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The effect of the lubricating oil fraction rate on the CO_2 evaporating thermal and hydraulic characteristics

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This paper presents the evaporating heat transfer characteristics of refrigeration cycle. Using CO_2 as working refrigerant and the effect of oil mixing rate on the thermal and hydraulic characteristics were investigated. The main test section is an ID of 3.0 mm stainless tube, which is directly heated by electricity from an electric pole. Oil mixing rate(0~4wt%) are adopted as experimental parameters. The more oil is mixed, the more the heat transfer coefficient deteriorates and this trend becomes much remarkable by increasing oil mixtures. Also, dryout quality is affected greatly by oil mixing rate. Through experiments, it is recognized that dryout quality depends on only oil mixing rate. On the other hand, the pressure drop depends on the mixing rate of oil. The qualitative trend is discussed in terms of the thermo physical properties. Finally, the empirical correlation equations for heat transfer coefficient and pressure drop are suggested.

1. INTRODUCTION

Global warming potential is extremely big, and the conventional refrigerant can go ahead through the policy that does not recognize a chlorofluorocarbon alternative to the refrigerant for car air-conditioners positively in EU in particular, and interest for the nature refrigerant rises. Though a characteristic is very sensitive for mixture of the oil, this characteristic is not grasped enough

Due to increasing environmental concern, the reduction of greenhouse effect gas, in particular CO_2 emission and direct leak of HCFC and HFC's has been considered to be one of the most important subjects in the field of refrigeration and air-conditioning system. At the present, the demand for higher efficiency of refrigeration system (COP) is promoted still more to compare with previous situation.

Among the various candidates of natural refrigerants, because CO_2 is environmentally safe, not toxic and non-flammable, CO_2 has advantages for practical reason . Moreover, CO_2 possesses a low viscosity, a high specific heat, a high thermal conductivity. In general, it has excellent thermodynamic and transport properties as refrigerant.

Although many evaporation heat transfer data are available in open literature (Koyama, 2004, Yamada, 2004, Katsuta, 2006) and it is recognized that the evaporation heat transfer is very sensitive for lubrication oil concentration rate (OCR), a few investigation have addressed the effect of OCR and its prediction. The objective of this research, therefore, using CO_2 as working refrigerant and the effect of oil mixing rate on the thermal and hydraulic characteristics are investigated.

2. Experimental Apparatus and Procedure

A schematic diagram of experimental facilities is shown in Fig. 1. The test loop consists of a compressor, a gas cooler, an expansion valve, a pre-heater and an evaporator, which are the components of the fundamental vapor compression refrigeration system. Additionally, to regulate the oil concentration inside the evaporator, a PGA oil supply system and oil mass flow meter is placed just anterior (upper side) of test section and oil sampling system (17) is also installed in test loop.

The test section is a horizontal smooth stainless tube with an inner diameter of 3mm (outer diameter is 4mm) and the length of 0.5m (0.5m long). The detail of the direct AC current heating test section is shown in Fig.2. The surface temperature of the test section is measured by K-type thermocouples. To measure heat transfer coefficient, the thermocouples are soldered at six axial locations of 90mm apart and additionally thermocouples are also placed on three circular positions, namely the top, the bottom and 90degrees from the top at each axial location.

The refrigerant mass flow rate entering into the test section is measured by the Coriolis type mass flow meter. Pressure transducers and T-type mineral insulated thermocouples monitor the refrigerant pressure at the inlet and the outlet of the test section and refrigerant temperature inside test tube respectively.

Throughout the experiment, the heat transfer coefficient and the pressure drop at the test section are measured under the condition where the evaporating temperature is -10,0,10℃, the quality range between 0 to 1.0 and heat flux from 5 to 15kW/m^2 and the mass flux 200 and 400 kg/m^{2}s as summarized in Table 1.

