EFFECT OF PAG OIL CIRCULATION RATE ON THE HEAT TRANSFER PERFORMANCE OF AIR-COOLED HEAT EXCHANGER IN CARBON DIOXIDE HEAT PUMP SYSTEM

Shun YOSHIOKA, Hyunyoung KIM, Kazushige KASAI,
Daikin Industries, LTD., Kanaoka-cho, Kita-ku, Sakai, Osaka, Japan

Abstract: In carbon dioxide (R744) heat pump systems, PAG oil is commonly used for lubrication of the compressor, while it is reported that the presence of oil is greatly influential on heat transfer performance due to its immiscibility against R744. This paper deals with an experimental study on the heat transfer performance of fin and tube heat exchangers working with R744 while taking the effect of PAG oil into account. The experimental apparatus was designed to enable control the oil circulation rate (OCR) independently by using an independent oil circulation line from the refrigerant circuit. Two types of heat exchangers with different tubes, smooth tube and internally grooved tube, have been tested while varying the OCR in the range from nearly zero to 5 wt %. It was found that the OCR change affects significantly in the heat transfer performance at the low range of OCR in both evaporation and gas cooling. The effect of the OCR, however, is different between the smooth tube and grooved tube. For understanding of these phenomena, the oil retention rate in each heat exchanger was measured.

