Inflow Condensation Heat Transfer Characteristics of CO_2 in Microchannel

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Introduction

Carbon dioxide refrigeration system has been utilized for water heaters, mobile air conditioning systems, bending machines, and room air conditioners. Now, the system expands its applications to large capacity systems, such as supermarkets, industrial low temperature applications, and commercial refrigeration storage. The operation temperature of the CO_2 refrigeration systems for the above applications is normally so low that the condensation process is accompanied with the heat rejection process. For example, CO_2/NH_3 cascade system is one of the promising options for commercial or industrial refrigeration systems. In this case, condensation of CO_2 occurs inside the cascade condenser. As operating conditions of the CO_2 system are widening, the condenser of the CO_2 system is becoming an important component. Therefore, understanding of CO_2 condensation phenomena with/without oil and development of a properly estimating model for CO_2 condensation heat transfer and pressure drop are required.

Park and Hrnjak[1)] tested the CO_2 condensation heat transfer and pressure drop with a microchannel having a hydraulic diameter of 0.89 mm. They suggested that the Thome et al. model[2)] and the Mishma and Hibiki model[3)] for estimating heat transfer coefficient and predicting pressure drop, respectively. In the previous studies, the researches on CO_2 condensation process were very limited especially in terms of flow patterns, test tubes with microchannels, and effects of lubricants. Besides, the existing prediction models for heat transfer coefficient and pressure drop need to be verified for the CO_2 condensation, and if necessary they should be developed. The objective of the present study is to investigate the flow patterns in narrow channel and the effects of oil on condensation heat transfer coefficient and pressure drop of CO_2

under relatively low temperature conditions. We developed the new models for estimating the CO_2 condensation heat transfer coefficient in smooth tube, microchannels, and microfin tubes, and suggested the previous models for estimating CO_2 condensation pressure drop.

Experiments

Figure 1 shows a schematic of the experimental setup. The test setup was composed of a magnetic gear pump, preheater, test section, subcooler, chillers, constant temperature bath, and receiver tank for safety. The working fluid was pure CO_2, and the secondary fluid for the preheater and the test section was an Ethylene Glycol (EG) and water mixture (brine), with a concentration of 40% of EG. The CO_2 condensation heat transfer coefficient (hi) was calculated by Eq. (1). The thermal resistance of the microchannel wall was neglected in Eq. (1), which was estimated by less than 0.2% compared to that of fluids. The UA value in Eq. (1) was obtained by using the heat transfer amount from CO_2 to brine, and temperatures of inlets and outlets of CO_2 and brine as shown in Eq. (2). The brine-side heat transfer coefficient was determined by utilizing the Wilson Plot method as shown in Eq. (3).

$$\frac{1}{UA}\frac{1}{h_0A_0}+\frac{1}{h_iA_i} \quad (1)$$

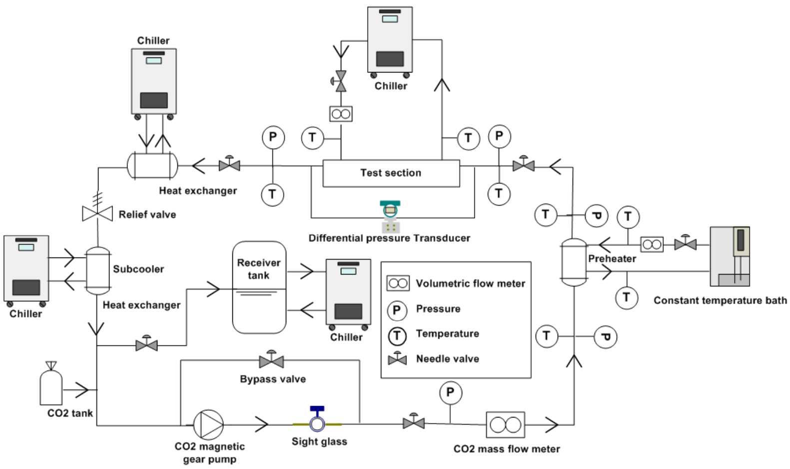
$$Q=UA\Delta T_{lm} \quad (2)$$

$$N_0=0.0971\times(\mathrm{Re}^{0.5}\mathrm{Pr}^{0.3}) \quad (3)$$

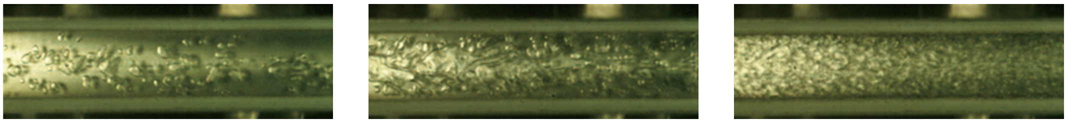
Results and discussion

Flow visualization

Figure 2 shows the representative images of flow patterns of CO_2 condensation in the narrow channel. The present flow patterns were classified by the following definitions. Bubbly flow : Small bubbles separately flow along channel. Intermittent flow : Large bubbles from merging small bubbles flow at the center of channel,



