Evaluation of Mixed Convection Heat Transfer Correlations at Supercritical Pressures

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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.

2. Mixed Convection Correlations

2.1 Earlier Mixed Convection Correlations

An analytical approach has been suggested by Jackson [1]. He 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. [2] 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.

2.2 Correlation Developed at KAERI

A series of experiments were carried out at the test facility, SPHINX, for an upward flow in a tube with the inner diameter of 4.57 mm at a pressure of 7.75 MPa. A new correlation was formulated as a function of a buoyancy parameter, $Bu = \overline{Gr}_b / Re_b^{2.7}$, as simple as possible for the sake of convenience. In Fig. 1, the experimental Nusselt numbers normalized by the forced convection correlation Nu_f and the predictions by using the present correlation (solid line) were plotted against the non-dimensional buoyancy parameter *Bu*.

The four correlations by Bae and Kim, Jackson, Cheng et al., and the one proposed here are summarized in Table 1.

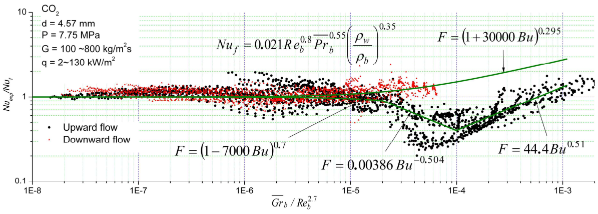


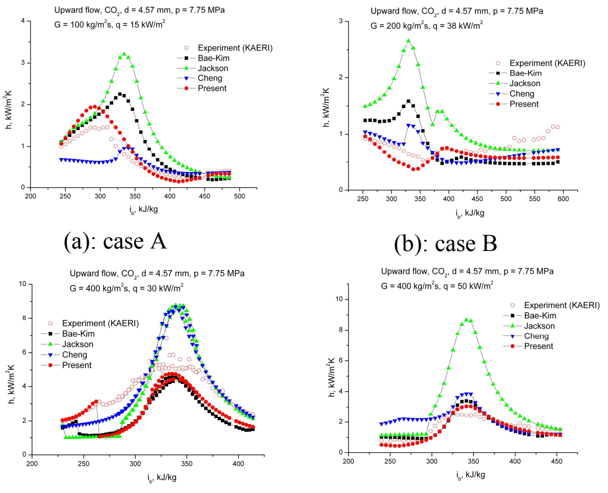
Fig. 1. Normalized experimental Nusselt number by forced convection correlation versus buoyancy parameter.

Table 1. Correlations evaluated in this paper

Correlations
Bae and Kim [3]: slightly modified (BK) $Nu = Nu_f f(Bu)$ $f(Bu) = (1 + 1.0 \times 10^8 Bu)^{-0.032}$ for $5.0 \times 10^{-8} < Bu < 7.0 \times 10^{-7}$ $f(Bu) = 0.00185 \times Bu^{-0.43465}$ for $7.0 \times 10^{-7} < Bu < 1.0 \times 10^{-6}$ $f(Bu) = 0.75$ for $1.0 \times 10^{-6} < Bu < 1.0 \times 10^{-5}$ $f(Bu) = 0.0119 \times Bu^{-0.36}$ for $1.0 \times 10^{-5} < Bu < 3.0 \times 10^{-5}$ $f(Bu) = 32.4 \times Bu^{0.40}$ for $3.0 \times 10^{-5} < Bu < 1.0 \times 10^{-4}$ $Nu_f = 0.0183 Re_b^{0.82} Pr_b^{0.5} (\rho_w / \rho_b)^{0.3} (\overline{c_p} / c_{pb})^n$, $Bu = \overline{Gr}_b \Big/ \left(Re_b^{2.7} \overline{Pr}_b^{0.5}\right)$, $\overline{Gr}_b = \frac{\rho_b(\rho_b - \overline{\rho})gd^3}{\mu_b^2}$
Jackson [1] (JA) $\frac{Nu_b}{Nu_f} = \left[\left\|1 \pm 1875 Bo_b F_{V1} \left(\frac{Nu_b}{Nu_f}\right)^{-1.1}\right\|\right]^{0.46}$ $Nu_f = 0.023 Re_b^{0.8} Pr_b^{1/3}$ $Bo_b = \frac{Gr_b}{Re_b^{2.625} Pr_b^{1/3}}$, $Gr_b = \frac{\rho_b(\rho_b - \rho_w)gd^3}{\mu_b^2}$, $F_{V1} = \left(\frac{\overline{\mu}}{\mu_b}\right)\left(\frac{\overline{\rho}}{\rho_b}\right)^{-0.5}$ (Minus sign: upward flow, plus: downward flow)
Cheng et al. [2] (CH) $Nu = 0.023 Re^{0.8} Pr^{1/3} F$ $F = \min(F_1, F_2)$, $F_1 = 0.85 + 0.776(\pi_A \cdot 10^3)^{2.4}$ $F_2 = \frac{0.48}{(\pi_{A,pc} \cdot 10^3)^{1.55}} + 1.21\left(1 - \frac{\pi_A}{\pi_{A,pc}}\right)$, $\pi_A = \frac{\beta_b q_w}{G c_{p,b}}$
Present (BA) $Nu = Nu_f F$ $F = (1 - 7000 Bu)^{0.7}$ *for* $Bu < 2 \times 10^{-5}$ $F = 3.86 \times 10^{-3} Bu^{-0.504}$ *for* $Bu < 2 \times 10^{-5}$ $F = 44.4 Bu^{0.51}$ *for* $Bu > 1 \times 10^{-4}$ $Nu_f = 0.021 Re_b^{0.8} \overline{Pr}_b^{0.55} \left(\frac{\rho_b}{\rho_w}\right)^{0.35}$, $Bu = \overline{Gr}_b / \mathrm{Re}_b^{2.7}$, $\overline{Gr}_b = \frac{\rho_b(\rho_b - \overline{\rho})gd^3}{\mu_b^2}$

