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AN EXPERIMENTAL INVESTIGATION OF OIL RETENTION CHARACTERISTICS IN CO_2 AIR-CONDITIONING SYSTEMS

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ABSTRACT

In a refrigeration cycle, some of the oil circulates and resides in cycle components. The worst scenario of oil circulation in the cycle is where a large amount of oil is retained outside the compressor. High oil retention causes system performance and reliability degradations. The purpose of this study is to experimentally clarify oil retention and pressure drop characteristics due to the presence of oil in CO_2 air-conditioning systems. In this study, the oil injection-extraction test method was adopted to examine the oil distribution for various oil circulation rates in CO_2 air-conditioning systems with CO_2 and PAG oil. The test facility consisted of a refrigeration cycle and an oil loop, which had oil injection ports and an oil extractor. The oil retention volume in each component was determined by the differential injection method that measures the difference of the oil retention volume between the inlet and outlet of each component. The oil retention test was performed at an evaporator, a gas cooler, and suction line at four different refrigerant mass flow rates varying from 14 g/s to 27 g/s and a range of oil circulation rate from 1 to 7 wt.%.

NOMENCLATURE

Roman Symbol

AB	Alkylbenzene
CFC	Chlorofluorocarbon
HCFC	Hydrochlorofluorocarbon
HFC	Hydrofluorocarbon
MFR	Mass Flow Rate, g/s
MO	Mineral Oil
PAG	Polyalkylene Glycol
PDPF	Pressure Drop Penalty Factor
POE	Polyolester
R	Tube Radius, m

Greek Symbol

δ	Oil Film Thickness, m

1. INTRODUCTION

The major role of refrigerant oils is lubricating the moving parts of the compressor. In a refrigeration cycle, a small portion of the oil circulates through the system by the viscous force induced by the refrigerant flow, while most oil stays in the compressor [1, 2]. Successful operation of the system requires that the circulating oil in the system components return to the compressor; otherwise, it causes a lack of proper lubrication and results in the compressor failure. Because oil retention can affect performance and reliability in refrigeration systems, it receives continuous attention from manufacturers and operators.

Introducing HFC refrigerants as alternative refrigerants for CFCs and HCFCs has raised a refrigerant and oil miscibility issue. Relate to this issue, several research results on the oil return characteristics of miscible and immiscible pairs of refrigerant/oil mixtures have been published as summarized below. Sundaresan and Radermacher [3] experimentally investigated the oil return characteristics of R-407C/MO in heat pumps and compared them with those of R-407C/ POE and R-22/MO. Measuring the oil level in a compressor through the vertical sight glass revealed that a significant amount of immiscible oil was present in the system outside of the compressor. Sumida et al. [4] tested R-410A/AB to evaluate oil return characteristics. They reported that the R-410A/AB pair showed reliable oil return characteristics. Hwang et al. investigated the oil return characteristics of R-134a with AB and MO oils in a vertical upward suction line of the freezer [5, 6]. They suggested an oil injection-extraction method to measure the oil accumulation volume in the suction line, and the mean oil film thickness ratio was calculated as a result of the oil volume accumulated in the tube. However, these studies neither quantify the oil volume retained in the systems, nor provide the oil distribution information.

Due to the global warming potential of HFC refrigerants, CO_2 has recently been reconsidered as a possible refrigerant in air-conditioning and heat pump applications. As CO_2 garners an attention, several research results on the proper oil selection and CO_2/oil mixture properties have been published [7-9]. However, oil retention in CO_2 air-conditioning systems has not been reported on yet in the open literature.

The objective of this study is to experimentally clarify the oil retention behavior in CO_2 air-conditioning systems to answer the following questions: where is the missing oil from the compressor and how much oil is residing outside the compressor?

2. TEST SETUP

The oil retention test was conducted with a modified CO_2 automotive air-conditioner test facility. The test facility for the oil retention mainly consists of a refrigeration loop and an oil loop.

Refrigeration Loop

A schematic of the refrigeration loop of the CO_2 system is shown in Figure 1. The refrigeration loop mainly consists of a variable speed compressor driven by an electric motor, a manually controlled expansion valve, a gas cooler, and an evaporator. The oil separator was installed at the compressor discharge to minimize the oil discharge to system components. Type T thermocouples were provided to measure the temperature at each system component. A mass flow sensor using the Coriolis effect was installed at the gas cooler outlet to measure the refrigerant mass flow rate. The absolute and differential pressure transducers were installed at each cycle component to measure absolute pressures and pressure drops across each component.

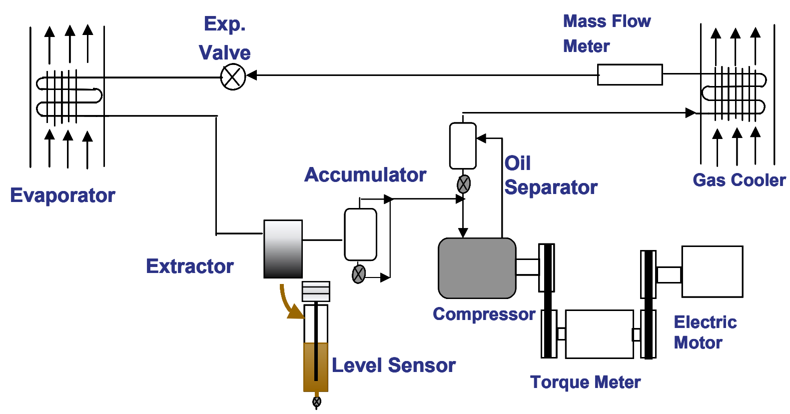

Figure 1 CO_2 Automotive Air-Conditioning System

Oil loop

As shown in Figure 2, a separate oil loop was installed parallel to the refrigeration loop in the test facility for the following two purposes:

- Inject the oil into the test section at the desired oil circulation rate;
- Extract the oil from the test section and measure the oil volume extracted.

