0\times10^{-5} < Bu < 1.0\times10^{-4}$ $Nu_f = 0.0183 Re_b^{0.82} Pr_b^{0.5} (\rho_w / \rho_b)^{0.3} \left(\overline{c_p} / c_{pb}\right)^{n}$, $Bu = \overline{Gr}_b \Big/ \left(Re_b^{2.7}\,\overline{Pr}_b^{0.5}\right)$, $\overline{Gr}_b = \dfrac{\rho_b(\rho_b - \bar{\rho})gd^3}{\mu_b^2}$ The index n can be found in the reference [6]
Jackson [13]	$\dfrac{Nu_b}{Nu_f} = \left[\left\|1 \pm 1875 Bo_b F_{V1}\left(\dfrac{Nu_b}{Nu_f}\right)^{-1.1}\right\|\right]^{0.46}$ $Nu_f = 0.023 Re_b^{0.8} Pr_b^{1/3}$ $Bo_b = \dfrac{Gr_b}{Re_b^{2.625} Pr_b^{1/3}}$, $Gr_b = \dfrac{\rho_b(\rho_b - \rho_w)gd^3}{\mu_b^2}$, $F_{V1} = \left(\dfrac{\bar{\mu}}{\mu_b}\right)\left(\dfrac{\bar{\rho}}{\rho_b}\right)^{-0.5}$ Minus sign is for upward flow and plus sign downward flow.
Cheng et al. [14]	$Nu = 0.023 Re^{0.8} Pr^{1/3} F$ $F = \min(F_1, F_2)$, $F_1 = 0.85 + 0.776\left(\pi_A \cdot 10^3\right)^{2.4}$ $F_2 = \dfrac{0.48}{\left(\pi_{A,pc}\cdot 10^3\right)^{1.55}} + 1.21\left(1 - \dfrac{\pi_A}{\pi_{A,pc}}\right)$, $\pi_A = \dfrac{\beta_b q_w}{G c_{p,b}}$
Bae	$Nu = Nu_f F$ $F = (1 - 7000 Bu)^{0.7}$ for $Bu < 2\times10^{-5}$ $F = 0.00386 Bu^{-0.504}$ for $2\times10^{-5} < Bu < 1\times10^{-4}$ $F = 44.4 Bu^{0.51}$ for $Bu > 1\times10^{-4}$ $Nu_f = 0.021 Re_b^{0.8}\,\overline{Pr}_b^{0.55}\left(\dfrac{\rho_b}{\rho_w}\right)^{0.35}$, $Bu = Gr_b / Re_b^{2.7}$, $Gr_b = \dfrac{\rho_b(\rho_b - \rho_w)gd^3}{\mu_b^2}$

The experimental data showed highly irregular behavior in the transition regime, $10^{-5} < Bu < 10^{-4}$. The normalized Nusselt number did not monotonically increase to unity, but they showed a sinusoidal behavior before reaching a fully forced convection regime.

For the CO_2 data, the KAERI's test result for upward flow in a 4.57 mm ID tube was used. The data for water were obtained from three different sources; Yamagata et al. [15], Shitsman [16], and Vikhrev et al. [17] were used to evaluate the selected correlations. The Yamagata's data was for normal heat transfer and the other two groups of data were for deteriorated heat transfer.

3. Result of evaluation

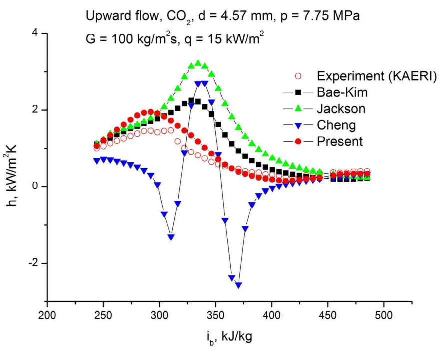
The experimental cases selected for comparison with predictions are summarized in Table 2. Since we are focusing on mixed convection regime, most of the selected cases were for severe or mild deterioration of heat transfer.