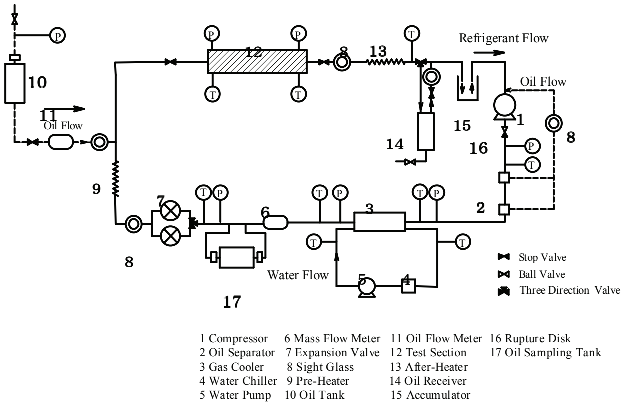


Fig.1 Schematic of Experimental Apparatus

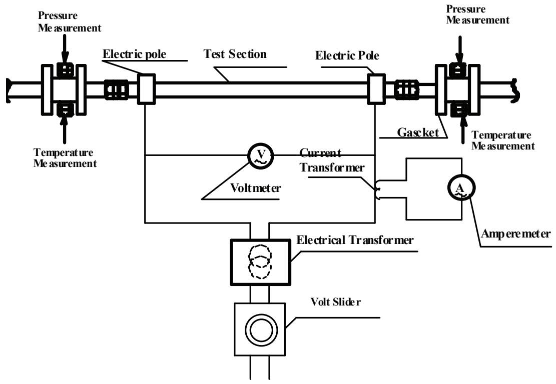


Fig. 2 Details of Test Section

Table 1 Experimental Conditions

Evaporating Temperature	℃	-10, 0, 10
Mass Flux	kg/m^{2}s	200, 400
Heat Flux	kW/m^2	5, 10, 15
Oil Type		PAG VG100
Oil Concentration	wt%	0～4.0
Quality		0～1.0

3. Experimental results and discussions

3.1 The effect of oil concentration on the pressure drop

The experimental pressure drop data under the mass flux 400kg/m^{2}s constant, the evaporating temperature at 10℃ and (with respect to) the heat flux adopted as experimental parameter varying from

5 to 15kW/m^{2,} as function of quality are shown in Fig. 3.

From this figure, the following features are recognized; (1) Pressure drop increases directly proportional to the quality, (2) Pressure drop almost independents on the heat flux. Judging from Fig.3, the transient quality at where the gradient of pressure drop increase becomes steeply, moves to the low quality region when the oil concentration becomes higher. The possible cause of this trend is that the local concentration of lubrication oil plays an important role in increasing pressure drop. Because the large amount of oil entrains into the gas phase with increasing quality, the pressure drop is dramatically increased by strong flow resistance of this oil entrainment. Another evidence of this trend can be obtained from the effect of mass flux on the pressure drop. Fig. 4 represents the effect of the evaporation temperature on the pressure drop under the constant mass and heat flux. Since the liquid and vapor density ratio becomes high at the lower evaporation temperature as shown Table 2, the pressure drop should be increased under the lower evaporation temperature condition.

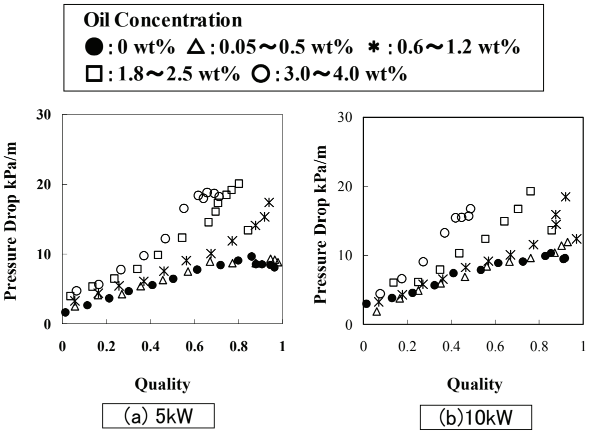


Fig. 3 Effect of Heat Flux on Pressure Drop (with Oil Concentration) (G=400kg/m^{2}s T_{sat} = 10℃)

