

An Experimental Study on Heat Transfer and Pressure Drop Characteristics of Carbon Dioxide During Gas Cooling Process in a Hellically Coiled Tube

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Abstract : The heat transfer coefficient and pressure drop during gas cooling process of CO₂ (R744) in a helically coiled copper tube with the inner diameter of 4.55 mm and outer diameter of 6.35 mm were investigated experimentally. The main components of the refrigerant loop are a receiver, a variable-speed pump, a mass flow meter, a pre-heater and a helically coiled type gas cooler (test section). The refrigerant mass fluxes are varied from 200 to 800 kg/m²s and the inlet pressures of gas cooler are 7.5 to 10.0 MPa. The heat transfer coefficients of CO₂ in a helically coiled tube are higher than those in a horizontal tube. The pressure drop of CO₂ in the gas cooler shows a relatively good agreement with those predicted by Ito's correlation developed for single-phase in a helically coiled tube. The local heat transfer coefficient of CO₂ agrees well with the correlation by Pitla et al. However, at the region near pseudo-critical temperature, the experiments indicate higher values than the Pitla et al. correlation. Therefore, various experiments in helically coiled tubes have to be conducted and it is necessary to develop the reliable and accurate prediction determining the heat transfer and pressure drop of CO₂ in a helically coiled tube.

Key words : Carbon dioxide, Cooling heat transfer coefficient, Design of hellically coiled type heat exchanger, Natural refrigerant, Pressure drop

Symbols			
A	: area	[m ²]	L : length [m]
d	: tube diameter	[m]	M : mass flow rate [kg/s]
D	: coil diameter	[m]	P : pressure [Pa]
f _c	: friction factor	[-]	Q : heat capacity [kW]
G	: mass flux	[kg/m ² s]	q : heat flux [kW/m ²]
h	: heat transfer coefficient	[kW/m ² K]	T : temperature [K]
κ	: thermal conductivity	[kW/mK]	ΔP : pressure difference [Pa]
			ΔT : temperature difference [K]
			Δz : subsection length [m]

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Dimensionless Numbers

Nu	: Nusselt number	{-}
Pr	: Prandtl number	{-}
Re	: Reynolds number	{-}

Subscripts

abs	: absolute
avg	: average
b	: bulk
cw	: cooling water
gc	: gas cooler
i	: inner
in	: inlet
loc	: local
o	: outer
out	: outlet
re	: refrigerant
sb	: subsection
w	: wall
wi	: inside wall
wo	: outside wall

1. Introduction

As the environmental concern is being increased, the use of CFCs and HCFCs is suppressed. In response to environmental problem, the use of the newly developed HFCs or natural refrigerants is discussed. But HFC refrigerants are listed together with five other gases by the Kyoto Protocol as greenhouse gases. The other natural refrigerants have a zero ozone depletion potential (ODP), and most of them also have zero global warming potential (GWP). Among natural refrigerants, CO₂ is not a new refrigerant and has a successful history of the use as a refrigerant. It has many advantages as

a working fluid. Namely the most relevant characteristics of CO₂ are no toxicity, inflammability, no ODP and no GWP. Moreover it is possible to make a system compact, because of high VCR (volumetric capacity for refrigerants) and working pressure of CO₂^[1].

Due to low critical temperature (31.1°C) and critical pressure (7.38 MPa) of CO₂, the CO₂ cycle takes place at transcritical state when the ambient temperature is near or higher than the critical temperature^[2]. So the process of heat rejection of CO₂ takes place at supercritical state without phase change. It is "gas-cooling". Like this, the gas cooling process of CO₂ system is different with the existing process. Therefore, the system needs attention of the stability, efficiency and durability.

In this research, to improve the efficiency of the gas cooler which is one of the most important CO₂ refrigeration and air-conditioning system parts, the gas cooler was designed as the helically coiled tube. The purpose of this study is to offer the heat transfer and pressure drop characteristics in the helically coiled tube during cooling of CO₂.

2. Experimental Apparatus and Methods

2.1 Test facility

Fig. 1 shows a schematic diagram of the experimental apparatus, which consists of three main parts : a refrigerant loop, a test section and cooling water loop. In the refrigerant loop, CO₂ is charged in the

receiver tank as liquid phase and CO₂ is circulated by a magnetic gear pump. After flowing through a mass flow meter, it is preheated to the desired supercritical temperature and pressure in a pre-heater.

