Evaporation Heat Transfer Characteristics of CO_2 in a Horizontal Tube

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ABSTRACT: The evaporation heat transfer coefficient of CO_2 (R-744) in a horizontal tube was investigated experimentally. The experiments were conducted without oil in a closed refrigerant loop which was driven by a magnetic gear pump. The main components of the refrigerant loop are a receiver, a variable-speed pump, a mass flow meter, a pre-heater and evaporator (test section). The test section consists of a smooth horizontal stainless steel tube of 7.75 mm inner diameter. The experiments were conducted at mass flux of 200 to 500 kg/m^2s, saturation temperature of −5℃ to 5℃, and heat flux of 10 to 40 kW/m^2. The test results showed the evaporation heat transfer of CO_2 has greater effect on nucleate boiling than convective boiling. The evaporation heat transfer coefficient of CO_2 is highly dependent on the vapor quality, heat flux and saturation temperature. The evaporation heat transfer coefficient of CO_2 is very larger than that of R-22 and R-134a. In comparison with test results and existing correlations, the best fit of the present experimental data is obtained with the correlation of Jung et al. But the existing correlations failed to predict the evaporation heat transfer coefficient of CO_2. Therefore, it is necessary to develop reliable and accurate predictions determining the evaporation heat transfer coefficient of CO_2 in a horizontal tube.

Nomenclature

d	diameter of tube [m]
dz	length of subsection [m]
G	mass flux [kg/m^2s]
h	heat transfer coefficient [kW/m^2K]
P	pressure [Pa]
Q	heat capacity [kW]
q	heat flux [kW/m^2]
T	temperature [℃]

Subscripts

cal	calculation
e	evaporation
exp	experiment
i	inside
in	inlet
loc	local
re	refrigerant

1. Introduction

CFCs and HCFCs have been used widely as working fluids for refrigerator and air conditioner since the 1930s. But nowadays these refrigerants have been identified as 'greenhouse

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gases', having artificial substances with higher ozone depletion potential (ODP) and global warming potential (GWP). This has prompted researchers worldwide to investigate the feasibility of natural refrigerants in novel refrigeration cycles.

The natural refrigerants are naturally occurring substances, namely, carbon dioxide (CO_2), nitrogen (N_2), helium (He) and water (H_2O) represent a further 'natural' alternative. Among these natural refrigerants, CO_2 is not a new refrigerant and has a successful history of the use as a refrigerant. It has many advantages as a working fluid. For instance, the most attractive characteristics of CO_2 include non-toxicity, inflammability, negligible ODP and GWP, economically efficient if CO_2 is recovered. Moreover, because CO_2 has the high volumetric capacity for refrigerants and working pressure, it is possible to make a system compact.(1)

For the refrigeration and air conditioning system using CO_2 as working fluid, the evaporator is a main component. Hence, study on the evaporation heat transfer characteristics is positively necessary. Especially, because of the large variation of specific volume, specific heat and surface tension in the evaporation heat transfer of CO_2, some researchers present that the evaporation heat transfer of CO_2 is greatly different from that of conventional refrigerants, like HCFCs and HFCs. Due to complex flow pattern and thermophysical property, the heat transfer mechanism occurred during evaporation process of CO_2 is difficult to examine. Accurate theory for the evaporation heat transfer of CO_2 is not yet established. And, study on the evaporation heat transfer characteristics of CO_2 is limited, and few results have been published on CO_2.

Therefore, more comprehensive and fundamental study for major components is required to develop the enhanced refrigeration system. Especially, to design heat exchanger for CO_2 during evaporation process, the basic data for heat transfer characteristics of CO_2 are necessary. The purpose of this study is to offer the heat transfer characteristics during evaporation process of CO_2.

