MEASUREMENT OF OIL CIRCULATION RATIO IN CO_2 HEAT PUMP SYSTEMS

L. Gao, Associate Professor, Department of Mechanical Engineering, Fukuoka University, 8-19-1 Nanakuma, Jonan-ku, Fukuoka, Japan;
A. Nakamura, Graduate Student, Graduate School of Engineering, Fukuoka University, 8-19-1 Nanakuma, Jonan-ku, Fukuoka, Japan;
Y. Watanabe, Graduate Student, Graduate School of Engineering, Fukuoka University, 8-19-1 Nanakuma, Jonan-ku, Fukuoka, Japan;
T. Honda, Professor, Department of Mechanical Engineering, Fukuoka University, 8-19-1 Nanakuma, Jonan-ku, Fukuoka, Japan;
R. Takigawa, Researcher, Measurement Technology R&D Center, Chino Corporation, 32-8 Kumano-cho, Itabasi-ku, Tokyo, Japan;
T. Shimizu, Director, Measurement Technology R&D Center, Chino Corporation, 32-8 Kumano-cho, Itabasi-ku, Tokyo, Japan;

Abstract: This paper deals with several measurement methods for oil circulation ratio (OCR) in CO_2 heat pump systems in which immiscible oil (PAG) is used. These methods can be used to investigate the effects of OCR, and the effect of an oil separator on the system performance. The visual or oil-droplet method (OCR measurement method by measuring the numbers of oil droplets and the time required) proposed by Gao and Honda, was modified for higher mass velocities and higher OCR conditions. The results agree well with those measured by the oil-volume method (OCR measurement method by measuring the oil-volume and the time required). The heat-balance method for measuring OCR was also proposed, and the results show that the method is reliable for high OCR conditions although the accuracy was about ±1 mass%. Measurement of oil concentration using the densimeter method was also conducted, and results showed that oil concentration is different from OCR in a system with immiscible oil.

Key Words: measurement, oil circulation ratio, CO_2 heat pump, immiscible oil

1 INTRODUCTION

In a CO_2 heat pump system, PAG oil is charged in the system, and used to lubricate the compressor. When the system is in operation, some of the oil is discharged with the refrigerant from the compressor. The oil circulates through all of the cycle components and finally returns to the compressor. The existence of oil in heat exchangers has a great undesirable influence on heat transfer, pressure drop, and reduces the performance of the heat exchangers [Tanaka et al. (2001), Katsuta et al. (2002), Koyama et al. (2005), Gao et al. (2007)]. The oil circulation ratio (OCR) has been used in evaluation of performance of a compressor or a system as an index of the amount of oil. Accordingly, the measurement of OCR is required to evaluate the influence of the oil, the performance of systems, and is inevitable for improvement of the system performance.

Generally, lubricating oil of good solubility with the refrigerant has been conventionally used in refrigeration and heat pump systems. In these systems, the oil concentration at the liquid line of the condenser outlet gets a value equal to OCR, because the refrigerant and oil dissolve uniformly with each other. OCR, therefore, can be measured by measuring the oil concentration in the liquid line. This is why measurement of OCR (or oil concentration), such as the sampling method, must be performed at the outlet of the condenser.

There are several methods reported in open literature measuring oil concentration. The most general way for measuring oil concentration is the sampling method (ASHRAE, 1996). However, this method is time-consuming and reduces the amount of refrigerant and oil in the cycle. To resolve these problems, several other methods have been proposed as online measurement. Baustian et al. (1988a, b) used a bypass viscometer and an acoustic velocity sensor to measure oil concentration for three kinds of mixtures of refrigerants and miscible oil. Kutsuna et al. (1991) and Suzuki et al. (1993) proposed a light absorption method for measuring oil concentration of two kinds of refrigerant/oil mixtures. Baustian et al. (1988c) and Bayani et al. (1995) used a densimeter to measure oil concentration of four kinds of refrigerant/oil mixtures. Baustian et al. (1986) described capacitance and refractive index sensor methods as potential methods of measuring oil concentration. Fukuta et al. (1999, 2004) applied these methods to measure refrigerant solubility and oil concentration in a compressor. Meyer et al. (1994) and Fukuta et al. (2008) measured oil concentration by measuring the sound speed of refrigerant/oil mixtures.

On the other hand, in systems with immiscible oil, such as CO_2 heat pump system with PAG oil, the oil separates with refrigerant liquid in the liquid line. Accordingly, oil concentration will get a different value from OCR even in the liquid line, due to the difference in velocity of the refrigerant liquid and oil. Even at the same OCR conditions in the same system, the oil concentration will also get a different value if the flow pattern changes with the change in the mass flow rate of refrigerant. That is to say, it is not exact to use oil concentration instead of OCR in this case. And, a big error may take place depending on the conditions of operation.

