Development of a Convective Heat Transfer Correlation of a Supercritical CO_2 with Vertical Downward Flow in Circular Tubes

Tae Ho YOO[ab*], Hwan Yeol KIM[a] and Yoon Yeong BAE[a]
[a]*Korea Atomic Energy Research Institute, Yusung, Daejeon 305-600, Korea*
[b]*Hannam University, Ojeong-dong, 133 Daedeok-Gu, Daejeon 306-791, Korea*
[*]*Corresponding author: thyoo82@kaeri.re.kr*

1. Introduction

Pressure of coolant flowing through a SCWR core subchannel is supercritical and the heat transfer behavior is known to be quite different from those at a subcritical pressure. Therefore the heat transfer study in a supercritical pressure is required for the acquisition of a reliable heat transfer correlation. A downward flow as well as an upward flow occurs in a multi-pass reactor core. The heat transfer at a supercritical pressure in downward channel has been known to result in a quite different behavior from an upward flow. An experiment for a supercritical CO_2 flowing vertically downward in circular tubes with inner diameters of 6.32 mm and 9 mm was performed by using SPHINX(Supercritical Pressure Heat transfer Investigation for NeXt generation) at KAERI. The obtained test results are compared with the estimations from the existing correlations and an empirical formula for a downward flow is suggested.

2. Experiments and Results

2.1 Experimental condition

The experiments are performed by changing the mass flux and heat flux under the constant pressures which are 1.05 and 1.1 times the critical pressures. Table 1 shows the experimental condition.

Table 1 Experimental condition

Condition	Unit	Value
Inner diameter	mm	6.32, 9.00
Inlet pressure	MPa	7.75, 8.12(1.05, 1.1P_{cr})
Inlet temperature	^oC	5 ~ 38
Mass flux	kg/m^2sec	400, 600, 1000, 1200
Heat flux	kW/m^2	Up to 90

2.2 Comparison of the test results with the reference correlations

First of all, we checked the results calculated from reference correlations by inserting our experimental data. Table 2 shows the reference correlations.

Table 2 Correlations selected for comparison [1]

Bishop et al.

$$Nu_x = 0.0069Re_x^{0.9}\overline{Pr}_b^{0.66}\left(\frac{\rho_w}{\rho_b}\right)_x^{0.43}\left(1+2.4\frac{D}{x}\right)$$

Jackson & Fewster

$$Nu_x = 0.0183Re_b^{0.82}\overline{Pr}_b^{0.5}\left(\frac{\rho_w}{\rho_b}\right)^{0.3}$$

Watts & Chou

$$Nu_b = Nu_{var}f(k)\,,\; Nu_{var} = 0.021Re_b^{0.8}\overline{Pr}_b^{0.55}\left(\frac{\rho_b}{\rho_w}\right)^{0.35}$$

$$f(k) = \left(1-3000\frac{Gr_m}{Re_b^{2.7}\mathrm{Pr}_b^{0.5}}\right)^{0.295} \quad for\ f(k) \le 1.0\times10^{-4}$$

$$f(k) = \left(7000\frac{Gr_m}{Re_b^{2.7}\mathrm{Pr}_b^{0.5}}\right)^{0.295} \quad for\ f(k) > 1.0\times10^{-4}$$

Table 3 shows the calculated results gotten from *Nu number* correlations by using about 3,033 experimental data. Fig 1 shows a comparison of *Nu number* between the experiment s and the selected correlations.

Table 3 Comparison of percentage of data in several error bounds for the selected Nu number correlations

Correlations	±10%	±20%	±30%
Bishop et al.	14.89	38.80	57.83
Jackson & Fewster	27.10	51.47	69.57
Watts &Chou	36.72	68.28	83.98

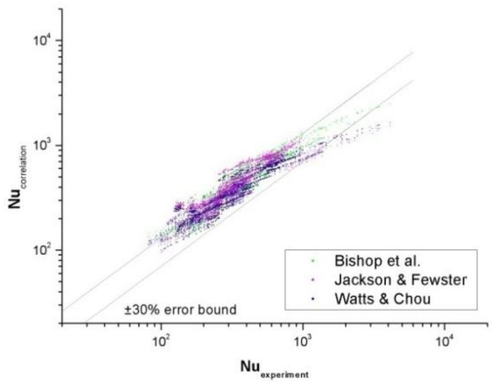

Fig. 1 Comparison of Nu number between the experiments and the selected correlations

2.3 Development of correlation

Heat transfer deterioration experienced for an upward flow was not visible in a downward flow. Estimation of the heat transfer coefficient from the Bishop et al. correlation lies toward upper error bound. It was expected that the Bishop et al. correlation could resulted in better estimation with some modification.