2. Experimental apparatus and procedure

2.1 Test facility

As shown in Fig. 1, the test rig is composed

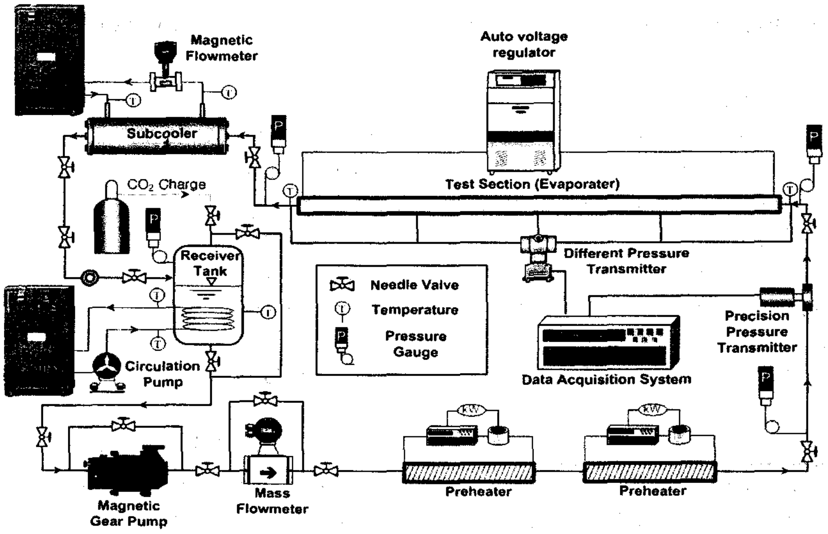

Fig. 1 Schematic diagram of experimental apparatus for heat transfer test.

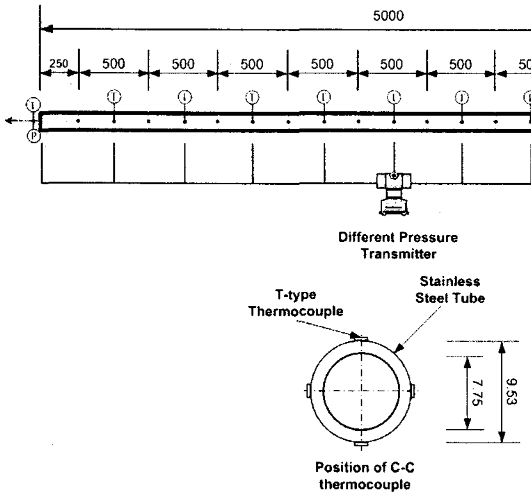

Fig. 2 Schematic diagram of test section for evaporation heat transfer test.

Table 1 Experimental conditions

Refrigerant	R-744
ID of stainless steel tube (mm)	7.75
Mass flux (kg/m^2s)	200, 300, 400, 500
Saturation temperature (℃)	−5, 0, 5
Heat flux of test section (kW/m^2)	10, 20, 30, 40

of magnetic gear pump, mass flow meter, preheater, heat transfer test section, liquid receiver, subcooler and brine chiller. The subcooling liquid of CO_2 in receiver was circulated through the mass flowmeter by means of magnetic gear pump. The refrigerant leaving the mass flowmeter in subcooling phase enters the preheater. The preheater is installed to obtain the desired inlet quality and pressure of CO_2 refrigerant. The CO_2 enters the test section and then it is evaporated when flowed through the pipe. The CO_2 refrigerant leaving the evaporator is completely condensed in subcooler and enters the receiver. The brine chiller is set up to control the given saturation temperature.

As can be seen in Fig. 2, the outer tube of the test section was made of stainless steel tube (SUS 316) with the inner and outer diameter of 7.75 and 9.53 mm, respectively. The electrical power for the preheater was regulated by the auto voltage transformer and the electrical power is provided for nichrome wire winding the outer wall of inner tube. The outside wall temperature on the heated tube was measured by T-type thermocouple mounted at the regular interval of 500 mm along the tube. T-type thermocouples to measure the temperature of the outer wall of the tube are attached at ten locations along the test section. At each point, the temperature at four circumferential locations was measured and the average values are used in calculating the heat transfer coefficient. The inlet and outlet pressure in the test section were measured with a precision pressure transmitter. Table 1 presents the experimental conditions for evaporation heat transfer.