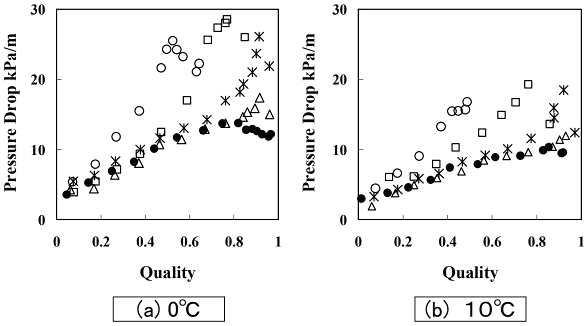


Fig. 4 Effect of Evaporating Temp. on Pressure Drop (with Oil Concentration) (G=400kg/m^{2}s q= 10kW/m^2)

Table 2 Properties of R744

Evaporating Temperature ℃	Liquid Density kg/m^3	Vapor Density kg/m^3	ρ_l/ρ_g
-10	982.93	71.185	13.808
0	927.43	97.647	9.4978
10	861.12	135.16	6.3711

3.2 The effect of oil concentration on the evaporation heat transfer

The evaporation heat transfer coefficient of pure CO_2 as function of mass flux (varies from 200 to 600 kg/m^{2}s) under the constant heat flux (15 kW/m^2) and the evaporation temperature (-10℃) are shown in Fig. 5. In this figure to emphasize the difference between the top and bottom evaporation heat transfer coefficient, the measured heat transfer coefficient ratio is used for the axis of ordinate. From this figure, it is recognized that the circumferential distribution of liquid film thickness approaches uniform with increasing mass flux until 400kg/m^{2}s, however beyond this value the liquid film thickness at the top becomes much thinner as compares that of the low mass flux condition. This trend might play an important role in the onset of CO_2 dryout phenomena.

The experimental heat transfer data under the mass flux 400kg/m^{2}s constant, the evaporation temperature at 10℃ and the heat flux adopted as experimental parameter, as function of the quality are shown in Fig. 6. On the other hand, Fig. 7 represents the effect of the evaporation temperature and the oil concentration on the evaporation heat transfer. From these figures, it is proved that the small amount of lubrication oil contamination has significant effect to deteriorate the evaporation heat transfer performance which is dominated by the nucleate boiling heat transfer (Koyama et al., 2004). As typical example of this fact, the heat transfer coefficient decreases dramatically with increasing oil concentration as shown in Fig 6(b). This might be due to the nucleate boiling heat transfer depression by adhering oil film on the heat transfer surface (Gao and Honda, 2005). It is also recognized that the heat transfer deterioration effect of oil contamination with increasing concentration gradually saturates and converge at around 4kW/m^2.

In addition, the dryout point moves to the low quality region with increasing oil concentration under every experimental conditions as shown both of figures. In Fig.8, the relation between onset dryout quality decreasing rate (onset dryout point of pure CO$_2$ is unity) and oil concentration is shown. It is concluded that the onset dryout quality decreasing rate depends on oil concentration and almost independent to mass flux and the evaporation temperature.

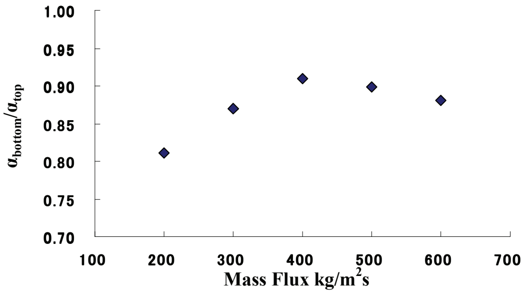
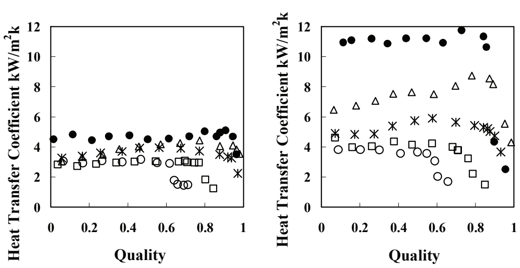