Key Words: ***heat exchanger, heat transfer, carbon dioxide, lubricant oil***

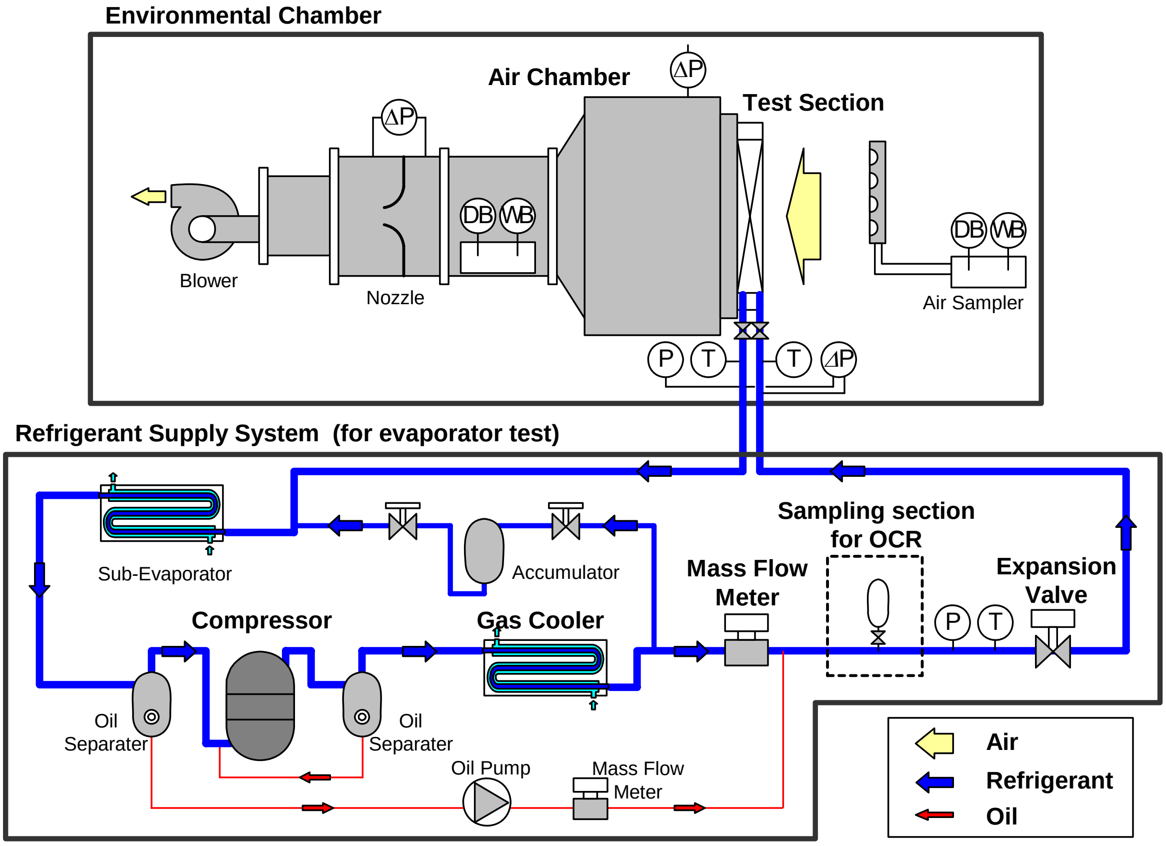
1 INTRODUCTION

In recent years, the problem of global warming is a one of great issue from an environmental point of view, and there have been many attempts to eliminate its cause. In the refrigeration and air conditioning field, there have been many studies in these regards. In the refrigeration industry, factors affecting global warming include not only emission of carbon dioxide in its operation, but also emission of refrigerant having global warming potential (GWP). Since the currently used freon refrigerant has a high GWP, many researchers are interested in using a natural refrigerant with low GWP. Carbon dioxide (R744) is one of the promising alternatives due to its low GWP. The refrigerating cycle using R744 operates in high pressure that is almost three times higher than that of R410A and forms trans-critical cycle. Since the high-pressure side works above super-critical pressure, temperature gliding is displayed in its cooling process. By using these characteristics, this cycle has been successfully commercialized for hot water supply heat pump system in Japan.

In designing a heat exchanger for a refrigerator or air conditioning system using R744, an understanding of the heat transfer performance is required. However, the heat transfer characteristics of R744 are greatly different from that of fluorocarbon due to a large difference of the working condition and its properties. Additionally, Polyalkylene glycol (PAG) is commonly used for lubricant of the compressor in R744 systems, while it is reported that the oil is relatively influential.

A few experimental studies on the heat transfer characteristics of R744 in a horizontal single tube have been reported. Hihara and Dang (2007) have measured the boiling heat transfer characteristics in a smooth tube with 1 to 6mm in an inner diameter at 4.5-36kW/m^2 in heat flux and 360-1440kg/m^{2}s in mass flux, and reported that the boiling heat transfer coefficient of R744 is strongly influenced by the heat flux but it is negligible for the mass flux in the pre-

dryout region. Katsuta et al. (2007) have measured the boiling heat transfer characteristics with PAG oil in a smooth tube with 3mm in an inner diameter. They reported that the boiling heat transfer coefficient of two phase flow decrease with the presence of PAG. They suggested a correlation for the heat transfer coefficient with PAG in terms of the oil circulation rate (OCR). Higashiue et al. (2007) have measured the heat transfer characteristics of R744 with PAG in super critical gas cooling inside a inner micro-fin copper tube with 6mm in an outer diameter at 8 and 10MPa in pressure, 340-660kg/m^{2}s in mass velocity and 0.06-2.26% in the mass percent concentration of PAG. They reported that the heat transfer coefficient in gas cooling decreases with the presence of PAG.
However, the data provided from these open literatures are not sufficient in designing actual heat exchangers, since these data were obtained under different conditions of the range in which the heat exchanger is operated within the air conditioning system. In addition, it is necessary to take into account of the effect of inner surface geometry change caused by the mechanical tube expanding, which is essential in reducing the thermal contact resistance between fin collars and tubes.
The objective of this study is to provide the experimental data on heat transfer in reference to designing heat exchangers applied to R744 heat pump systems. This paper deals with an experimental study on the heat transfer performance of fin and tube heat exchangers utilizing R744 as a refrigerant taking the effect of PAG into account. The experimental study for the heat transfer of fin and tube heat exchangers with two different types, smooth tube and grooved tube, at a varying the OCR was carried out. The heat transfer performance and oil retention rate of each heat exchanger for both evaporator and gas cooler was measured in order to understand the difference in heat transfer characteristics with a change in OCR and tube type.