2.2 Data reduction

The local evaporation heat transfer coefficient of CO_2 had great influence on the performance of this system. The local heat transfer coefficient in evaporation process could be evaluated by the following Eq. (1);

$$h_{e,loc} = \frac{q_e}{(T_{e,w,in} - T_e)} \tag{1}$$

where, $h_{e,loc}$ represents the local heat transfer coefficient in subsection of evaporator, T_e is bulk refrigerant temperature, and $T_{e,w,in}$ is inner wall temperature calculated by one dimensional steady state concentric equation from measured outer wall temperature. The heat flux q_e supplied by auto voltage regulator was determined as follow.

$$q_e = \frac{Q}{\pi \cdot d_i \cdot dz} \tag{2}$$

where, dz indicates the effective length of a subsection, d_i is inner diameter of stainless steel tube.

3. Results and discussion

3.1 Evaporation heat transfer

3.1.1 Influence of heat flux

Fig. 3 presents the variation of heat transfer coefficient with respect to heat flux at a given mass flux. The heat transfer coefficient decreases with vapor quality for all heat fluxes. This indicates that nucleate boiling is generated even at high quality. As can be seen in Table 2, the reason is that the ratio of specific volumes of vapor to liquid phase of CO_2 is smaller than that of fluorocarbon refrigerants, and then the vapor velocity is not greater than the liquid velocity. Accordingly, the evaporation heat transfer coefficient of CO_2 has an effect on nucleate boiling at low quality as well as at high quality.

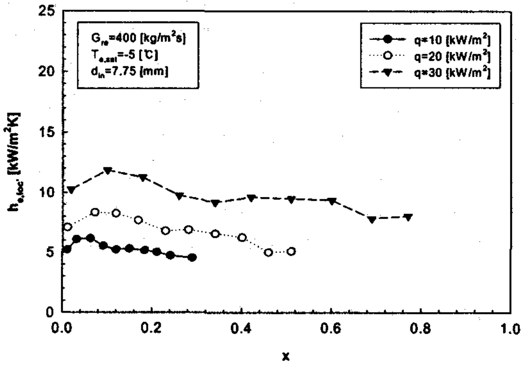

Fig. 3 Effect of different heat flux.

Table 2 Thermophysical properties of refrigerants investigated

Refrigerant			R744	R22	R134a
Density [kg/m³]	Liquid	−5	956.7	1298	1311
		0	928.1	1282	1295
		5	896.7	1264	1278
	Vapor	−5	83.14	18.09	12.08
		0	97.32	21.23	14.43
		5	114.1	24.79	17.13
Conductivity [mW/m·K]	Liquid	−5	116.7	97.09	94.24
		0	110.7	94.84	92.01
		5	104.5	92.61	89.8
	Vapor	−5	18.44	9.09	11.08
		0	19.93	9.42	11.51
		5	21.83	9.77	11.95

The heat transfer coefficient increases with heat flux, which is more evident over a wide range of quality. This shows that the increased heat flux has no affect on evaporation heat transfer of CO_2. Zhao et al.[2] showed that the heat transfer coefficient increased with a rise of heat flux at all qualities.

3.1.2 Influence of mass velocity

Fig. 4 shows the influences of varying mass flux on the heat transfer coefficient of CO_2 in a horizontal tube. As expected, the local evaporation heat transfer coefficient hardly increases mass flux increases. For this trend in Fig. 4, Pettersen[3] showed that varying mass flux has almost no influence on heat transfer over a

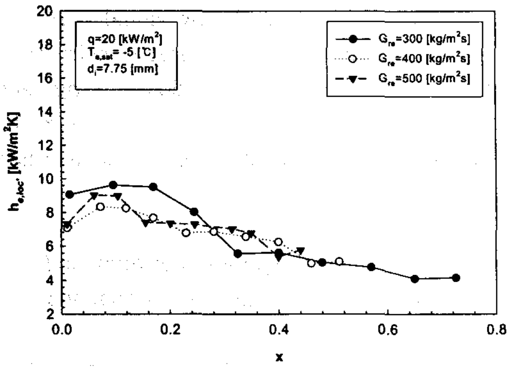

Fig. 4 Effect of different mass fluxes at constant heat flux.