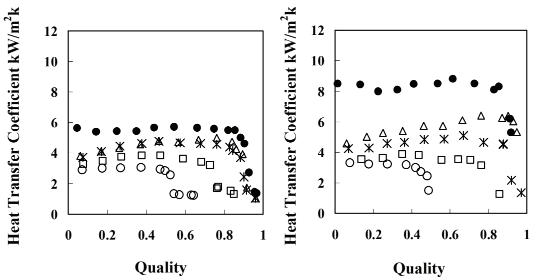
Fig.5 Relation between $\alpha_{bottom}/\alpha_{top}$and Mass Flux (q=15kw/m^2 T_{sat}=-10℃)

Oil Concentration
●: 0 wt% △: 0.05～0.5 wt% ∗: 0.6～1.2 wt%
□: 1.8～2.5 wt% ○: 3.0～4.0 wt%



(a) 5kW (b) 15kW

Fig. 6 Effect of Heat Flux on Heat Transfer Coefficient (with Oil Concentration) (G=400kg/m^{2}s T_{sat} = 10℃)



(a) 0℃ (b) 10℃

Fig. 7 Effect of Evaporating Temp. on Heat Transfer Coefficient (with Oil Concentration) (G=400kg/m^{2}s q= 10kW/m^2)

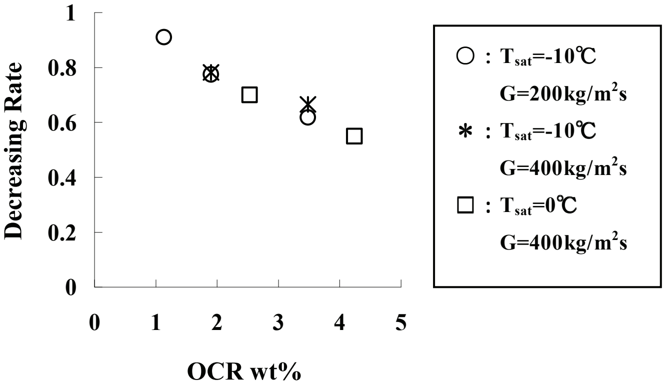


Fig. 8 Effect of OCR on Dryout

4. Derivation of the experimental correlations

4.1 Pressure drop

Based on the above-mentioned experimental results and discussion, the empirical correlations to predict the heat transfer and hydraulic characteristics of CO_2 are derived taking into account the oil contamination effect. In this research, an attempt is made to correlate the present pressure drop data in terms of Lockhart and Marineklli parameter expression. It is well-known that the pressure drop of the two-phase flow in horizontal tube is composed of two terms, namely friction loss and acceleration loss. The former term describes as Eq. (1). The two phase multiplier used in the prediction of latter term is evaluated from Eq. (2). In addition, to propose the empirical correlation covered throughout quality (from 0 to 1), another terms to correct the two phase flow pattern and maximum pressure drop (ω) are added. Therefore, our final empirical correlation is as follows;

$$\left(\frac{\Delta P}{\Delta L}\right)_{ac} = G^2\left\{\left[\frac{{x_{out}}^2}{{\alpha_{out}}^2\rho_g}+\frac{(1-x_{out})^2}{(1-\alpha_{out})\rho_l}\right]-\left[\frac{{x_{in}}^2}{\alpha_{in}\rho_g}+\frac{(1-x_{in})^2}{(1-\alpha_{in})\rho_l}\right]\right\} \tag{1}$$

$$\Phi_{l0} = \sqrt{\frac{(\Delta P/\Delta z)_f}{(\Delta P/\Delta z)_{l0}}} \tag{2}$$