DB : Dry bulb temperature (Pt100 sensor)
WB : Wet bulb temperature (Pt100 sensor)
T : Tempereture (Pt100 sensor)
P : Pressure (Pressure gauge)
ΔP : Pressure drop (Differencial pressure gauge)

Figure 1: Schematic diagram of experimental apparatus

2 EXPERIMENT

2.1 Experimental apparatus

Figure 1 shows the schematic diagram of the experimental apparatus. This apparatus consists of a refrigerant supply system, an air chamber that can control air velocity for the test heat exchanger, and an environmental chamber that can control air temperature and humidity to adjust each experimental condition. The refrigerant supply system, which has a compressor for the R744 super critical cycle, was designed enabling control R744 conditions such as the pressure, temperature, quality, and mass flow rate flowing into the test heat exchanger. In addition, it is able to control the PAG oil circulation rate (OCR) by using a separated oil circulation line, which is prepared independently from the refrigerant circuit.

2.2 OCR measurement

It is known that PAG flows separately from the R744 main flow, since PAG is almost immiscible against R744. In addition, the flow pattern of the mixture will vary with the refrigerant condition. Therefore, it seems that the accurate measurement of the OCR is not easy.
Several methods for measurement of the OCR of PAG in R744 circuit have been reported so far. Higashiue et al. (2007) used the method of immediately collecting the refrigerant in the refrigerant circuit. They prepared a sampling tube with two normally opened air actuated valves at both ends and a bypass loop with a normally closed actuated valve in the refrigerant circuit, and reversed each valve at the same time while driving the system and measured weight of refrigerant and oil. Gao and Honda (2006) used the method that measures quantities of the oil visually at the place after an evaporator. They set up a sight-glass chamber that was able to observe the behaviour to which oil fell in the droplet, and counted fall frequency and size of the oil droplet during a certain time interval.
In this study, the OCR was measured by collecting the refrigerant into the sampling tank, which was set in the circuit, referring to ASHRAE standard (1996). The measuring point is the line just next to the gas cooler and before the expansion valve in both the evaporator test and the gas cooler test. In that point, pressure and temperature of the refrigerant is about 10MPa and 20 to 30 °C respectively, and the density of PAG becomes near that of R744. Therefore, it is seemed that the oil flows relatively homogeneously in R744, and it is able to be caught the oil and R744 accurately. Incidentally, the oil behaviour in the refrigerant before the point can be observed in a tube type sight glass. To collect the refrigerant, considering the oil retention in the connecting tube, the vacuumed sampling tank and another sub-tank was set above the main flow tube as shown in figure 2. And then, the refrigerant was caught into the sampling tank just after cleaning the connecting tube by using the sub-tank. The volume of the sampling tank is 150cc, and an electronic scale was used to measure the weight.

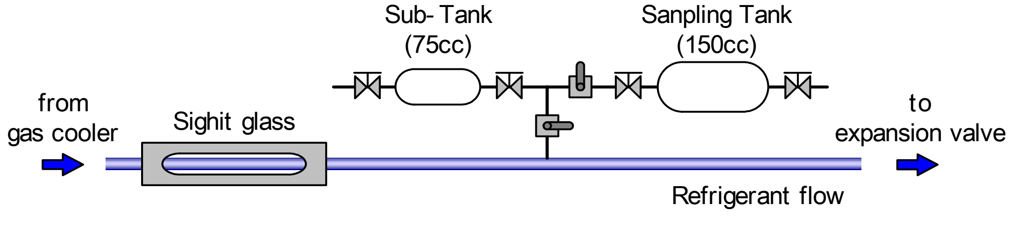


Figure 2: Details in OCR sampling section

2.3 Test heat exchanger

Table 1 shows the specifications of the test heat exchangers. The test heat exchangers are composed of copper tubes with a 7mm outer diameter and aluminium fins with a 0.1mm thickness, which are generally used in actual air conditioners. In order to evaluate detailed R744 heat transfer characteristics of a heat exchanger in this study, two types of heat exchangers with different shaped tubes were prepared, one with smooth surface tubes, and the other with inner grooved tubes that have micro fins for enhancing heat transfer generally utilizing Fluorocarbon refrigerant.