In Figure 2, the heat transfer coefficients predicted by using the selected correlations in Table 1 are overlapped on the experimental values for CO_2. CH wholly failed to predict the experimental data for CO_2 in most cases, except for the case E of G = 800 kg/m^{2}s and q = 50 kW/m^2. It severely under or over-predicted around the pseudo-critical temperature. It probably indicated an inadequacy of acceleration parameter in analyzing mixed convection with strong buoyancy. The acceleration parameter is determined by the properties at bulk conditions, and it, consequently, fails to reflect the flow conditions at the wall, which are considered to be a very important factor for characterizing the heat transfer with strong buoyancy. Since the change of heat transfer rate will be influenced by the property change near a wall, a proper prediction of heat transfer rate should be based on properties near a wall as well as bulk properties. As expected, BK, BA were in reasonably good agreement with the experimental data, since they were compared with the experimental data, from which they were derived. The correlation JK generally over-predicted in most cases, regardless of whether the heat transfer was deteriorated or not. Exceptionally good performance of BK and BA was shown in the cases of strong buoyancy or low mass flux (cases

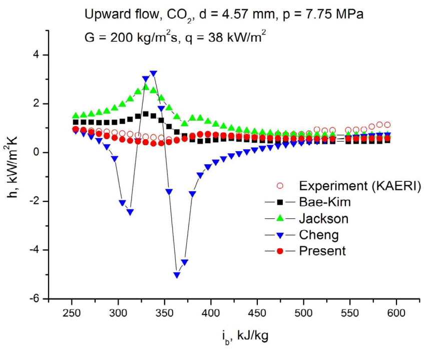
Table 2 Selected experimental cases

<table>
<tr><th>Case</th><th>Fluid</th><th>Flow direction</th><th>d (mm)</th><th>G (kg/m^{2}s)</th><th>q_w (kW/m^2)</th><th>P (MPa)</th><th>Author(s)</th></tr>
<tr><td>A</td><td rowspan="6">CO_2</td><td rowspan="10">Upward</td><td rowspan="6">4.57</td><td>100</td><td>15</td><td rowspan="6">7.75</td><td rowspan="6">KAERI</td></tr>
<tr><td>B</td><td>200</td><td>38</td></tr>
<tr><td>C</td><td>400</td><td>30</td></tr>
<tr><td>D</td><td>400</td><td>50</td></tr>
<tr><td>E</td><td>800</td><td>50</td></tr>
<tr><td>F</td><td>800</td><td>120</td></tr>
<tr><td>G</td><td rowspan="4">Water</td><td>7.5</td><td>1260</td><td>233</td><td>24.5</td><td rowspan="2">Yamagata et al.</td></tr>
<tr><td>H</td><td>10</td><td>1260</td><td>465</td><td>24.5</td></tr>
<tr><td>I</td><td>12</td><td>375</td><td>348</td><td>24.5</td><td>Shitsman</td></tr>
<tr><td>J</td><td>20.4</td><td>495</td><td>570</td><td>26.5</td><td>Vikhrev et al.</td></tr>
</table>

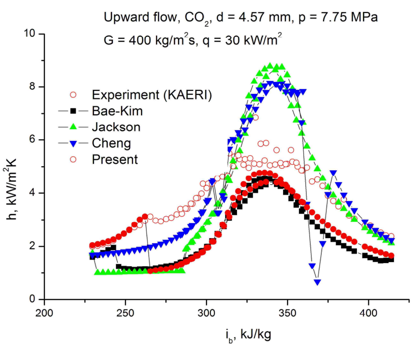
A, B, and D). However, noticeable deviations from the experimental values were shown in the cases C, E and F. Those cases corresponded to the region $10^{-7} < Bu < 4\times10^{-5}$ (see Figure 1). An overshoot ($Nu/Nu_f > 1$) in this region may be a reason for this large discrepancy. The transition from near natural convection regime ($Bu > 10^{-4}$) to forced convection regime ($Bu < 10^{-7}$) through transition regime was such uncertain that the transition path seemed to highly depend on a local flow condition. The good prediction performance of BK and BA in normal heat transfer regime