Hwang et al. (2008) applied the capacitance method to measure the OCR (they called it as oil mass fraction) of CO_2 with PAG oil. They calibrated the capacitance sensor for the range of OCR 0-7mass% by using an oil mass flow meter, and showed that the error of the measurement method is less than 0.5mass%. However, it is not clear whether the amount of CO_2 dissolved into the oil was taken into consideration when they measured the oil mass flow rate.

Takigawa et al. (2009) proposed a real-time optical measuring method of OCR in CO2 heat pump system using infrared ray. They found that the cloudiness of the liquid mixture changes with the OCR. So they proposed to install a mixing chamber at the outlet of gascooler in order to make oil-refrigerant liquid mixture uniform, and by applying infrared ray to the liquid mixture, they clarified the relationship between the transmittance of infrared ray and oil circulation ratio (OCR). They calibrated the OCR sensor for the range of OCR 0-0.8mass% by using the oil-droplet method proposed by Gao and Honda (2006). However, the oil-droplet method has a shortcoming that the measurement accuracy decreases at high mass velocity and high oil circulation rate conditions.

In this study, the oil-droplet generation component was redesigned for improvement in the measurement range and accuracy. The heat-balance method which calculates OCR from the difference in the heat balance of an evaporator between pure refrigerant and oil mixtures was also proposed. Comparing with the oil-volume method (OCR measurement method by measuring the oil volume flow rate at the evaporator outlet), the measurement accuracies of the new oil-droplet method and the heat-balance method were examined. The oil concentration was measured using the densimeter method.

2 EXPERIMENTAL APPARATUS AND METHOD

The experimental apparatus used in the present research is shown in Figure1. It is a heat pump system consisting mainly of a two-stage compressor (1), an oil-separator (2), two gas-coolers (5, 6), two expansion valves (13a, 13b), a pre-heater (4), an evaporator (14), an auxiliary evaporator (17), and an accumulator (18). In order to measure OCR by oil-droplet method, a sightglass (7b) was installed after the evaporator. A glass-cylinder (21) was equipped under the sightglass to measure OCR by the oil-volume method. The OCR was adjusted by the oil-control valve (3).

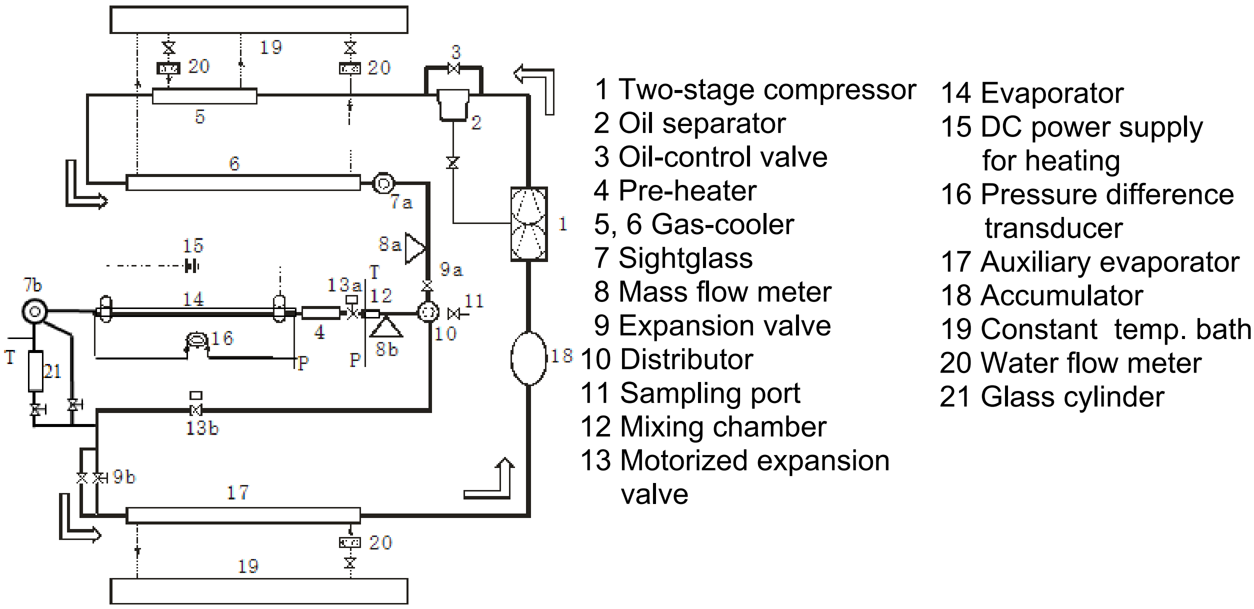
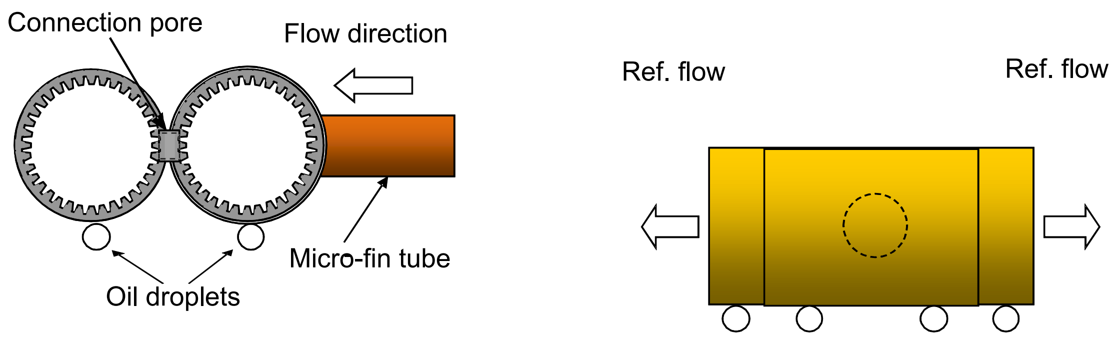


