Transactions of the Korean Nuclear Society Autumn Meeting
Gyeongju, Korea, October 26-27, 2017

Study of Condensation Heat Transfer and Pressure drop of CO_2 near the critical point

Seong Jun Bae [a], Jinsu Kwon [a], Jeong Ik Lee [a*]
[a]*Korea Advanced Institute of Science and Technology 373-1 Guseong-dong Yuseong-gu, Daejeon, 305-701, Korea*
[*]*Corresponding author: jeongiklee@kaist.ac.kr*

1. Introduction

A supercritical carbon dioxide (S-CO_2) cycle has many advantages such as a high thermal efficiency at relatively low temperature, compactness of major components, and a simple layout. Those merits are come from its low compressing work by pressurizing the CO_2 near the critical point, which the cycle reduces the compressing work due to its high density and low compressibility at that point [1-4]. However, this design point close to the critical point or under the critical point for a trans-critical cycle case would cause the system operating condition to be under two-phase conditions during off-design or on-design operating conditions [5].

To analyze the CO_2 condensation for S-CO_2 cycles, the appropriate condensation heat transfer and wall frictional loss models are necessary. Thus, in this study, several condensation models were evaluated from the literature which performed the studies related with CO_2 condensation.

The experiment for the CO_2 two-phase flow were performed with the CO_2 pressurizing and heat transfer test loop in KAIST called SCO2PE (Supercritical CO_2 Pressurizing Experiment) in this study. The heat transfer experiments were carried out with the PCHE (Printed Circuit Heat Exchanger) type pre-cooler of the facility. The pressure drop test section is the pipe, having 1 1/2˝ inner diameter, between the PCHE and the compressor of SCO2PE loop. The experiment range is from 26.4 to 27.5, 6.65 to 6.82 MPa and the mass flux was 880 $kg/m^2 s$.

2. Test facility review

2.1 Heat transfer test section

The heat transfer test was performed with the PCHE designed with 896 channels having a 1.8mm diameter on each side [6]. The PCHE geometry information are shown in Figs. 1 and 2, respectively the overall view and the schematic diagram of the PCHE of SCO2PE [6]. The size of the PCHE is 200mm x 99.2mm x 84mm and it is composed of semi-circular zigzag flow channels. Each plate has 1.5mm thickness and 0.75mm minimum thickness and made by SS316L.

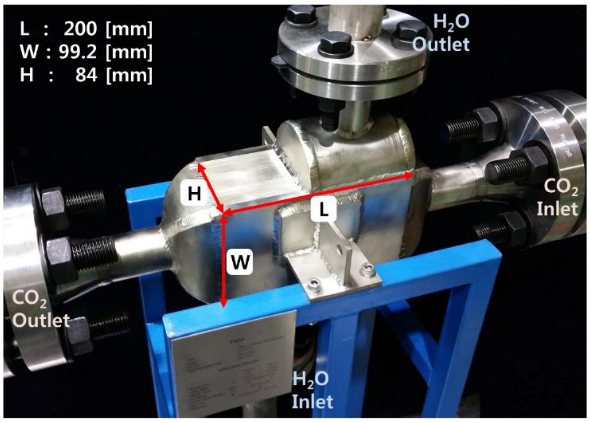

Fig. 1. The PCHE of SCO2PE facility. [6]

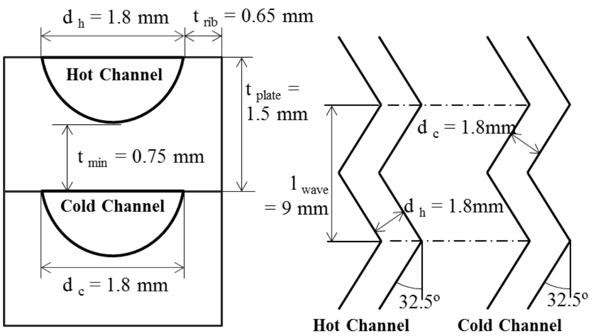

Fig. 2. The schematic diagram of the PCHE of SCO2PE facility [6]

The test section of the pressure drop experiment was the pipe, having 1 1/2˝ inner diameter, which connects the PCHE and the compressor of SCO2PE. The overall view and schematic diagram of the test section are shown in Fig. 3. For modeling the test section, the authors assumed the pipe roughness to be 45×10^{-6} m and 0.7 form loss coefficient at each standard 90° elbow.