$$\begin{aligned}\left(\frac{\Delta P}{\Delta L}\right) = \left(\frac{\Delta P}{\Delta L}\right)_{fl} \times {\Phi_{l0}}^2 \\ + G^2\left\{\left[\frac{{x_{out}}^2}{{\alpha_{out}}^2\rho_g}+\frac{(1-x_{out})^2}{(1-\alpha_{out})\rho_l}\right]-\left[\frac{{x_{in}}^2}{\alpha_{in}\rho_g}+\frac{(1-x_{in})^2}{(1-\alpha_{in})\rho_l}\right]\right\}\end{aligned} \tag{3}$$

Annular

$$\Phi_{l0}^2 = \left[0.374\ln\left(\frac{1}{X_{tt}}\right)+0.908\right]\times\left(\frac{\rho_l}{\rho_g}\right)\times\omega \tag{4}$$

Slug or Froth

$$\Phi_{l0}^2 = \left[0.309\ln\left(\frac{1}{X_{tt}}\right)+0.773\right]\times\left(\frac{\rho_l}{\rho_g}\right)\times\omega \tag{5}$$

$$\begin{cases} \mathrm{Re}_l<2500 & \omega=1 \\ \mathrm{Re}_l \geqq 2500 & \omega=1.30\times\left(\dfrac{1}{X_{tt}}\right)^{-0.197} \end{cases} \tag{6}$$

4.2 Heat transfer coefficient

As mentioned earlier, the evaporation heat transfer of CO_2 is dominated by the nucleate boiling heat transfer and has very high heat transfer coefficient so that the previous proposed correlations for HCFC and HFC's can not be simply adaptable. However, in recent open references on the evaporation heat transfer, various correlations based on Chen's type (Chen, 1996) were proposed and successfully predicted. In our previous research, we used modified Chen's type correlation successfully (Katsuta et al., 2006). Therefore, to predict the effect of oil contamination on the evaporation heat transfer, this correlation is continuously adopted.

$$\alpha = \alpha_{con} + \alpha_{bo} \tag{7}$$

In Eq.(7), convective heat transfer term and nucleate boiling heat transfer term are given as follows;

$$\alpha_{con} = F \times 0.023 \frac{\lambda_l}{D} \left(\frac{G(1-x)D}{\mu_l} \right)^{0.8} \mathrm{Pr}^{0.4} \tag{8}$$

$$\alpha_{bo} = S \alpha_{SA} \tag{9}$$

$$\alpha_{SA} = 207 \frac{\lambda_l}{D_b} \left(\frac{q D_b}{\lambda_l T_{sat}} \right)^{0.745} \left(\frac{\rho_g}{\rho_l} \right)^{0.581} \mathrm{Pr}_l^{0.533} \tag{10}$$

Based on the qualitative trend of evaporation heat transfer, to take into account the local oil concentration and the evaporation temperature, the convection enhanced factor F is modified as Eq.(13). On the other hand, the nucleate boiling suppression factor S in considering the effect of heat flux and the latent heat of evaporation, namely Boiling number, is revealed as Eq.(16).

$$\alpha = \alpha_{con} + \alpha_{bo} \tag{11}$$

$$\alpha_{con} = F \times 0.023 \frac{\lambda_l}{D} \left(\frac{G(1-x)D}{\mu_l} \right)^{0.8} \mathrm{Pr}^{0.4} \tag{12}$$

$$F = 1 + 0.258 \times \left(\frac{1}{X_{tt}} \right)^{0.886} + 92.32 \left(\frac{\rho_g}{\rho_l} \right)^{3} \left(\frac{1}{X_{tt}} \right)^{0.9} \tag{13}$$

$$\alpha_{bo} = S \alpha_{SA} \tag{14}$$

$$\alpha_{SA} = 207 \frac{\lambda_l}{D_b} \left(\frac{q D_b}{\lambda_l T_{sat}} \right)^{0.745} \left(\frac{\rho_g}{\rho_l} \right)^{0.581} \mathrm{Pr}_l^{0.533} \tag{15}$$

$$S = \ln \left(2.332 \frac{Bo^{0.518} Bd^{1.27} Fr^{0.964}}{\mathrm{Re}_{TP}^{0.834}} \right) \tag{16}$$