Figure 1: Schematic diagram of experimental apparatus

The mass flow rates were measured using two coriolis type mass flow meters (8a, 8b), for measuring the total mass flow rate and that flowing through the test section. The precisions of the mass flow rate meters are ±0.25%full-scale (Full-scale:100kg/h). The densities were also measured using the mass flow meter. The precisions of the density measurement are less than 0.2 kg/m^3. The pressures and bulk temperatures at the mixing chambers prepared before the expansion valve and the outlet of the evaporator were measured using two pressure transducers and two sheathed thermocouples. The precisions of the pressure transducers and sheathed thermocouples are ±0.01 MPa and ±0.05 K, respectively. The pressure drop over the test section was measured using a pressure difference transducer (16) with a precision of ±0.2 kPa. The evaporator and auxiliary evaporator are horizontal copper tubes, and they are heated by film or sheathed heater which is wound outward of the tube. The electric current for heating was measured using a 1 mΩ (±0.01%) standard resistor.

OCR measurement using oil-droplet method was conducted as follows: (1) The total mass flow rate (m) was kept constant; (2) The electric current to evaporator was increased until CO_2 liquid disappears at the outlet of the evaporator. Then, the oil flowed out out from the exit pipe of the evaporator which is set in the sightglass (6b), and form a droplet under the pipe; (3) After being stabilized, the size of droplet falling in the sightglass chamber and the falling interval of droplets were measured, and then the oil mass flow rate (m_{oil}) was calculated from Equation (2). Here, the density and the solubility of refrigerant in the oil were taken into account. (4) OCR was obtained from the ratio of the two mass flow rates. Figure 2 shows details of the oil-droplet generation component for the oil-droplet method, while Figure 3 shows a snapshot of OCR measurement using the oil-droplet method.

OCR measurement using oil-volume method was carried out simultaneously (at the same time) with oil-droplet method. Figure 4 shows the details of the test parts for the oil- volume method. By closing the valve under the glass-cylinder, oil was accumulated in a cylinder. From the relation between volume change and the time required, OCR could be obtained. Figure 5 shows a snapshot of OCR measurement using the oil-volume method.