Table 1; Specification of test heat exchangers

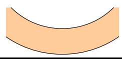
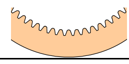
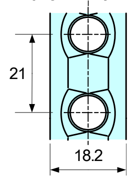
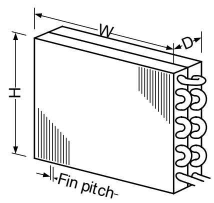
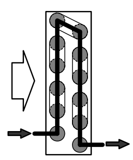
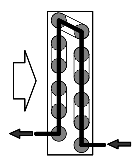
			HEX A	**HEX B**
Tube	Type		Smooth tube 	Grooved tube 
	Outside diameter	mm	7.0	7.0
	Bottom wall thickness	mm	0.9	0.6
	Number of grooves	-	-	60
	Fin height	mm	-	0.15
	Apex angle	deg	-	60
	Lead angle	deg	-	18
Fin	Type		Wavy fin (hydrophilic coated) 	
	Fin pitch	mm	1.3	
Size	W×H×D	mm	400×252×36.4 	
	Step×Row	-	12×2	

Table 2; Experimental conditions

				Evaporator	**Gas cooler**
Air	Dry bulb / Wet bulb		°C	27 / 19	20 / 15
	Velocity	V_a	m/s	1.0	1.0
Refrigerant (R744)	Pressure	P	MPa	4.18	10.00
	Inlet quality	x_i	-	0.2	-
	Super heat temp.	T_{sh}	K	3.0	-
	Inlet temperature	T_i	°C	-	90
	Outlet temperature	T_o	°C	-	30
	Flow pattern			 Parallel flow	 Counter flow
Oil (PAG)	Oil circulation rate	*OCR*	wt%	0 ~ 5	