3. Results of Evaluations

In Fig. 2, the heat transfer coefficients predicted by using the selected correlations in Table 1 are overlapped on the experimental values for CO_2. 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. CH showed a good prediction performance in most cases. JK severely over-predicted in all cases, probably reflecting the fact that it was developed based on the data at atmospheric pressure. As expected, BK, BA were in a reasonably good agreement with the experimental data. Exceptionally good performance of BK and BA was shown in the cases of strong buoyancy or low mass flux (cases A, B, and D). However, noticeable deviations from the experimental values were shown in the case C. An overshoot ($Nu/Nu_f > 1$) in this region may be a reason for this large discrepancy.



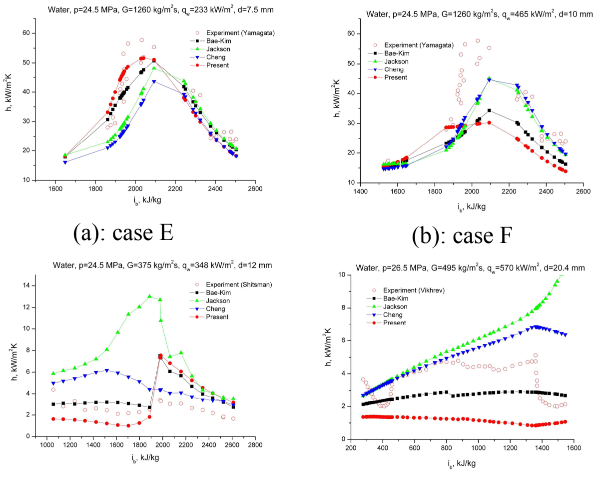
(a): case A (b): case B

(c): case C (d): case D

Fig. 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.

In Fig. 3, the distribution of heat transfer coefficients predicted by using the selected correlations are compared with the experimental data for water. For the case E 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 F), 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 G of heat transfer deterioration, BK and BA predicted the experimental data somewhat closely; however, the prediction started to deviate as soon as the wall temperature became higher than the pseudo-critical temperature. CH showed a good prediction only over the high enthalpy range, while it over-predicted over the low enthalpy range. JK over-predicted over the whole enthalpy range. In the case H, None was satisfactory.



(a): case E (b): case F

(c): case G (d): case H

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

4. Conclusions

- Although BK and BA were derived from the data for CO_2, they predicted both water and CO_2 data with reasonable accuracy.
- All correlations failed, partially or wholly, to accurately predict the data in the region of strong buoyancy, since the deviation of the data was too large to be accommodated by a single correlation.

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