To establish the heat transfer prediction including oil contamination effect, the heat transfer due to this effect φ is introduced here. By using the heat flux, latent heat of evaporation and surface tension, these are the major contribution factors to deteriorate the nucleate boiling heat transfer, the following dimensionless groups (Boiling Number and Bond Number) take into account;

$$\alpha_{bo} = S \alpha_{SA} \times \phi \tag{17}$$

$$\phi = \frac{1}{\left(1 + OCR^{0.698} Bo^{0.207} Bd^{0.912} \right)} \tag{18}$$

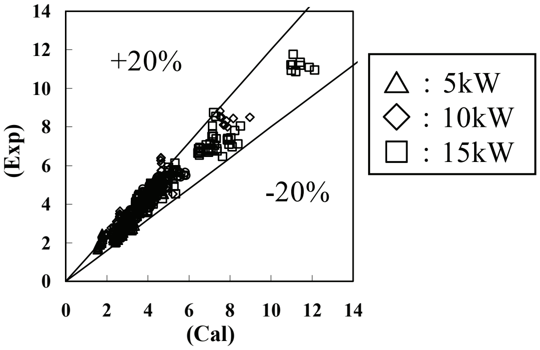


Fig.9 Correlation Accuracy of Heat Transfer Coefficient with Oil Concentration

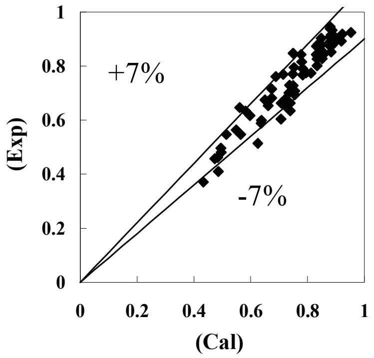


Fig.10 Correlation Accuracy of Dryout Quality

4.3 Dryout Phenomena

To correlate the onset duality of dryout, Eq.(19) is proposed to take into consideration the dominated factor, namely Re, Fr and Bo Numbers.

$$x_{dry} = 0.269 \times \frac{\mathrm{Re}^{0.0571} Fr^{0.0697}}{Bo^{0.0519}} \tag{19}$$

Premature Dryout factor η with oil contamination is determined using oil concentration as follows;

$$OCR < 1 \qquad \eta = 1 \tag{20}$$

$$OCR \geqq 1 \qquad \eta = 1.169 e^{-0.17 \times OCR} \tag{21}$$

$$x_{dry} = 0.269 \times \frac{\mathrm{Re}^{0.0571} Fr^{0.0697}}{Bo^{0.0519}} \times \eta \tag{22}$$

4. CONCLUSIONS

(1) Pressure drop of CO_2 increases directly proportional to the quality and almost independents on the heat flux. On the other hand, the heat transfer coefficients increase as the higher evaporation temperature. The heat transfer deterioration effects of oil contamination with increasing concentration is very significant and gradually saturates at around 4wt% and settle down at around $4kW/m^2$

(2) The dryout point moves to the low quality region with increasing oil concentration under every experimental conditions. It is concluded that the onset dryout quality decreasing rate depends on oil concentration and almost independent to mass flux and evaporation temperature.

(3) The empirical correlation equations for heat transfer coefficient and pressure drop taken into account the evaporation temperature and oil concentration are suggested. The accuracy of these correlations are ±20% for evaporation heat transfer coefficient and ±7% for dryout quality.

NOMENCLATURE

Re : Reynolds Number
Bo : Boiling Number
Bd : Bond Number
Fr : Froude Number

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