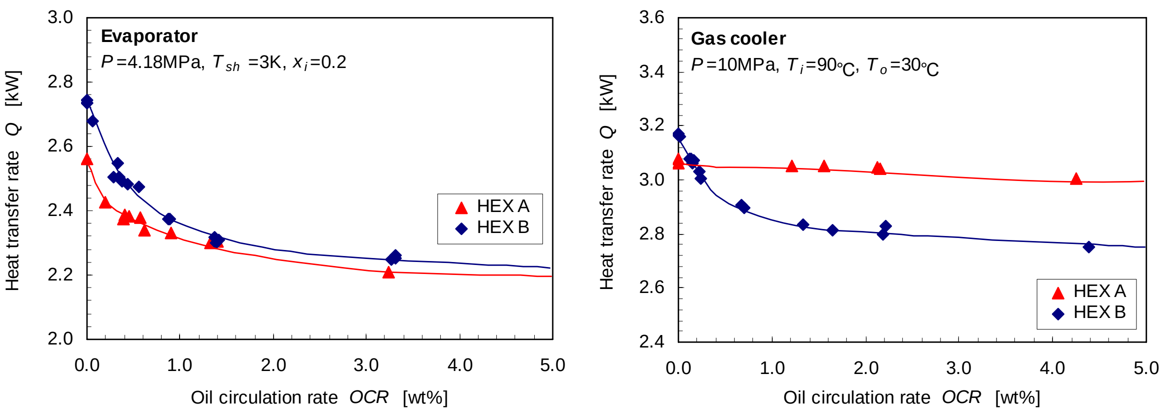
2.4 Experimental condition

Table 2 shows the experimental conditions. Each value was adjusted to actual operating conditions for the heat exchanger of an inside unit of an air conditioner. The OCR is varying within the range from nearly zero to 5wt%. The refrigerant pressure is adjusted at the vapor side in each test, therefore, that is outlet side in the evaporator test, or inlet side in the gas cooler test. The refrigerant outlet condition such as the super heated temperature in the evaporator test or outlet temperature in the gas cooler test is adjusted by changing the refrigerant flow rate.
Controlling to adjust these experimental conditions in each test, data of the heat transfer rate and pressure drop of the air and refrigerant are measured after confirmation of a constant state. The heat transfer rate is calculated from the air side enthalpy and flow rate, which is confirmed less than ±3% difference from the calculated value at the refrigerant side enthalpy and flow rate in each test.

3 EXPERIMENTAL RESULT AND CONSIDERATION

3.1 Experimental result of heat transfer rate

Figure 3 shows the experimental results. Heat transfer performances against oil circulation rate were measured under the conditions of evaporator and gas cooler.
In the evaporator test shown on Figure 2(a), it is clear that the heat transfer performance decreases as OCR increases in both HEX A and HEX B. Especially, that of HEX B using grooved tubes decreases as much as 13% at only 0.5wt% oil mixture, and approaches to that of HEX A using smooth tubes. In the gas cooler test shown on Figure 2(b), it is found that the performance of HEX A doesn't change against OCR, however, HEX B decreases greatly and becomes less than that of HEX A at more than 0.4wt% of OCR.
From these experimental results, it is confirmed that the OCR change affects significantly on the heat transfer performance at the low range of OCR.



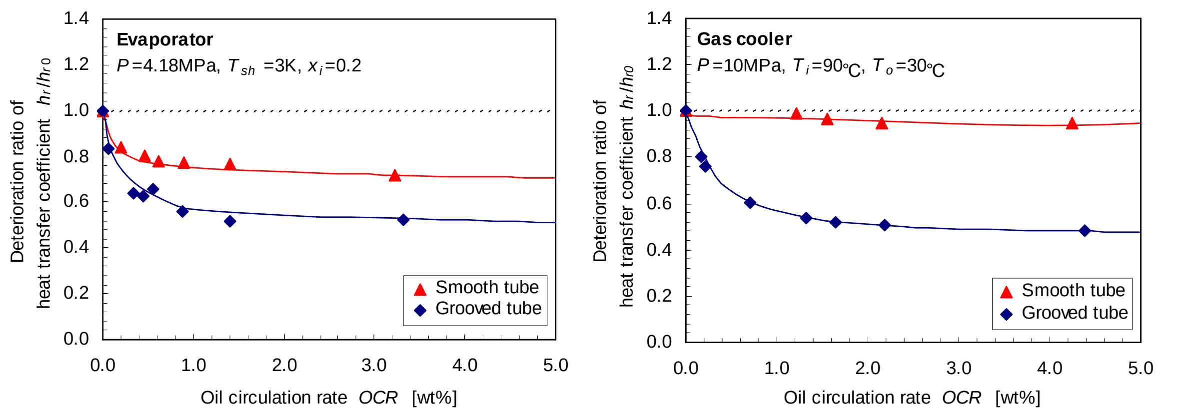
(a) Evaporator test **(b) Gas cooler test**