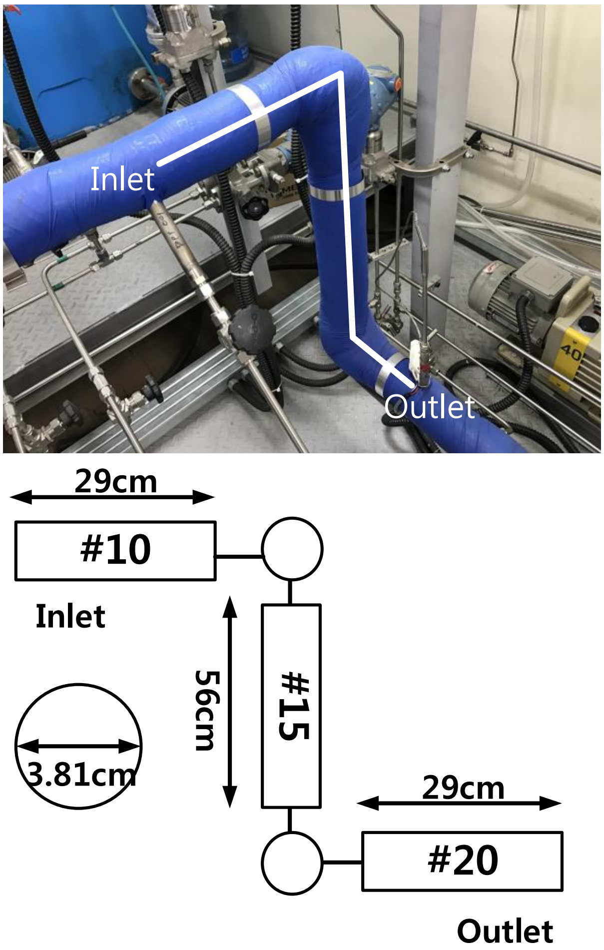

Fig. 3. The overall view and schematic diagram of the test section for the pressure drop test

3. Evaluation of heat transfer and pressure drop models for CO_2 two-phase conditions

2.1 Heat transfer model evaluation

Five heat transfer correlations were evaluated, Dittus-Boelter [7] as a reference, the PCHE correlation by S. Baik [6], Shah's correlation [8], Thome's correlation [9] and Holaman correlation [10]. The heat transfer correlations are showed in Table I. Fig. 4 represents the comparison between the measured data and the predictions from the five heat transfer correlations. The methods of Baik and Shah predicted the results with higher accuracies compared the experimental data within about -5%. The Dittus-Boelter correlation also gives good performance within about -10% gaps.

Table I: The lists of the heat transfer correlations evaluated in this study.

Heat transfer correlations	
Author(s)	**Methods**
Thome	$h = \frac{\lambda_l}{D_h} 0.003 Re_l^{0.74} Pr_l^{0.5} f_i$
Holaman	$h = 0.725 \left[\frac{\rho_l (\rho_l - \rho_g) g h_{lg} k_l^3}{D_h \mu_l (T_{sat} - T_w)} \right]^{\frac{1}{4}}$
Shah	$h = h_{sf} \left(1 + \frac{3.8}{Z^{0.95}}\right)$
Baik	$Nu = 0.8405 Re^{0.5704} Pr^{1.08}$
Dittus-Boelter	$Nu = 0.023 Re^{0.8} Pr^{0.4}$

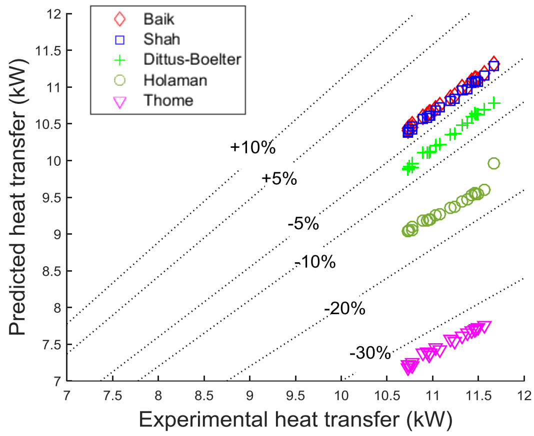

Fig. 4. The comparison results of the measured and predicted heat transfer according to the heat transfer correlations

2.2 Pressure drop model evaluation

To select the appropriate correlation for the pressure drop in CO_2 two-phase flow, hree wall frictional loss models, Friedel [11], Müller-Steinhagen and Heck [12], Churchill [13] models, were compared with the experimental data from SCO2PE. Table II shows the lists of the pressure drop correlations for the CO_2 two-phase flow evaluated in this study. The comparison results for the pressure drop during the CO_2 two-phase flows in the test section are shown in Fig. 5. As a result, the model of Müller-Steinhagen and Heck gives the best agreement within about 30% gaps, outperforming the other methods.

Table II: The lists of the pressure drop correlations evaluated in this study.