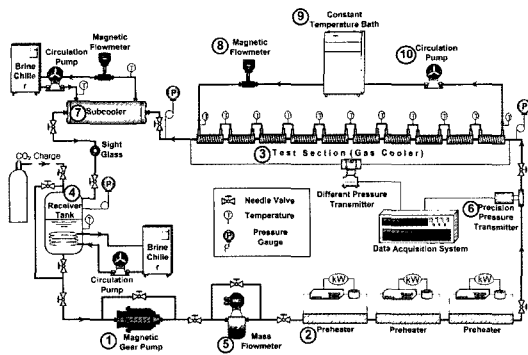


Fig. 1 Schematic diagram of the experimental apparatus

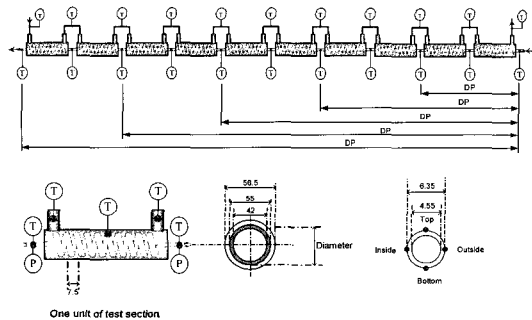


Fig. 2 Schematic diagram of the test section

The CO₂ flows into the test section where the heat transfer coefficients and pressure drops are measured, and then it is cooled down in the cooling water loop.

Fig. 2 shows a schematic diagram of the test section, which consists of 10 subsections. Each subsection is a tube-in-tube type and a counter-flow heat exchanger. The CO₂ flows in the inner tube and water flows in the annulus. The inner tube is helically coiled type heat exchanger which is made of a copper tube

with an inner diameter of 4.55 mm and a curvature diameter of 42 mm. The gas cooler is 10000 mm long and contains ten subsections with 1000 mm in length of each subsection. In the inlet and outlet of each subsection, T-type thermocouples are used to measure the CO₂ temperature.

The experiment of the CO₂ cooling heat transfer at a supercritical condition is conducted for various inlet pressure and mass flux of the gas cooler. The inlet pressure is varied from 7.5 to 10.0 MPa. Mass fluxes of 200, 400, 600 and 800 kg/m²s are tested to investigate the effect of heat transfer coefficient and pressure drop. The experimental parameters are summarized in Table 1.

Table 1 Experimental conditions for cooling heat transfer of CO₂

Refrigerant	R-744(CO ₂)
Test section	Helically coiled tube
d _i (d _o), [mm]	4.55(6.35)
G _{re} , [kg/m ² s]	200, 400, 600, 800
P _{gc.in.} [MPa]	7.5, 8.0, 8.5, 9.0, 9.5, 10.0
T _{cw.in.} [°C]	15

2.2 Data Reduction

The local heat transfer coefficient of refrigerant is calculated by the following Eq. (1):

$$h_{gc,loc} = \frac{q_{gc}}{T_{gc} - T_{gc,w.in}} \tag{1}$$

where, h_{gc,loc} represents the local heat transfer coefficient in the test section, T_{gc} is bulk refrigerant temperature in gas cooler. q_{gc} is determined as follows.

$$q_{gc} = \frac{M_{cw} \cdot (T_{cw,out} - T_{cw,in})}{\pi \cdot d_i \cdot \Delta z} \tag{2}$$

In Eq. (1), $T_{gc,w,in}$ is determined from average of the measured wall temperatures via one dimension steady state heat conduction equation as shown in Eq. (3):

$$T_{gc,w,in} = T_{gc,w,out} + \frac{Q_{gc,sb}}{2\pi \cdot k_w \cdot \Delta z} \cdot \ln\left(\frac{d_o}{d_i}\right) \quad (3)$$

where, $T_{gc,w,out}$ is the outside wall surface average temperature of copper tube as shown in Eq. (4) and k_w is the thermal conductivity of the copper tube.

$$T_{gc,w,out} = \frac{T_{w,top} + 2T_{w,side} + T_{w,bottom}}{4} \quad (4)$$

In the Eq. (4), $T_{w,top}$, $T_{w,side}$ and $T_{w,bottom}$ are the measured temperature at the top, both sides and bottom of inner tube wall, respectively.