Figure 3: Heat transfer rate versus oil circulation rate

3.2 Heat transfer coefficient of R744

The heat transfer performance of the heat exchanger mainly consists of the heat transfer coefficient of the air side and that of refrigerant side. Because the heat transfer coefficient of the air doesn't change with the change of the OCR, the deterioration of the heat transfer rate of the heat exchanger is caused by the deterioration of the heat transfer coefficient of the

refrigerant flowing inside of the tube. Using data from the heat transfer rate shown on Figure 3, to calculate refrigerant heat transfer coefficient was attempted.
Using a calculation tool which can calculate heat transfer performance of air-cooled heat exchangers by the tube by tube method, and installing an air side heat transfer coefficient that had been measured in advance by using Wilson-plot method, the refrigerant heat transfer coefficient was calculated to match the calculation value of the heat transfer rate and pressure drop to the corresponding experimented value. To determine the shape of the refrigerant heat transfer coefficient against the quality or the temperature of the refrigerant, it was decided to utilize Gnielinski (1976) correlation to single-phase region and Kandlikar (1990) correlation to two-phase region by multiplied moderate coefficient. Using this calculation method, two-phase mean heat transfer coefficient in evaporator and single-phase mean heat transfer coefficient in gas cooler was calculated.
Figure 4 shows the calculated heat transfer coefficient of refrigerant divided by that of oil less. It is found that the effect of OCR on the heat transfer coefficient is different between the smooth tube and grooved tube. The heat transfer coefficient of grooved tube decreases to a half with over 1wt% of OCR, however, it is found that the smooth tube doesn't change so significantly with OCR.



(a) Evaporator test **(b) Gas cooler test**

Figure 4: Heat transfer coefficient of refrigerant versus oil circulation rate

3.3 Oil retention in heat exchanger

In order to investigate the decline of heat transfer performance of heat exchanger by oil mixture, the oil retention rate in the heat exchangers were measured. In each test, after confirmation of the constant state, ball valves set up on each end of the test heat exchanger make refrigerant flow intercepted at the same time. The test heat exchanger is detached from the system, and R744 in the heat exchanger is emitted, and the heat exchanger is measured the weight and calculated oil quantity. Furthermore, taking the oil quantity corresponding to refrigerant quantity from that value, oil retention rate m [g/m^2] is calculated as:

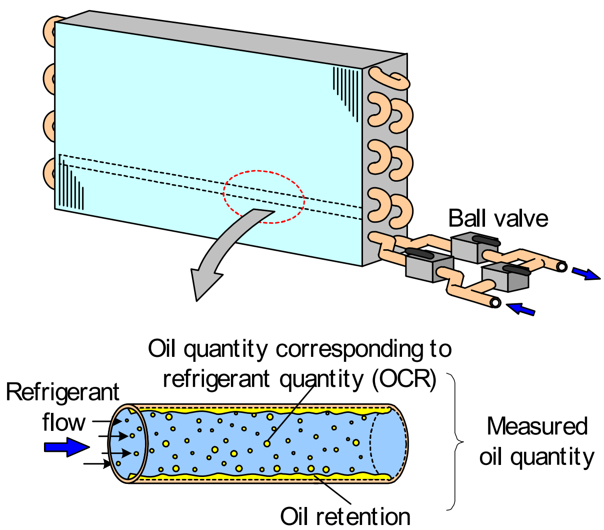
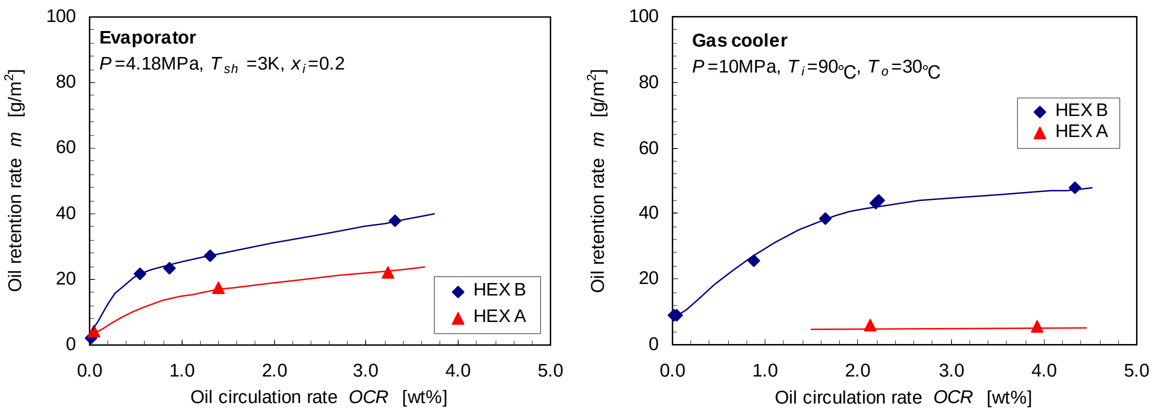


