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Condensation heat transfer characteristics of CO_2 in a horizontal smooth tube

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ABSTRACT

The condensation heat transfer characteristics of CO_2 flowing in a horizontal smooth tube were investigated. The tube diameter was 5.15 mm. The condensation temperature ranged from −10 to 5 °C, and the mass flux was from 600 to 1000 kg m^{-2} s^{-1}. When the temperature changed from 0 to −10 °C, the increase rate of the heat transfer coefficient was from 9.4 to 14.6%, and the pressure drop increased from 6.2 to 52.9%. When the mass flux increased from 600 to 1000 kg m^{-2} s^{-1}, the heat transfer coefficient increased from 6 to 35%, and the pressure drop increased from 60 to 165%, which were dependent on the condensation temperature. The increases come from the change of vapor velocity and thermophysical properties with condensation temperature. Considering large variation of mass flux from 200 to 1200 kg m^{-2} s^{-1} by including the existing studies, the effect of mass flux on condensation heat transfer coefficient was minor.

Caractéristiques de transfert de chaleur du CO2 à l'intérieur d'un tube lisse horizontal

Mots clés : Transfert de chaleur lors de la condensation ; Dioxyde de carbone (CO_2) ; Coefficient de transfert de chaleur ; Chute de pression ; Basse température

1. Introduction

CO_2 refrigeration systems are now expanding their fields of application, from the conventional applications of automobile air conditioner, residential hot water heater, and small-sized vending machine, to large supermarket, industrial low temperature applications, and large-sized refrigeration storage. The CO_2 system utilized for the above applications, which normally operates at low temperature conditions, has a condensation process, which is different from the transcritical cycle for the applications of air-conditioning and hot water heater system of CO_2, due to the low temperature refrigeration cycle. For example, to achieve a low temperature of about −25 °C for food storage or industrial process, the cascade system has priority, compared to the single parallel or two stage CO_2 systems (Sawalha, 2008). In this case,

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Nomenclature

A	area, m^2
G	mass flux, kg m^{-2} s^{-1}
h	heat transfer coefficient, Wm^{-2} K^{-1}
i	specific enthalpy, kJ kg^{-1}
$\dot{m}$	mass flow rate, kg s^{-1}
$\dot{Q}$	heat transfer rate, kW
T	temperature, K
x	vapor quality
Subscript	
cond	condensation
f	liquid saturation,
g	gas saturation
w	wall

condensation of CO_2 occurs in the cascade condenser. As the operation conditions of the CO_2 system are widening, the condenser for the CO_2 system is becoming an important component. Therefore, a fundamental understanding of CO_2 condensation, in terms of heat transfer and pressure drop, is required to properly design a CO_2 condenser.

The existing studies of CO_2 condensation are summarized in Table 1, which shows the specifications of test tubes and test conditions. According to Jang and Hrnjak (2004), the effects of condensation temperature on the heat transfer coefficients were minor compared to those of the mass flux, and over-predicting from the existing models increased with vapor quality. They also observed the flow patterns of CO_2 condensation in a tube. Haui and Koyama (2004) showed large data scattering of the condensation heat transfer coefficient, and the effects of vapor quality on the heat transfer coefficients were not clear. They also concluded that the existing model failed to predict the experimental data. Kim et al. (2009) observed the effects of tube diameter on the heat transfer coefficient. It was found that the condensation heat transfer coefficient with a smaller tube (ID: 3.48 mm) was higher than that with a larger tube (ID: 6.1 mm) at the same test conditions. Park and Hrnjak (2009) tested the CO_2 condensation with a microchannel, and suggested the Thome et al. (2003) model and the Mishima and Hibiki (1996) model for estimating heat transfer coefficient and predicting pressure drop, respectively. Choi (2011) investigated CO_2 condensation at high condensation temperature conditions. Comparing the results with the existing models, the heat transfer coefficient was very low, even at a high mass flux condition. Iqbal and Bansal (2012) conducted tests of CO_2 condensation under low mass flux conditions. They developed a new model to predict the condensation heat transfer coefficients for CO_2, using their experimental data.

As can be seen in Table 1, the researches on CO_2 condensation and the conditions of the tests were limited. More researches are necessary to find the heat transfer characteristics of CO_2 condensation, in terms of the effects of the condensation temperature, mass flux, and flow patterns. The objective of the present study is to investigate the condensation heat transfer coefficient and pressure drop for CO_2, under relatively low temperature conditions.

2. Experiments

2.1. *Test setup and test methods*

Fig. 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 is pure CO_2 (99.99%), and the secondary fluid for the preheater and the test section is an Ethylene Glycol (EG) and water mixture, with a concentration of 40% of EG. The magnetic gear pump, which can work without oil, circulates the CO_2 through the test section. The preheater was utilized to adjust the inlet vapor quality of the test section, and a plate heat exchanger was used as the preheater. Two plate heat exchangers were utilized for the subcooler, which liquefied the CO_2 from the outlet of the test section. The constant temperature bath was connected to the preheater, to provide heat to the liquefied CO_2. The chiller, which was connected to the test section, removes heat from the CO_2, to condense it throughout the test section. Other

Table 1 – Existing experimental studies.

Ref.	Test tubes and orientation	Test conditions	Measurements
Jang and Hrnjak (2004)	Smooth (ID: 6.1 mm) and microfin tube (ID: 6.1 mm), horizontal and vertical (upflow)	G: 200, 300, 400 kg m^{-2} s^{-1} T_{cond}: −15, −25 °C	Heat transfer coefficient, pressure drop
Haui and Koyama (2004)	Microchannel (ID: 1.31 mm, 10 multiports), horizontal	G: 123.2–315.2 kg m^{-2} s^{-1} T_{cond}: 21.63–31.33 °C	Heat transfer coefficient
Kim et al. (2009)	Smooth (ID: 3.48 mm) and microfin tube (ID: 3.51 mm), horizontal	G: 200, 400, 800 kg m^{-2} s^{-1} T_{cond}: −15, −25 °C	Heat transfer coefficient
Park and Hrnjak (2009)	Microchannel (ID: 0.89 mm), horizontal	G: 200–800 kg m^{-2} s^{-1} T_{cond}: −15, −25 °C	Heat transfer coefficient, pressure drop
Choi (2011)	Smooth (ID: 4.95 mm) and microfin tube (ID: 4.6 mm), horizontal	G: 800, 1200, 1600 kg m^{-2} s^{-1} T_{cond}: 20, 25, 30 °C	Heat transfer coefficient
Iqbal and Bansal (2012)	Smooth tube (ID: 6.52 mm), horizontal	G: 50, 100, 200 kg m^{-2} s^{-1} T_{cond}: −15, −10, −5, 0 °C	Heat transfer coefficient