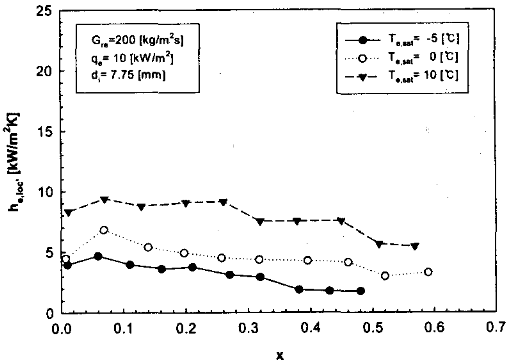

Fig. 5 Effect of different saturation temperature for constant heat and mass flux.

wide range of vapor quality. Hihara and Tanaka(4) also observed this trend in their experiments. As can be seen in Table 2, because the ratio of liquid to vapor density of CO_2 is small, the heat transfer of CO_2 has a greater effect on nucleate boiling than convective boiling. Therefore, mass flux of CO_2 does not affect on nucleate boiling too much, and there is no mass flux effect on evaporation heat transfer of CO_2.

An important consequence of the test results with varying mass flux of CO_2 is that efficient compact CO_2 evaporators for refrigeration and air conditioning application can be designed with low mass flux. One reason for selecting low mass flux is that the evaporation heat transfer coefficient of CO_2 has no influence on increasing mass flux. Another reason is that flow distribution between parallel channels can be improved especially at low mass flux.(3)

3.1.3 Influence of saturation temperature

Fig. 5 presents the variation of the heat transfer coefficients with respect to saturation temperature for a fixed mass flux. As expected, the heat transfer coefficient increases with saturation temperature of CO_2. This clearly shows that the increased heat transfer coefficient at higher saturation temperature is a result of nucleate boiling, which become more effective at higher pressure.(3)

These trend were also observed in the test results of Cho et al.(5) They showed that the heat transfer coefficients increase at all qualities as the evaporation temperature increases. They explained this reason that nucleate boiling is the predominant mechanism of evaporation heat transfer. In nucleate boiling, the vapor bubbles detach from heated surface plays an important role. As saturation temperature increases, the ratio of density of liquid to vapor is increased. Due to this reason, the buoyancy of vapor bubble increases, and the bubble detach is increased and finally, the nucleate boiling is activated.

Cooper(6) also explained that the heat transfer coefficient of nucleate boiling increases with increasing saturation temperature. The density difference between vapor and liquid is decreased at increasing saturation temperature. Due to this reason, the flow area of vapor bubble increases. In the end, the evaporation heat transfer coefficient of CO_2 has a great influence on saturation temperature.

3.1.4 Comparison of CO_2, R-22 and R-134a

Fig. 6 presents the comparison between the heat transfer coefficients of R-744 (CO_2) and those of R-22 and R-134a as Freon's refrigerant. The test conditions are the same. The inlet saturation temperature is 5℃ and the mass

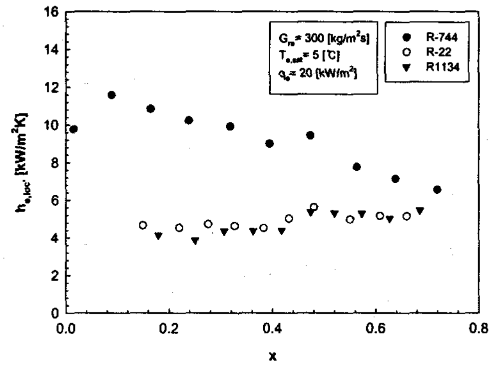

Fig. 6 Comparison of the heat transfer coefficient of R-744 with R-22 and R-134a.

flux is kept at 300 kg/m^{2}s. Heat flux is 20 kW/m^2. As shown in Fig. 6, at the quality region of $0.15 < x < 0.66$, the heat transfer coefficient of CO_2 is about 87.2% and 93% higher than that of R-22 and R-134a, respectively. This phenomenon could be attributed to higher liquid and vapor conductivity of CO_2 than those of R-22 and R-134a.