Figure 5: Measurement of oil retention rate in heat exchanger

$$m = \frac{\left(M_0 - \rho_r \, V \, \frac{OCR}{100} \cdot 1000 \right)}{A_i} \qquad (1)$$

where M_0 is measured oil quantity [g], ρ_r is density of refrigerant [kg/m^3], V is inner volume [m^3], and A_i is inner surface area of heat exchanger [m^2].
Figure 6 shows the results of oil retention rate versus OCR. From this figure, it can be found that a large quantity of oil remains in the heat exchanger with a slight oil mixture. Furthermore, it is found that oil retention rate of HEX B is larger than that of HEX A, especially that of gas cooler is larger, and the variation of the oil retention rate becomes small with over 1wt% of OCR.
From these results, it can be supposed that the oil retention rate in the tube of the heat exchanger can possibly be a factor of deterioration of the refrigerant heat transfer coefficient shown on Figure 4. It is found that the deterioration of the heat transfer coefficient of the grooved tube with higher oil retention rate is larger than that of the smooth tube.



(a) Evaporator test **(b) Gas cooler test**

Figure 6: Oil retention rate in heat exchanger versus oil circulation rate

4 CONCLUSION

For the design of the air-cooled heat exchanger in R744 heat pump system, the heat transfer performance of fin and tube heat exchangers flowing R744 with PAG oil. From the analysis of the experimental results, it can be found that the heat transfer performance of the fin and tube heat exchanger declines greatly by accumulating PAG oil in the tube when R744 including slight PAG oil emitted from the compressor flows into the heat exchanger. Therefore, it can be found that it is necessary to pay attention to the effect of PAG oil circulation rate on the heat transfer performance in designing heat exchangers.

5 REFERENCES

Hihara, E. and Dang, C. 2007. “Boiling heat transfer of carbon dioxide in horizontal tubes”, *Proceedings of ASME-JSME Thermal Engineering Summer Heat Transfer Conference*, Vancouver, Canada, HT2007-32885

Katsuta, M., Okuma, K., Kishi, S., and Miyachi N. 2007. “The evaporating heat transfer characteristics on refrigeration cycle of CO_2 in the refrigerator oil mixture state”, *Proceedings of 2007 JSRAE Annual Conference*, E103 (in Japanese)

Higashiue, S., Kuwahara, K., Yanachi, S. and Koyama, S. 2007. "Experimental investigation on heat transfer characteristics of supercritical carbon dioxide inside a horizontal micro-fin copper tube during cooling process", *Proceedings of ASME-JSME Thermal Engineering Summer Heat Transfer Conference,* Vancouver, Canada, HT2007-32724

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", *Proceedings of 7th IIR-Gustav Lorentzen Conference on Natural Working Fluids,* Trondheim, Norway

ANSI/ASHRAE Standard 41.4-1996 (RA 2006). "Standard Method for Measurement of Proportion of Lubricant in Liquid Refrigerant," American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta.

Gnielinski, V. 1976. "New equations for heat and mass transfer in turbulent pipe and channel flow", *International Chemical Engineering,* Vol.16, pp.359-368.

Kandlikar, S.G. 1990. "A general correlation for saturated two-phase flow boiling heat transfer inside horizontal and vertical tubes", *Transactions of the ASME, Journal of Heat Transfer* 112, pp.219-228.