(a) Side view (b) Front view

Figure 2: Details of the test part for the oil-droplet method

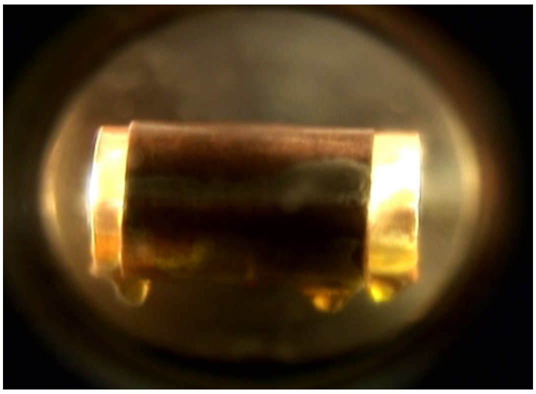


Figure 3: A snapshot of the oil-droplet method

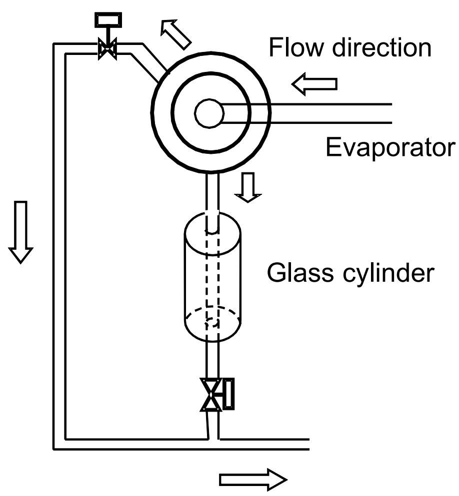


Figure 4: Test parts for the oil-volume method

Figure 5: A snapshot of the oil-volume methods

The CO_2 solubility and density of PAG oil were measured by Gao et al. (2008) at the pressure range of 3.5-5 MPa. For measuring the OCR using oil-droplet and oil-volume methods, the change in CO_2 solubility and the change in the density of the oil were taken into consideration using the measured data of Gao et al. The purity of CO_2 used in the present research is 99.95mass%. The thermophysical properties of CO_2 were calculated using software package PROPATH (PROPATH Group, 2001). The experimental conditions are shown in Table 1.

Table 1: Experimental conditions

Mass velocity, kg/(m^{2}s)	100 ～ 300
Saturation temperature, °C	10
Superheat at the test section exit, °C	5 ～ 34
Oil circulation ratio, mass%	0.048 ～ 4.31

3 DATA REDUCTION

The oil circulation ratio (*OCR*) is defined as follows:

$$OCR = \frac{m_{oil}}{m} \tag{1}$$

where m_{oil} is the mass flow rate of the oil, and m is the total mass flow rate of the refrigerant and oil.

3.1 Oil-droplet Method

The oil mass flow rate (m_{oil-D}) measured using the oil-droplet method is calculated from the following equation by assuming the oil droplet as a perfect sphere.

$$m_{oil-D} = \frac{4}{3}\pi\left(\frac{d_{oil}}{2}\right)^3 \rho_{oil} N \frac{1}{t}(1-y) \tag{2}$$

where d_{oil} is the diameter of the oil droplet, ρ_{oil} is the density of the oil, N is the numbers of the oil droplet for measurement, t is the time required for measurement (the generation of the oil droplets), and y is the solubility of the refrigerant in the oil.

3.2 Oil-volume Method

The oil mass flow rate ($m_{oil\text{-}V}$) measured using the oil-volume method is calculated from the following equation.

$$m_{oil-V} = V\rho_{oil}\frac{1}{t}(1-y) = \frac{\pi}{4}D^2 H\rho_{oil}\frac{1}{t}(1-y) \quad (3)$$

where V is the volume of the cylinder, D is the inner diameter of the glass cylinder, and H is the height for measurement.

3.3 Heat-balance Method

The value of the heat balance (the heat transfer rate calculated from refrigerant side/the heat transfer rate calculated from heating side) of the evaporator is affected by the heat transfer between the surroundings and experiment setup from the inlet of expansion valve to the outlet of the evaporator. The heat transfer rate between the surroundings and experiment setup can be evaluated (measured) from the following equation which is obtained from the relation of the heat balance in the pure refrigerant conditions.

$$Q_{sur} = Q_R - Q_E \quad (4)$$

where Q_R is the heat transfer rate calculated from refrigerant side which is obtained from the enthalpy change of refrigerant, and Q_E is the heat transfer rate calculated from the heating side, which is obtained from the amount of electronic power supply. The correlation for the heat transfer rate between the surroundings and experiment setup was obtained from the results of the pure refrigerant conditions.

In the case of CO_2-oil mixtures, by taking the total mass flow rate as the flow rate of the pure CO_2, the heat transfer rate obtained from the enthalpy change of the refrigerant can be calculated as

$$Q_R = m(h_2 - h_1) \quad (5)$$

where h_1 and h_2 are the enthalpies of the refrigerant at the inlet of the expansion valve and the outlet of the evaporator, respectively.