A Buoyancy parameter (Bo) is defined as a function of the *Gr number* and the *Re number* as shown in Eq. (1). For an upward flow, the heat transfer coefficient is a strong function of the Buoyancy parameter [2] [3] [4].

$$\frac{\Delta\tau_B}{\tau_w} = 1.33\times10^4\,\frac{\overline{Gr}_b}{Re_b^{2.7}}\left(\frac{\mu_w}{\mu_b}\right)\left(\frac{\rho_b}{\rho_w}\right)^{\frac{1}{2}},\quad Bo = \frac{\overline{Gr}_b}{Re_b^{2.7}} \quad (1)$$

In this experiment the ratio of *Nu number* between the test results and the estimations from the Bishop et al. correlation lies around the line y=1.2 as shown in Fig 2. So, we simply modify the constant of the Bishop et al. appropriately. The suggested correlation is shown in Eq. (2). The red points in Fig. 2 are the estimations from the suggested correlation.

$$Nu = 0.0056\left(Re_b^{0.9}\overline{\Pr}^{0.66}\right)\left(\frac{\rho_w}{\rho_b}\right)^{0.4}\left(1+1.5\times\left(\frac{D}{x}\right)\right) \quad (2)$$

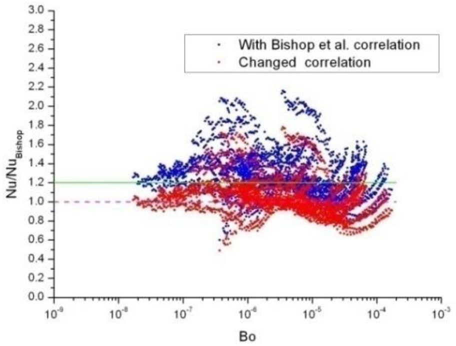

Fig. 2 Estimation of the ratio of Nu number

In Fig 3 the *Nu numbers* are compared between the experiments and the suggested correlation. Evidently most of the data are within the ±30% error bound; 47.48% within ±10% error bound, 77.81% is within ±20% error bound and 89.84% is within ±30% error bound.

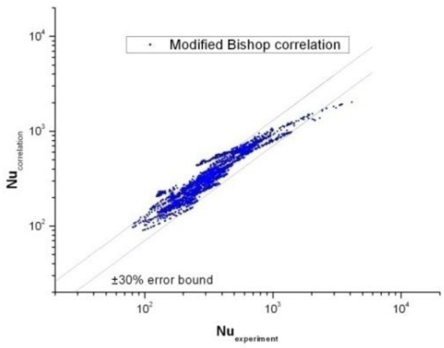

Fig. 3 Comparison of *Nu number* between the experiments and the modified correlation

Fig 4 shows a comparison of the heat transfer coefficients obtained from the experiments and the correlations. The suggested correlation, i.e., modified Bishop, predicts the heat transfer coefficients better than the other correlations.

3. Conclusions

An experiment for a supercritical CO_2 flowing vertically downward in circular tubes with inner diameters of 6.32 mm and 9 mm was performed. The heat transfer deterioration was not experienced for a downward flow unlike the upward flow. We suggested a *Nu number* correlation with modifying the existing Bishop et al. correlation. Prediction with the suggested correlation shows that about 90% of the *Nu numbers* are within ±30% error bound.

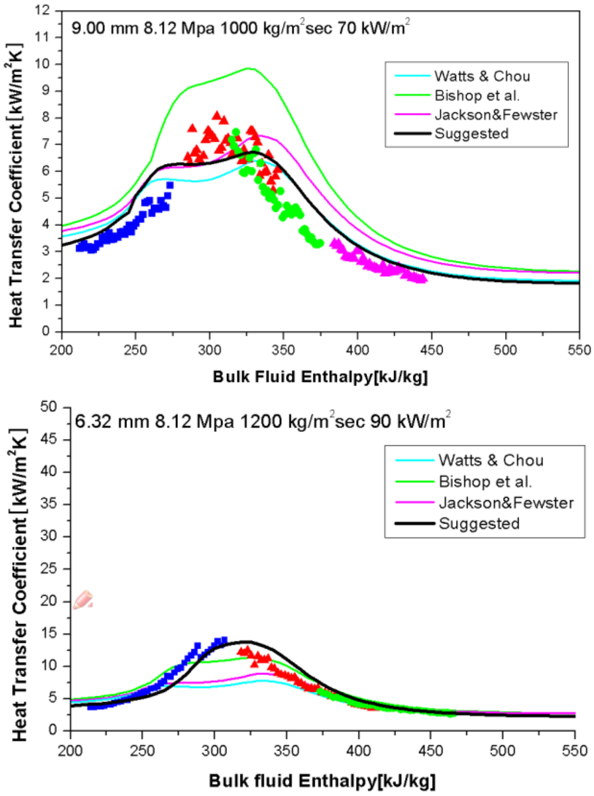

Fig. 4 Comparison of the heat transfer coefficients

REFERENCES

[1] I. L. Pioro, H. F. Khartabil, R. B. Duffey, "Heat Transfer to Supercritical Fluids Flowing in Channels-Empirical Correlations(Survey)", Nuclear Engineering Design 230(1-3), 69-91, 2004.

[2] Y. Y. Bae, H. Y. Kim, H. Kim, and D. J. Kang, "Correlations for Convective Heat Transfer to Fluids at Supercritical Pressure Vertically Upward Flowing in Tubes and Annulus Channel", 3rd Sino-Korea Workshop on Nuclear Reactor Thermal Hydraulics, WORTH-3, Chengdu, China, 2007.

[3] J. D. Jackson, W. B. Hall, "Influence of Buoyancy on Heat Transfer to Fluids Flowing in Vertical Tubes under Turbulent Conditions", IMechE conference publications, V.2, pp. 613-640., 1979.

[4] D. J. Kang, H. Y. Kim, Y. Y. Bae "Development of a correlation on the convective heat transfer of supercritical pressure CO_2 vertically upward flowing in a circular tube", Proceedings of the 5th National Congress on Fluids Engineering March 26-28, 2008, Jeju, Korea