3. Results and Discussion

3.1 Heat transfer coefficient

Fig. 3 shows measured heat transfer coefficients of CO₂ at different inlet pressure when the CO₂ refrigerant temperature changes along the gas cooler at a fixed mass flux. In the Fig. 3, the variation of heat transfer coefficient is not large at the same mass flux condition because a variation of specific heat with respect to refrigerant temperature variation in inlet region of gas cooler is small. However, the local heat transfer coefficient increase and decrease largely because the variation of specific heat changes greatly with respect to the temperature variation in the middle and final stage of gas cooling process with the near pseudo-critical temperature (T_{pc}). As

the cooling pressure increases in the inlet region of gas cooler, the local heat transfer coefficient of CO₂ presents tendency to increase on the contrary with the near pseudo-critical temperature. Also, the maximum value of heat transfer coefficient presents in the final stage of gas cooler in case of 7.5 MPa and in the middle stage in case of 10.0 MPa. The reason is that the refrigerant temperature reaches T_{pc} in the final stage because T_{pc} is low at 7.5 MPa and in the middle part because T_{pc} is high at 10.0 MPa.

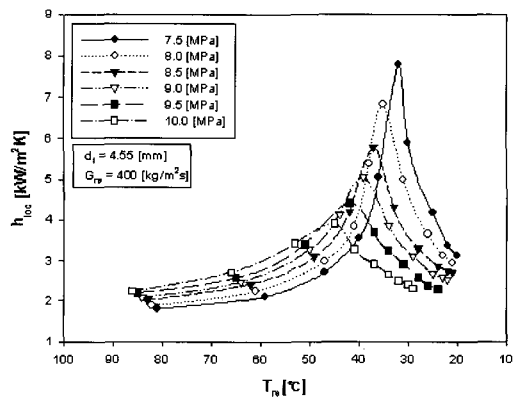


Fig. 3 Variation of cooling heat transfer coefficient of CO₂ with respect to cooling pressure

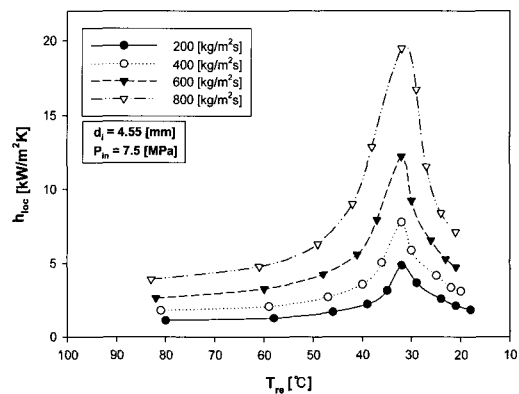


Fig. 4 Variation of cooling heat transfer coefficient of CO₂ with respect to mass flux

Fig. 4 shows the local heat transfer coefficients with respect to the variation of mass flux for constant pressure of gas cooler. As shown in the Fig. 4, the heat transfer coefficient of CO₂ increases when mass flux increase at the constant pressure, which corresponds to the increase of the heat transfer coefficient for increased Reynolds number. For the constant pressure of gas cooler, the increase of heat transfer coefficient with the mass flux obviously appears at the pseudo-critical temperature. The increase of heat transfer coefficient is large at 7.5 MPa, and small at 10.0 MPa. Because the variation of specific heat is large at 7.5 MPa and small at 10.0 MPa.

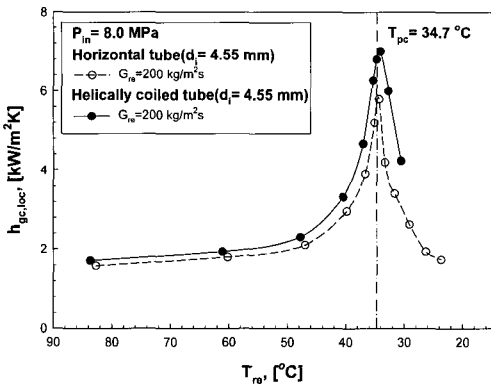


Fig. 5 Comparison of heat transfer coefficients for the horizontal and the helically coiled gas cooler at the same mass flux

Fig. 5 shows the heat transfer coefficient of horizontal and helically coiled tubes at the same mass flux and cooling pressure. In the Fig. 5, the variation of heat transfer coefficient is small in the first and middle stage, but large in the final stage with near T_{pc}. And the heat transfer coefficient in the helically coiled tube is a little higher than that in the horizontal tube.