By neglecting the sensible heat which is due to the oil temperature change, the net heat transfer rate can be obtained as follows from refrigerant side:

$$Q_{R0} = Q_E + Q_{sur} = m(h_2 - h_1)(1 - OCR) \quad (6)$$

Then, the relation between the evaporator heat balance (η_{oil}) and the oil circulation ratio (OCR) can be obtained as follows in the case of CO_2-oil mixtures.

$$\eta_{oil} = \frac{Q_R}{Q_E + Q_{sur}} = \frac{Q_R}{Q_{R0}} = 1/(1 - OCR) \quad (7)$$

3.4 Densimeter Method

By assuming that the volume of CO_2-oil mixtures equals to the sum of the volumes of pure refrigerant and oil, the following relation can be obtained.

$$\frac{M}{\rho}=\frac{M_R}{\rho_R}+\frac{M_{oil}}{\rho_{oil}}=\frac{M-M_{oil}}{\rho_R}+\frac{M_{oil}}{\rho_{oil}} \tag{8}$$

where M_R, M_{oil} and M are the mass of the pure CO_2, oil and CO_2-oil mixtures, respectively. ρ_R and ρ are the density of pure CO_2 and CO_2-oil mixtures, respectively. Substituting the oil concentration w (= M_{oil} / M) into the above equation, the following equation is obtained.

$$\frac{1}{\rho}=\frac{1-w}{\rho_R}+\frac{w}{\rho_{oil}}=\frac{1}{\rho_R}-\left(\frac{1}{\rho_R}-\frac{1}{\rho_{oil}}\right)w \tag{9}$$

Substituting density with specific volume, the following equation is obtained.

$$(v-v_R)/(v_R-v_{oil})=-w \tag{10}$$

where v_R, v_{oil} and v are the specific volume of pure CO_2, oil and CO_2-oil mixtures, respectively.

4 EXPERIMENTAL RESULTS

Figure 6 shows a comparison of the measured results of the oil-droplet and the oil-volume methods. As shown in the figure, at the low OCR conditions ($OCR \leq 1$ mass%), the results of the oil-droplet method agree well those of the oil-volume method, although the results of the oil-droplet method are slightly lower than those of the oil-volume method(within -20 %, within -0.2 mass%). On the other hand, when the mass velocity G > 200 kg/(m^{2}s), the difference between the oil-droplet and the oil-volume method increases with the increase in mass velocity and OCR. Most of the results of the oil-droplet method are -20~ -50% lower than those of the oil-volume method. This is due to the increase in the amount of the oil entrained into the vapor flow with the increase in mass velocity and OCR.

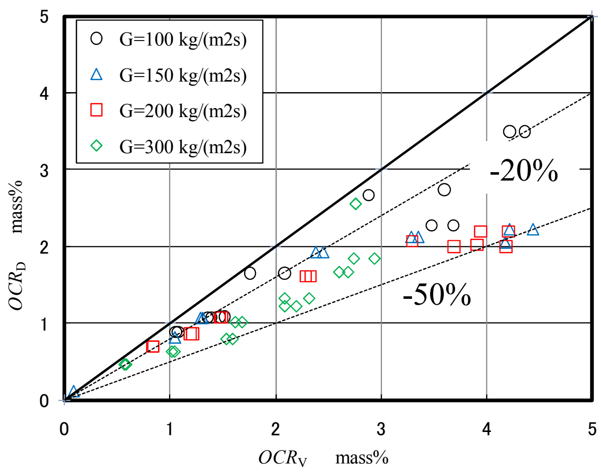


Figure 6: Relation between the oil-droplet method and the oil-volume method (T_S = 10°C, ΔT = 5 ~ 8 °C)

For heat-balance method, OCR is evaluated from the change in the heat balance as shown in equation (7). Therefore, the accuracy of the OCR measurement is determined by the estimation accuracy of the heat balance. Figure 7 shows the heat balance with/without a modification of the heat transfer rate Q_{sur} between the surroundings and the experiment setup in the case of pure refrigerant. The abscissa axis is the temperature difference between the room temperature and the evaporator outlet temperature of the refrigerant. The closed and open symbols show the results with and without the modification, respectively. As shown in the figure, the heat balance with the modification of Q_{sur} is within ±0.5%, while that without the modification of Q_{sur} is within ±5%.

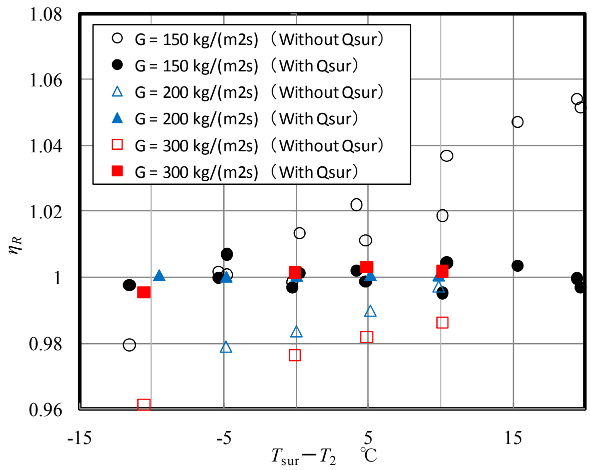


Figure 7: Heat balance with/without modification in the case of pure CO_2

Figure 8 shows the relation between the heat balance and the OCR measured using oil-volume method in the case of CO_2-oil mixtures. The solid line shows the calculation results of equation (7). As shown in the figure, measured results are slightly lower than calculated values, however, both values agree in similarity. The difference in both values is considered to be due to neglect of the sensible heat of the oil temperature change. On the other hand, if equation (7), with a modification based on the experiment data, is used for evaluation of OCR, the accuracy is estimated within ±1mass%. Therefore, the accuracy of the OCR measurement using the heat balance method is very poor for low OCR conditions, while the heat balance method is reliable for high OCR conditions.