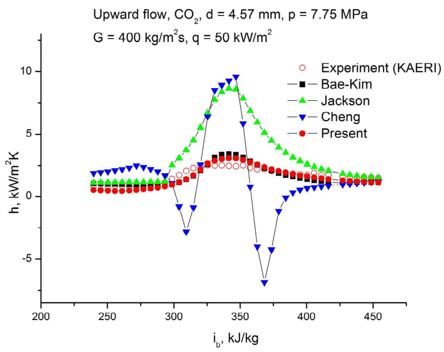
(a): case A



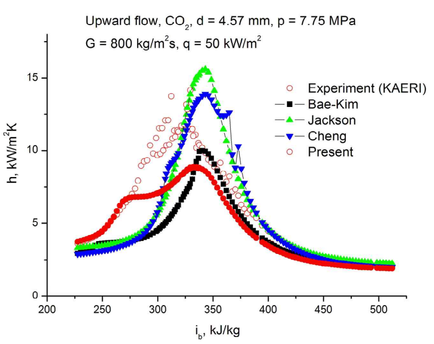
(b): case B



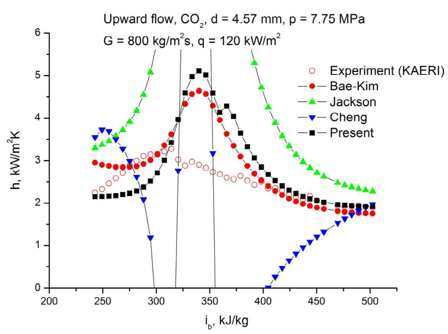
(c): case C



(d): case D



(e): case E

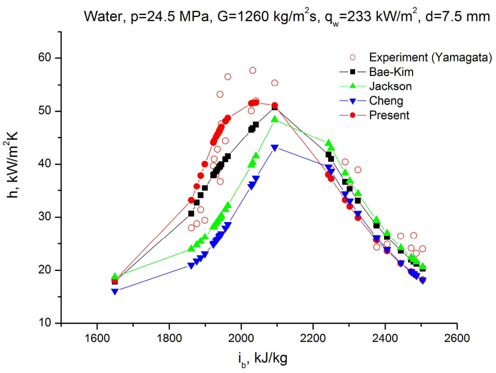


(f): case F

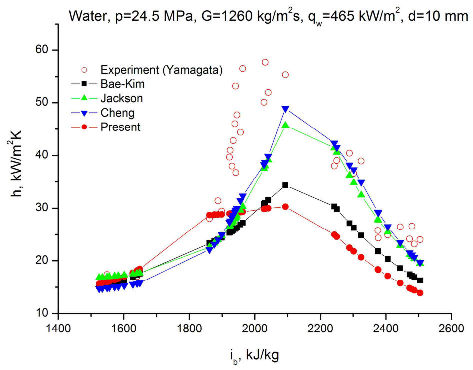
Figure 2 Heat transfer coefficients versus bulk enthalpy at various combinations of mass and heat fluxes: upward flow of CO_2, d = 4.57 mm, p = 7.75 MPa.

has been reported earlier [6, 7]. It is interesting to note that CH and JK generally over-predicted the CO_2 data.

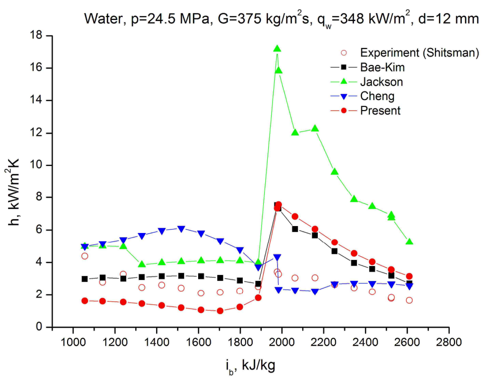
In Figure 3, the distribution of heat transfer coefficients predicted by using the selected correlations are compared with the experimental data for water. For the case G of normal heat transfer, BK, and BA showed excellent prediction performance, while JK and CH slightly under-predicted. As the heat flux increased with keeping mass flux constant (case H), the prediction performance of JK and CH improved, especially in the high enthalpy region, while BK and BA highly under-predicted over the entire region. In the case I of heat transfer deterioration, JK showed the best performance, but it severely over-predicted the Shitsman's data for high enthalpy. In this case, BK and BA predicted, in a very similar manner to JK, the experimental data quite closely; however, the prediction started to deviate as soon as the wall temperature became higher than the pseudo- critical temperature. On the contrary, the prediction performance of CH in the case I was the better when the wall temperature was higher than the pseudo-critical temperature. In the case J of more strong buoyancy, JK showed the best performance. The correlation CH also showed a good performance in this case; however, it started over-predicting the data for the enthalpy greater than 800 kJ/kg. BK and BA greatly under-predicted, and did not



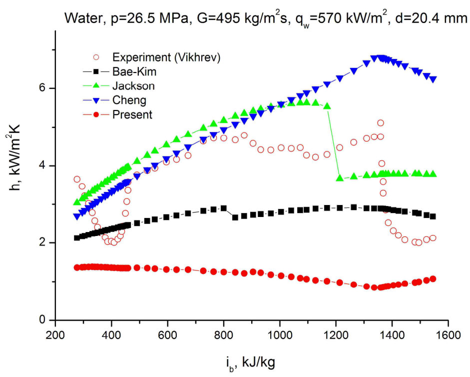
(a): case G



(b): case H



(c): case I



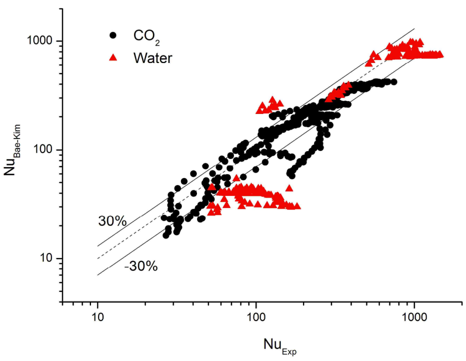
(d): case J

Figure 3 Heat transfer coefficients versus bulk enthalpy at various combinations of mass and heat fluxes: upward flow of water.