[Figure 1] Schematics of experimental setup



(a) Bubbly flow (b) Intermittent flow (c) Annular flow

[Figure 2] Flow patterns of CO_2 condensation in narrow channel

and liquid-phase CO_2 flows close to wall. The boundaries between bubbles can be found, and boundaries between liquid-phase and bubbles are wavy and irregular. Annular flow : Thin liquid film is formed at the wall and the shape of liquid film is very steady. Most part of channel is occupied by vapor-phase CO_2

Effects of oil on heat transfer coefficient and pressure drop

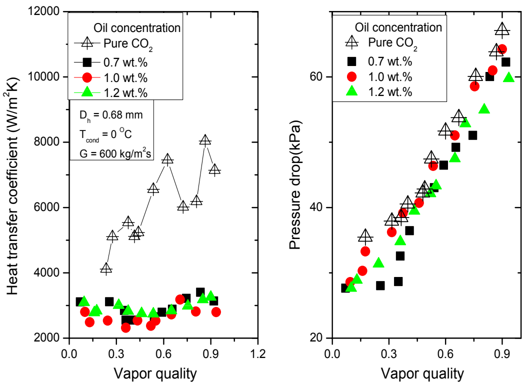
Figure 3 shows the effects of oil concentration on CO_2 condensation heat transfer coefficient and pressure drop. The heat transfer coefficient significantly decreased with oil concentration. Decrease of condensation heat transfer coefficient with oil addition came from the increased thermal resistance by oil-film at tube wall, which prevents the vapor CO_2 from directly contacting on tube wall.

Developing new models for condensation heat transfer coefficient of CO_2

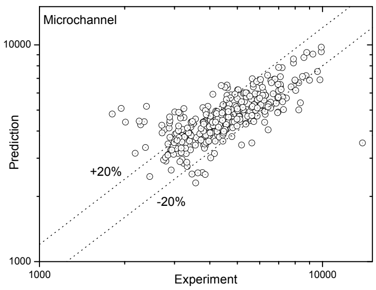
We developed a new model for the condensation heat transfer coefficient of CO_2 by allowing for the liquid film thickness and smooth interface shape of the liquid film. Eq. (4) shows the present model, and Table 1 shows constants in Eq. (4). The non-dimensional form of liquid film thickness, the ratio of the Weber number and the Froude number were utilized to

〈Table 1〉 Constants in the present model

Constants	Smooth tube	Microchannel
a	226.04	19.72
b	0.25	0.43
c	0.75	0.3
d	−0.39	−0.31
e	−0.3	−0.39
f	−0.21	−0.59



[Figure 3] Effects of oil on CO_2 condensation heat transfer coefficient and pressure drop



[Figure 4] Deviations between experiment and prediction for microchannels consider the thick liquid film and the interface shape between liquid and vapor for CO_2 condensation. The mean deviations between the present model and the experimental results were 28.9%, and 18.9% for smooth tube and microchannels, respectively. Figure 4 showed deviations between experiment and prediction for microchannels. Among the total data number of 346, data of 76% were within and 86% of data were within.

$$h = \alpha \times \mathrm{Re}_l^b \times \mathrm{Pr}_l^c \times \left(\frac{We}{Fr}\right)^d \left(\frac{\delta}{D}\right)^e P_r^f \tag{4}$$

Conclusions

In this study, two-phase flow patterns of CO_2 condensation in narrow channel and effects of oil concentration on the heat transfer coefficient and pressure drop of CO_2 condensation in microchannel were investigated. Besides, a prediction model of CO_2 condensation heat transfer coefficient in smooth tube and microchannels were developed.

(1) The present flow patterns were categorized by bubbly, intermittent, and annular flow. The transition vapor quality from intermittent flow to annular flow became advanced with an increase of mass flux and with a decrease of condensation temperature.

(2) When oil concentration was changed from 0.7 to 1.2 wt. % the heat transfer coefficient decreased by about 50% as compared to that of the pure CO_2. In contrast, the pressure drop slightly decreased as compared to that of pure CO_2.

(3) A model for the condensation heat transfer coefficient of CO_2 was developed by considering the film thickness and the interface shape of the liquid film. The mean deviations between the present model and the experimental results were 28.9% and 18.9% for smooth tube and microchannels, respectively.

References

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