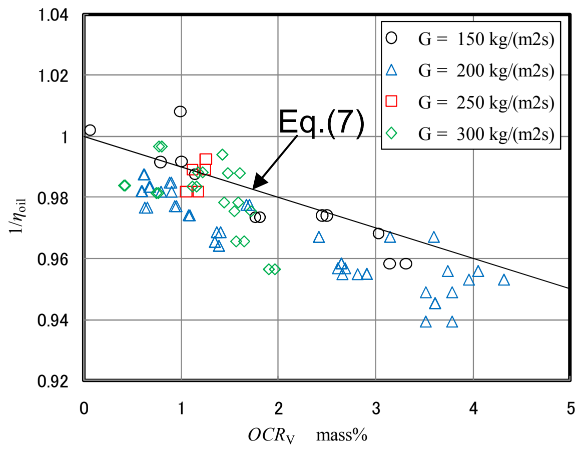


Figure 8: Relation between heat balance and *OCR_V*

For densimeter method, oil concentration is evaluated from the change in specific volume as shown in equation (10). Therefore, the accuracy of oil concentration measurement is determined by the estimation and measurement accuracy of the specific volume (or the accuracy of density). Figure 9 shows the density difference between the calculation and measurement in the case of pure CO_2 with/without modification. As shown in the figure, the density difference of pure CO_2 without modification increases with the increase in the gascooler outlet temperature. It can also be found that the maximum value of the density difference is about 9.35 kg/m^3. To reduce the density difference, a modification was introduced into the estimation equation of the density of pure CO_2. As a result, the density difference of pure CO_2 with modification is less than ±0.9 kg/m^3.

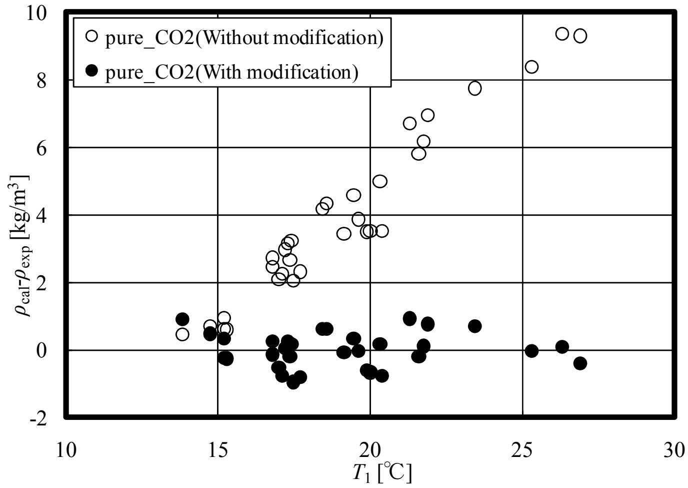


Figure 9: Relation between the density difference and the exit temperature of gascooler in the case of pure CO_2