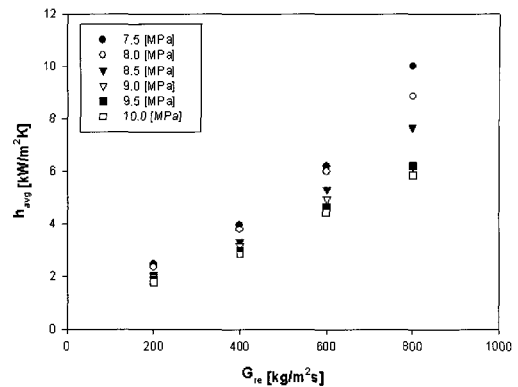


Fig. 6 Average heat transfer coefficients of CO₂ with respect to gas cooling pressure

Fig. 6 shows the average heat transfer coefficient of supercritical CO₂ in the gas cooler. As the mass flux increase, the average heat transfer coefficient of CO₂ linearly increases, and the average heat transfer coefficient increases large when the cooling pressure is low. This is due to the improvement of heat transfer effect for increase of Reynolds number caused by the increase of mass flux.

The average heat transfer coefficient increases 372% when the cooling pressure is 7.5 MPa and 308% when the cooling pressure is 10.0 MPa. As the mass flux vary from 200 to 800 kg/m²s, the total average heat transfer coefficient increases 334% at all pressure ranges.

3.2 Pressure drop

Fig. 7 shows the measured pressure drop with respect to mass flux at the mass velocity of 200 to 800 kg/m²s and the inlet pressure of 7.5 to 10.0 MPa. As shown in the Fig. 7, the pressure drop increases when the mass flux of CO₂ increases in the constant inlet pressure.

Also, the pressure drop increases at a high rate when the inlet pressure is low. And the pressure drop of CO₂ presents tendency to decreases when the inlet pressure increases in the constant mass flux. It is considered as the pressure drop decreases because the refrigerant density increases when the inside pressure of the system increases.

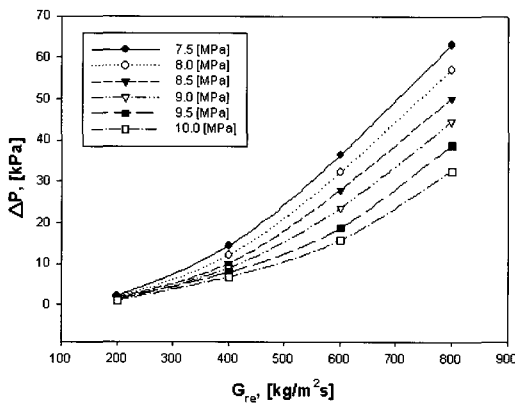


Fig. 7 Variation of the pressure drop with respect to varying mass flux at different inlet pressures during gas cooling process

The experimental data were compared with the single-phase pressure drop correlations of White⁽³⁾, Ito⁽⁴⁾ and Srinivasan⁽⁵⁾ which have widely used in a helically coiled tube. White developed the following equation for single-phase in a helically coiled tube.

$$f_c = 0.31 \left[\log \left(\frac{Re}{7} \right)^2 + 0.04 \left(\frac{d_i}{D} \right)^{0.5} \right] \quad (4)$$

Ito also developed the following equation for single phase in a helically coiled tube.

$$f_c = 1.216Re^{0.25} + 0.116 \left(\frac{d_i}{D} \right)^{0.5} \quad (5)$$

A modified Ito equation was developed for coil tube by Srinivasan et al.

$$f_c = 1.33Re^{0.2} \left(\frac{d_i}{D} \right)^{0.1} \quad (6)$$

Fig. 8, 9 and 10 display the comparison of measured pressure drop data with those predicted by White, Ito and Srinivasan et al., respectively. As can be seen from Fig. 8, 9 and 10, the pressure drop predicted by White, Ito and Srinivasan et al. is underestimated with experimental data and these correlations shows a large difference with the experimental data. The pressure drop of CO₂ helically coiled gas cooler shows a relatively superior agreement with that predicted by Ito's correlations.

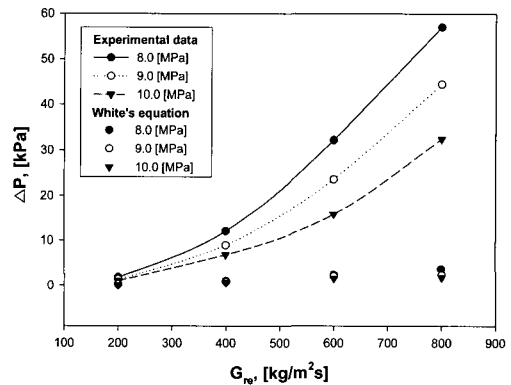


Fig. 8 Comparison of measured pressure drop data with those predicted by White's correlation