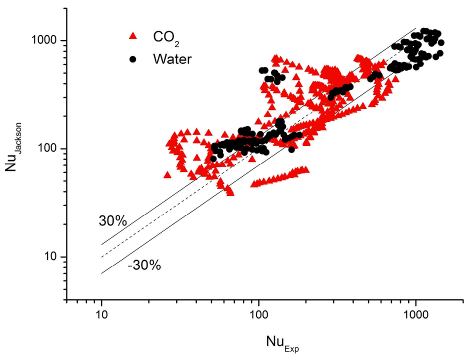
even follow the trend of heat transfer variation.

In general, the prediction performance was not good enough in the region of recovery from the highly buoyancy-influenced region (nearly natural convection-like region). Comparing the cases G and I with the cases H and J, the prediction performance of JK and CH seemed improving as the tube diameter increased, while BK and BA was getting worse. The tube size, on which the data for the correlations were based, may be an explanation for the different ranges of good prediction performance. Although JK failed to accurately predict the experimental data, it was encouraging that the distributions of the predictions by using JK were very similar to those of the data. It may indicate that a further improvement in JK hopefully provide us a better correlation.

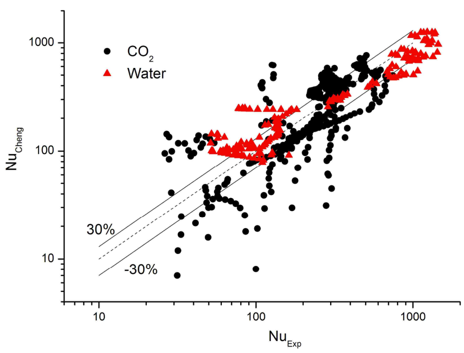
In Figure 4, the Nusselt numbers calculated by the selected correlations are compared with the experimental data for both water and CO_2. All correlations evaluated here failed to predict the experimental data within ±30% error range. JK and CH were not much satisfactory in reproducing the experimental data. BK and BA, which were formulated with heuristic approach showed better prediction performance than JK and CH. As can be seen in Figure 1, the normalized Nusselt numbers were distributed with a high degree of scattering. Therefore, any correlations were not expected to be able to predict the data belonged to this region with



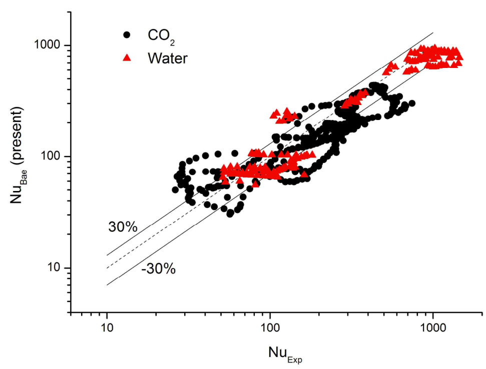
(a) Bae-Kim



(b) Jackson



(c) Cheng et al.



(d) Present

Figure 4 Predicted Nusselt number versus experimental Nusselt number.

sufficient accuracy.

CH was claimed to correlate experimental data against a simple acceleration parameter $\pi_A = \beta q/(c_p G)$, which precluded any variables at a wall temperature. The fluid properties at a bulk temperature will not interpret the heat transfer at a supercritical pressure, which has been shown in many previous literatures a function of a wall temperature, and consequently, of fluid properties at a wall. The semi-empirical correlation JK was expected to perform very nicely, since it was derived from a sound theoretical basis as well as empirical equations; but the result was not as satisfactory as expected. Considering, an inevitable iteration in order to reflect an influence of property variation near a wall and a partial success of JK, BK or BA can be utilized as an alternative to a supercritical heat transfer correlation to appear in the future.

4. Conclusion

Four supercritical heat transfer correlations were evaluated against the experimental data for water and CO_2. As a result of evaluation, following conclusions were drawn.

- Although BK and BA were derived from the data for CO_2, they predicted both water and CO_2 data with reasonable accuracy.