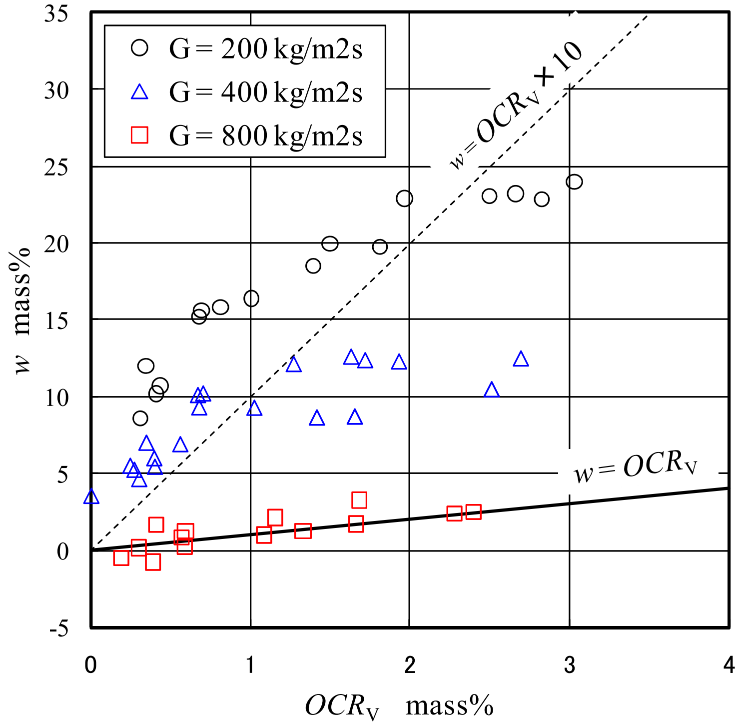


Figure 10: Relation between oil concentration and OCR_V

Figure 10 shows the relation between oil concentration obtained from equation (10) and OCR measured by the oil-volume method in the case of CO_2-oil mixtures. Symbols show the measured results, the solid line shows that oil concentration equals to OCR, and the broken line shows that oil concentration is 10 times larger than OCR. As shown in the figure, the oil concentration at mass velocity of 374 kg/m^{2}s is larger than OCR by 0-95% at *OCR* > 1 mass%, while it is nearly proportional to OCR. However, the oil concentrations at mass velocity of 94 and 187 kg/m^{2}s are not proportional to OCR, and are even 10 times larger than OCR. These results imply that oil concentration differs from OCR in the systems with immiscible oil, and the relation between oil concentration and OCR changes according to mass velocity. That is to say that oil concentration changes with the change in mass velocity even at the same OCR conditions. The change in oil concentration is considered to be caused by changes in the flow pattern of CO_2-oil mixtures.

The differences between oil concentration and OCR can be explained from their definitions: OCR is defined as the ratio of oil mass flow rate to the total one, while oil concentration (or mass fraction) is defined as the ratio (or fraction) of oil mass to the total one in a specified volume. Under a steady state condition, both mass flow rates of the refrigerant and oil are kept constant at any cross section, so that the OCR is also kept constant. While, oil concentration changes due to the change in slip ratio of oil-refrigerant, and therefore it will take different values at every different component of a system and different positions of each component. And you must notice that, due to the slip ratio changes at different conditions of the total mass flow rate or pipe dimension (type, size, shape et al.) even at a same OCR condition, oil concentration will take different values.

5 CONCLUSIONS

Experiments and analysis on measurement of oil circulation ratio (OCR) in a CO_2 heat pump system with immiscible oil were conducted, and the following results were obtained.

1. At low mass velocity and low OCR conditions, the oil-droplet method is suitable for measurement of OCR, while the measurement accuracy decreases with the increase in mass velocity and OCR.
2. The heat-balance method for OCR measurement is suitable for high OCR conditions, while the accuracy of OCR measurement is very poor for low OCR conditions. In order to improve the accuracy of the OCR measurement, it is necessary to take into account the sensible heat of oil.
3. The oil concentration is different from OCR in the system with immiscible oil, and takes a different value at a different mass velocity condition even at a same OCR condition. The densimeter method for oil concentration measurement cannot be used for measuring OCR, while it is suitable for measuring oil concentration at high oil concentration conditions.

6 NOMENCLATURE

D	diameter of the glass cylinder	m
d_{oil}	diameter of the oil droplet	m
G	mass velocity	kg/(m^{2}s)
H	height of the glass cylinder	m
h	specific enthalpy	kJ/kg
M	mass	kg
m	mass flow rate	kg/s
N	numbers of oil droplets	-
OCR	oil circulation ratio	mass%

Q	heat transfer rate	W
T	temperature	°C
ΔT	temperature of superheated	°C
t	time	s
V	volume	m^3
v	specific volume	m^3/kg
w	oil concentration ($=M_{oil}/M$)	mass%
y	solubility of CO2 in the oil	mass%
η	heat balance $\{ = Q_R/(Q_E + Q_{sur})\}$	-
ρ	density	kg/m^3

Subscript

1	exit of gascooler
2	exit of evaporator
cal	calculated
D	oil-droplet method
E	electric
exp	experimental
oil	oil or in the case of CO_2-oil mixtures
R	pure refrigerant
sat	saturation
sur	surrounding
V	oil-volume method

7 REFERENCES

ASHRAE, 1996. "ANSI/ASHRAE Standard 41.4: Standard method for measurement of proportion of lubricant in Liquid Refrigerant," Atlanta, GA.

Baustian, J.J., Pate, M.B., and Bergles, A.E. 1986. "Properties of oil-refrigerant liquid mixtures with applications to oil concentration measurement: part II – electrical and optical properties", *ASHRAE Trans.* 92 (1), pp.74–92.