Pressure drop correlations	
Author(s)	**Methods**
Müller-Steinhagen and Heck	$\left(\frac{dP}{dx}\right)_{f,tp} = \beta(1-x)^{1/3} + Bx^3$ $\beta = A + 2(B-A)x$ $\left(\frac{dP}{dx}\right)_f = f_f \frac{G^2}{2\rho_f D_h} = A$ $\left(\frac{dP}{dx}\right)_g = f_g \frac{G^2}{2\rho_g D_h} = B$
Churchill	$f_{Lo} = 8\left[\left(\frac{8}{Re_{Lo}}\right)^{12} + \frac{1}{(A+B)^{\frac{3}{2}}}\right]^{\frac{1}{12}}$ $A = \left\{-2.457 \ln\left[\left(\frac{7}{Re_{Lo}}\right)^{0.9} + 0.27\frac{\varepsilon}{D_h}\right]\right\}^{16}$ $B = \left(\frac{37530}{Re_{Lo}}\right)^{16}$ $\phi^2 = \left(\frac{1-x}{1-\alpha}\right)^{1.75}$
Friedel	$f_{Lo} = \frac{0.316}{Re_{Lo}^{0.25}}$
	$\phi^2 = E + \frac{3.24FH}{Fr_H^{0.045} We_L^{0.035}}$

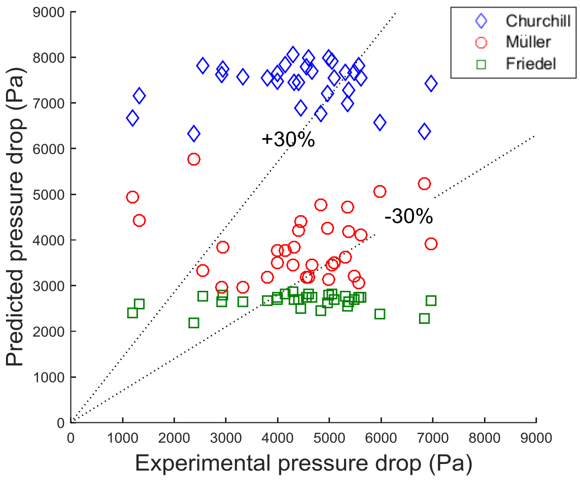

Fig. 5. The comparison results of the measured and predicted pressure drop according to the pressure drop correlations

3. Conclusions

In this study, several heat transfer and pressure drop models were investigated and evaluated with the experimental data near the critical point of CO_2 from SCO2PE facility in KAIST.

As comparison results of the several previously suggested models, the heat transfer correlation of Baik's study and the wall frictional method of Müller-Steinhagen and Heck showed the best-performances in this region. The interesting thing is that the Baik's correlation gives the best fit of the CO_2 two-phase flow data even if it was originally developed and evaluated under CO_2 single-phase conditions. It means that the two-phase conditions of CO_2 near the critical point would be not much different in CO_2 single-phase condition in terms of heat transfer.

REFERENCES

[1] Y. Ahn, J. I. Lee, Study of various Brayton cycle design for small modular sodium-cooled fast reactor, Nucl. Eng. Des., Vol.276, p.128–141, 2014

[2] H. J. Yoon, Y. Ahn, J. I. Lee, Y. Addad, Potential advantages of coupling supercritical CO2 Brayton cycle to water cooled small and medium size reactor, Nucl. Eng. Des., Vol.245, p.223-232, 2012.

[3] S. J. Bae, Y. Ahn, J. Lee and J. I. Lee, Various supercritical carbon dioxide cycle layouts study for molten carbonate fuel cell application, Journal of Power Sources, Vol.270, p.608-618, 2014.

[4] S. J. Bae, J. Lee, Y. Ahn and J. I. Lee, Preliminary studies of compact Brayton cycle performance for small modular high

temperature gas-cooled reactor system, Annals of Nuclear Energy, Vol.75, p.11-19, 2015.

[5] S. J. Bae, Y. Ahn, J. Lee, S. G. Kim, S. Baik and J. I. Lee, Experimental and numerical investigation of supercritical CO2 test loop transient behavior near the critical point operation, Applied Thermal Engineering, Vol.99, p.572-582, 2016

[6] S. Baik, S. G. Kim, J. Lee and J. I. Lee, Study on CO2-Water printed circuit heat exchanger performance operating under various CO2 phases for S-CO2 power cycle application, Applied Thermal Engineering, Vol.113, p.1536-1546, 2017.

[7] F. W. Dittus and L. M. K. Boelter, Heat transfer in Automobile Radiators of the Tubular Type, University of California Publications in Engineering, Vol.2, p.443-461, 1930.

[8] M. M. Shah, A General Correlation for Heat Transfer during Film Condensation inside Pipes, Int. J. Heat Mass Transfer, Vol.22, p.547-556, 1979.

[9] J.R. Thome, V. Dupont, A.M. Jacobi, Heat transfer model for evaporation in micro channels. Part I. Presentation of the model, Int J Heat Mass Transfer, Vol.47, p.3375–3385, 2004.

[10] J. P. Holaman, Heat Transfer, 6th edition, McGraw-Hill, New York, 1986.

[11] L. Friedel, Improved friction pressure drop correlations for horizontal and vertical two-phase pipe flow, in: European Two-Phase Flow Group Meeting, Ispra, Italy, 1979.

[12] H. Mu ̈ller-Steinhagen, K. Heck, A simple friction pressure drop correlation for two-phase flow in pipes, Chem Eng Process, Vol.20, p.297–308, 1986.

[13] S. W. Churchill, Frictional Equation Spans All Fluid Flow Regions, Chem. Eng., Vol.84, p.91–92, 1977.