The heat transfer coefficients of R-134a and R-22 increase with quality. But, those of CO_2 decrease with vapor quality. Such differences are as a result of the different flow pattern of CO_2. The flow pattern of CO_2 is greatly affected by these fluid properties such as a much higher pressure, high vapor density, and low surface tension and low liquid viscosity. Thus, CO_2 offers outstanding heat transfer characteristics compared to traditional refrigerants such as CFCs and HCFCs. These attractive characteristics are mainly due to the excellent thermal properties of CO_2.

3.2 Comparison of experimental data and evaporation heat transfer correlations

In order to predict the local evaporation heat transfer coefficient in a horizontal tube, some researchers proposed their correlations, and these correlations are presented by Shah,(7) Gungor-Winterton,(8) Kandlikar,(9) Jung et al.(10) and Liu-Winterton.(11) In this section, some general correlations will be reviewed and compared to the experimental data, and confirmed this applicable possibility of their correlations.

Fig. 7 displays the comparison between the evaporation heat transfer coefficients obtained from the experiment and the correlations predicted by Shah, Gungor-Winterton, Kandlikar, Jung et al. and Liu-Winterton. All the correlations tend to underestimate the experimental heat transfer coefficients. Among the correlations, the best fit of the present test data is obtained with the correlation of Jung et al. Table 3 presents the errors between the calcu-

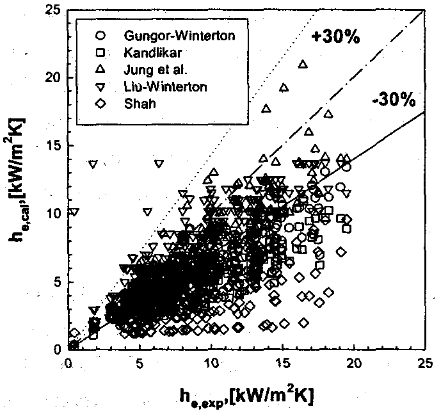

Fig. 7 Comparison between measured and calculated heat transfer coefficient.

Table 3 The errors between measured and calculated heat transfer coefficient

	Average deviation (%)	Mean deviation (%)
Shah (1982)	−47.28	49.05
Gungor-Winterton (1986)	−32.39	32.7
Jung et al. (1989)	−14.26	21.64
Kandlikar (1989)	−38.9	39.22
Liu-Winterton (1991)	12.59	32.61

Average deviation (%): $\left[\left\{\sum_{i=1}^{N}\left(\frac{h_{cal,i}-h_{exp,i}}{h_{exp,i}}\right)\right\}\Big/N\right]\times 100$

Mean deviation (%): $\left[\left\{\sum_{i=1}^{N}\left|\frac{h_{cal,i}-h_{exp,i}}{h_{exp,i}}\right|\right\}\Big/N\right]\times 100$

lated and experimental heat transfer coefficients.

4. Conclusions

In this section, for optimum design of refrigeration and air conditioning evaporator using CO_2 as working fluid, the heat transfer coefficients during the evaporation process of CO_2 in a horizontal tube have been investigated and the followings are the findings of this study.

(1) The heat transfer coefficients of R-134a and R-22 increase with quality, and those of CO_2 decrease with vapor quality. At the quality region of $0.15 < x < 0.66$, the heat transfer coefficient of CO_2 is about 87.2% and 93% higher than that of R-22 and R-134a, respectively. The resulting "unusual" properties of CO_2 give heat transfer characteristics that are very different from those of conventional refrigerants.

(2) In a horizontal tube, the evaporation heat transfer coefficient obtained in the experimental data of CO_2 was compared with the several existing heat transfer correlations. The existing correlations for heat transfer coefficient underestimated the experimental data of CO_2. Among existing correlations, Jung et al.'s correlation shows an agreement to experimental data.

(3) As mentioned earlier, comprehensive studies relatedto evaporation heat transfer were carried out experimentally, including heat transfer during evaporation process of CO_2. The local heat transfer coefficients of CO_2 during evaporation process are highly dependent on heat flux and saturation temperature. In these circumstances, conventional models of the local heat transfer coefficient do not apply, so, the new evaporation heat transfer correlation of CO_2 in a horizontal tube should be developed through various experimental data.

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