Baustian, J.J., Pate, M.B., and Bergles, A.E. 1988a. "Measuring the concentration of a flowing oil–refrigerant mixture with a bypass viscometer," *ASHRAE Trans*. 94 (2), pp.588–601.

Baustian, J.J., Pate, M.B., and Bergles, A.E. 1988b. "Measuring the concentration of a flowing oil-refrigerant mixture with an acoustic velocity sensor," *ASHRAE Trans*. 94 (2), pp.602–615.

Baustian, J.J., Pate, M.B., and Bergles, A.E. 1988c."Measuring the concentration of a flowing oil- refrigerant mixture with a vibrating U-tube densimeter," *ASHRAE Trans*. 94(2), pp.571–587.

Bayani, A., Thome, J.R., and Favrat, D. 1995. "Online measurement of oil concentrations of R-134a/oil mixtures with a density flow meter," *HVAC&R Res*. 1 (3), pp.232–241.

Fukuta, M., Yanagisawa, T., Kinoshita, E., and Ogi, Y. 1999. "Measurement of concentration of refrigerant in refrigeration oil by capacitance sensor," *Trans. JSRAE*. 16 (3), pp.239–248. (in Japanese)

Fukuta, M., Yanagisawa, T., Miyamura, S., and Ogi, Y. 2004. "Concentration measurement of refrigerant/refrigeration oil mixture by refractive index," *Int. J. Refrigeration,* 27, pp.346-352.

Fukuta, M., Suzuki, T., and Yanagisawa, T. 2008. "Concentration measurement of refrigerant/ refrigeration oil mixture by sound speed", *Trans. JSRAE*. 25 (4), pp.391–400. (in Japanese)

Gao, L., and Honda, T. 2006. "Flow and heat transfer characteristics of refrigerant and PAG oil in the evaporator of a CO_2 heat pump system," *Proc. of 7th IIR Gustav Lorentzen Conference on Natural Working Fluids,* Trondheim, Norway. pp.491-494.

Gao, L., Honda, T., and Koyama, S. 2007."Experiments on flow boiling heat transfer of almost pure CO_2 and CO_2-oil mixtures in horizontal smooth and micro-fin tubes", *Int. HVAC&R Research*, Vol.13, No.3, pp.415-425.
Gao, L., Sato, M., Matsuzaka, Y., Honda, T., Takigawa, R.,and Shimizu, T. 2008. "Measurement of solubility and density of CO_2-oil mixtures in a CO_2 heat pump system", *Proc. of 2008 JSRAE Annual Conference*, pp.283-284. (in Japanese)
Hwang, Y., Radermacher, R., Hirata, T., 2008. "Oil mass fraction measurement of CO2/PAG mixture", *Int. J. Refrigeration,* 31, pp.256-261.
Katsuta, M., Takeo, N., Kamimura, I., and Mukaiyama, H. 2002. "A study on the evaporator of CO_2 refrigerant cycle," *Proc. of ACRA-2002*, Kobe, Japan. pp.67-74.
Koyama, S., Ito, D., Lee, S., Kuwahara, K., Saeki, C., and Ogawa, H. 2005. "Experimental investigation for flow boiling of pure CO_2 and CO_2-oil mixture inside horizontal copper tubes," *Proc. of IIR International Conference,* Vicenza, Italy. pp.245-252.
Kutsuna, K., Inoue, Y., Mizutani, T., Sudo, E., and Araga, T. 1991. "Real time oil concentration measurement in automotive air conditioning by ultraviolet light absorption," *SAE Technical Paper Series* 910222.
Meyer, J.J., and Jabardo, J.M.S. 1994. "An ultrasonic device for measuring the oil concentration in flowing liquid refrigerant," *Int. J. Refrigeration,* 17, pp.481-486.
PROPATH Group, 2001, "PROPATH: A program package for thermophysical properties," Ver.12.1, also see http://gibbs.mech.kyushu-u.ac.jp/propath/.
Suzuki, S., Fujisawa, Y., Nakazawa, S., and Matsuoka, M. 1993. "Measuring method of oil circulation ratio using light absorption," *ASHRAE Trans*. 99, pp.413-421.
Tanaka, S., Daiguji, H., Takemura, F., and Hihara, E. 2001. "Boiling heat transfer of carbon dioxide in horizontal tubes," *Proc. of 38th National Heat Transfer Symposium of Japan*, Saitama, Japan. pp.899-900.
Takigawa, R., Shimizu, T., Matsusaka, Y., Gao, L., and Honda, T. 2009. "Real-time measurement of oil circulation ratio in CO_2 heat pump system using optical method," *Trans. JSRAE*. 26 (2), pp.37–42. (in Japanese)