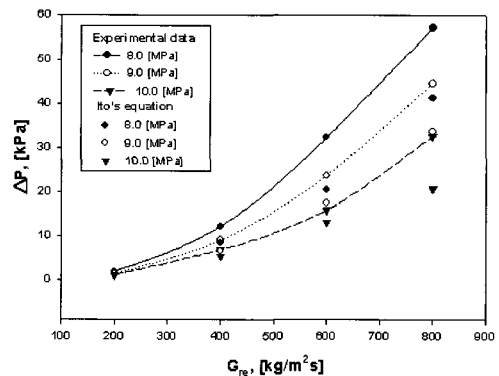


Fig. 9 Comparison of the measured pressure drop with that predicted by Ito's equation

3.3 Comparison of experimental data and cooling heat transfer correlations

In order to predict the cooling heat transfer coefficient in a helically coiled tube, some researchers proposed their correlations, and these representative correlations are presented by Bringer-Smith, Petuhkov et al., Petrov-Popov, Gnielinski, Pitla et al. and Fang. Some general correlations will be compared to the experimental data, and confirmed this applicable possibility of their correlations. The cooling heat transfer coefficients obtain as comparing with the experimental data and the correlations predicted by Bringer-Smith^[6], Petuhkov et al.^[7], Petrov-Popov^[8], Gnielinski^[9], Pitla et al.^[10] and Fang^[11]. As shown Table 2, All the correlations tend to underestimate the experimental heat transfer coefficients. Among these correlations, the best fit of the experimental data is obtained with the Pitla et al.'s correlation. Table 2 presents the comparison results of the heat transfer coefficients calculated by the other correlations. As shown in Table 2, Pitla et al.'s correlation shows the best agreement within deviations of 37.9%.

Pitla et al. was concerned with developing a suitable heat transfer correlation for CO₂ flow in the supercritical region during in-tube cooling. The correlation was developed, based on the numerical and experimental work. Based on the numerical predictions of heat exchanger problem, it was attempted to develop a new correlation for the Nusselt number(Nu) in terms of other dimensionless parameters. For this

purpose, the numerically predicted Nu was correlated. The final outcome was a new correlation that is based on the "mean Nu" and is defined as shown in equation (7).

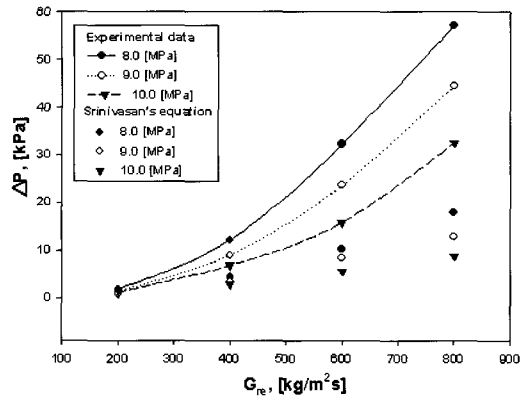


Fig. 10 Comparison of the measured pressure drop with that predicted by Srivivasan et al.'s equation

Table 2 Deviations between measured and calculated heat transfer coefficients

Correlations	σ_{avg} and σ_{abs} (%)
Petuhkov et al. (1961)	49.9
Bringer-Smith(1957)	51.6
Petrov-Popov (1985)	54.6
Gnielinski (1994)	45.7
Pitla et al. (1998)	37.9
Fang (2000)	43.7

4. Conclusion

The heat transfer coefficient and pressure drop of CO₂ were measured in a helically coiled tube with the inner diameter of 4.55 mm and outer diameter of 6.35 mm. Test range cover the mass flux of 200 to 800 kg/m²s and the inlet pressure of 7.5 to 10.0 MPa. The main results are summarized as follows.

- (1) In fixed inlet pressure, a larger mass

flux corresponds to a larger pressure drop. And a larger inlet pressure in fixed mass flux corresponds to a smaller pressure drop.

(2) In comparison with the heat transfer coefficient of horizontal and helically coiled tubes at the same mass flux and cooling pressure, the variation of heat transfer coefficient is small in the first and middle stage, but large in the final stage with near pseudo-critical temperature. And the heat transfer coefficient in the helically coiled tube is a little higher than that in the horizontal tube.

(3) The pressure drop during cooling process of supercritical CO₂ decreases when the inlet pressure of gas cooler increases. The pressure drop of CO₂ helically coiled gas cooler shows a relatively superior agreement with that predicted by Ito's correlations.

(4) As the experimental data compares with the existing correlations for the supercritical heat transfer coefficient, which generally under-predicts the measured data. However, the experimental data shows a relatively good agreement with correlations by Pitla et al. except for pseudo critical temperature.

Acknowledgements

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