- JK and CH showed good prediction performance for water data obtained with larger tube diameter. JK's prediction performance was especially good enough for water, except the data of heat transfer deterioration in a small tube with inner diameter of 10 mm. It may indicate that a diameter effect should be incorporated in the correlation in any way.

- All correlations failed, partially or wholly, to predict the data in the region of strong buoyancy, since the deviation was too large to be accommodated by a single correlation.

5. References

[1] M. J. Watts, C. T. Chou, "Mixed convection heat transfer to supercritical pressure water," Int. Heat Transfer Conf. München, Vol. 3, 1982, pp. 495-500.

[2] H. Komita, S. Morooka, S. Yoshida, H. Mori, "Study on the heat transfer to the supercritical pressure fluid for supercritical water cooled power reactor development," Proc. of NURETH-10, Seoul, Korea, 2003.

[3] H. Mori, S. Yoshida, S. Morooka, H. Komita, "Heat transfer study under supercritical pressure conditions for single rod test section," Proc. of ICAPP05, Seoul, 2005, Paper No. 5303.

[4] H. Mori, m Ohno, K. Ohishi, Y. Hamamoto, "Research and development of a super Fast reactor (7) Heat transfer to a super critical pressure fluid flowing in a sub-bundle channel," Proc. of 16th Pacific Basin Nuclear Conference, Aomori, 2008, Paper ID P16P1297.

[5] E. N. Pis'menny, V. G. Razumovskiy, E. M. Maevskiy, A. E. Koloskov, I. L. Pioro, "Heat transfer to super-critical water in gaseous state or affected by mixed convection in vertical tubes," Proc. of ICONE14, Miami, 2006.

[6] Y. Y. Bae, 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, 2009, pp. 329-339.

[7] Y. Y. Bae, "Mixed Convection Heat Transfer to Carbon Dioxide Flowing Upward and Downward in a Vertical Tube and an Annular Channel," Proc. of 1st Meeting of International Specialists on Supercritical Pressure Heat Transfer and Fluid Dynamics, University of Pisa, Pisa, Italy, July 5-8, 2010.

[8] A. A. Bishop, R. O. Sandberg , L. S. Tong, "Forced convection heat transfer to water at near-critical temperatures and supercritical pressure," Am. Inst. Chem. Engrs. – I. Chem. E. Symposium Series No. 2, (London Instn. Chem. Engrs.) 1965.

[9] J. D. Jackson, W. B. Hall, "Forced convection heat transfer to fluids at supercritical Pressure, turbulent forced convection in channels and bundles," Vol. 2, Hemisphere, 1979, pp. 563-611.

[10] V.A. Grabezhnaya, P.L. Kirillov, "Heat transfer under supercritical pressures and heat transfer deterioration boundaries," Therm. Eng. Vol. 53, No. 4, 2006, pp. 296–301.

[11] Y. Y. Bae, H. Y. Kim, D. J. Kang, "Forced and mixed convection heat transfer to supercritical CO_2 vertically flowing in a uniformly-heated circular tube," Experimental Thermal and Fluid Science Vol. 34, 2010, pp. 1295–1308.

[12] J. Fewster, J. D. Jackson, "Experiments on supercritical pressure convective heat transfer having relevance to SCWR," Proc. Int. Cong. on Advances in Nuclear Power Plants (ICAPP'04), Pittsburgh, USA, 13–17 June, 2004, Paper 4342.

[13] J.D. Jackson, "An extended model of variable property developing mixed convection heat transfer in vertical tubes," Proc. of 1st Meeting of International Specialists on Supercritical Pressure Heat Transfer and Fluid Dynamics, University of Pisa, Pisa, Italy, July 5-8, 2010

[14] X. Cheng, Y. H. Yang, S. F. Huang, "A simplified method for heat transfer prediction of supercritical fluids in circular tubes," Ann. Nucl. Energy Vol. 36, 2009, pp. 1120–1128.

[15] K. Yamagata, K. Nishikawa, S. Hasegawa, T. Fujii, and S. Yoshida, "Forced Convection Heat Transfer to Supercritical Water Flowing in Tubes," Int. J. Heat Mass Transfer Vol. 15, 1972, pp. 2575–2593.

[16] M. E. Shitsman, "Deteriorated Regimes of Heat Transfer under Supercritical Pressures," Teplofiz. Vys. Temp. Vol. 1, No. 2, 1963, pp. 267–275.

[17] Yu. V. Vikhrev, Yu. D. Barulin, A. S. Konkov, "A study of heat transfer in vertical tubes at supercritical pressures," Thermal Engineering, Vol.14, No. 9, 1967, pp. 116-119.