Initially 1.5 liters of PAG oil, whose viscosity and density are 43 cSt at 40 °C and 996 kg/m^3 at 25 °C, respectively, were charged at the oil reservoir. The variable speed gear pump controlled by the DC motor was installed next to the oil reservoir in order to inject the oil into the system, and the mass flow meter was installed just before the oil injection port to measure the amount of oil injected. The check valve was installed at the injection port to prevent reverse flow from the refrigeration loop into the oil

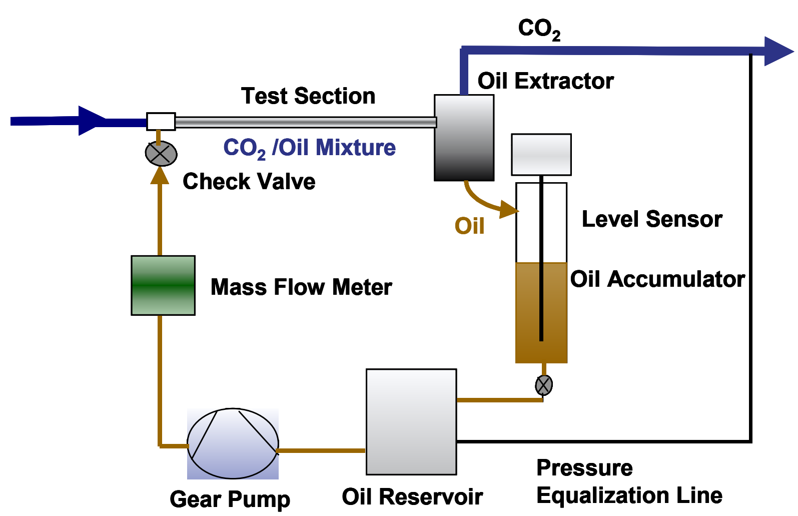

Figure 2 Schematic of Oil Loop

loop. While the oil injection ports were installed at the inlet and outlet of the heat exchangers, the helical type oil extractor, whose oil extraction efficiency is around 85 to 100% depending upon the refrigerant mass flow rate, was placed at the suction line before the suction accumulator in order to effectively extract the injected oil. The extracted oil flows down to the oil accumulator by gravitation. Then the extracted oil volume in the oil accumulator was measured by the level sensor, which was installed inside the oil accumulator.

The principle of the oil injection and extraction method is shown in Figure 3. In Figure 3, a solid line indicates the oil volume injected into the test section. A dotted line (line 1) indicates the oil volume extracted by the oil extractor. There is an initial time delay between the oil injection and extraction, which is caused by the initial oil filming between the injection port and the oil extractor. After the initial time delay, the oil film accumulation in the heat exchanger and tube reaches its steady state. Lines 2 and 1 represent the volume of oil extracted when the extractor efficiency is 100% and less, respectively. If the oil extractor efficiency is less than 100%, the oil extraction line is not parallel to the oil injection line as represented by line 1, since the part of the oil returned to the extractor bypasses the accumulator. The vertical distance between the oil injection line and line 2 indicates that the oil volume has been retained in the test section. Therefore, in each test, the measured oil volume (line 1) is calibrated into line 2 to compensate for the extractor efficiency.

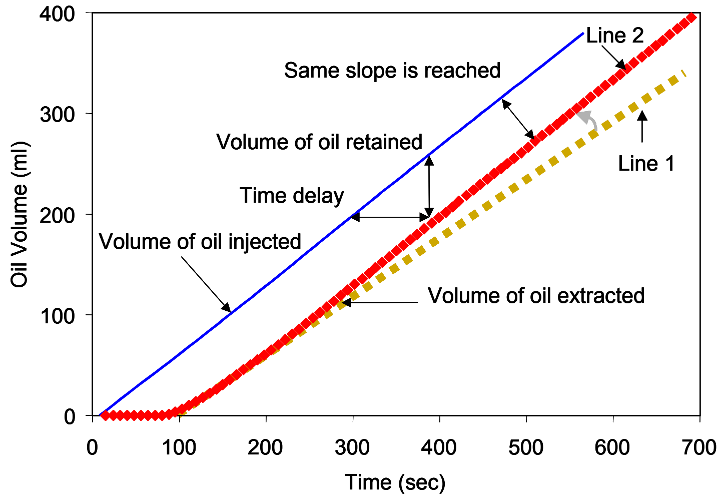

Figure 3 Oil Retention Characteristics

3. EXPERIMENTAL PROCEDURE

When the refrigeration cycle reaches its steady state and the oil level in the oil accumulator is saturated, the oil mass flow rate is set to the desired value. Then, the oil is injected into the test section by the gear pump. The oil flow rate and density are measured by the oil mass flow meter that is installed before the oil injection port. The level sensor in the oil accumulator, which enables the on-time measurement of the oil volume change rate, measures the oil volume flow rate extracted by the oil extractor. The oil injection test is continued until the oil volume change rate in the oil accumulator reaches its steady state. During the oil injection test, the refrigeration system is kept running.

The oil circulation rate, which is defined as the ratio of the mass flow rate of the oil to that of the refrigerant/oil mixture, was varied from 1 to 7 wt.%. The refrigerant mass flow rate was varied from 14 g/s to 27 g/s to investigate the effect of the refrigerant flow rate on the oil retention. The refrigerant mass flow rate was selected based on the compressor idling/driving conditions. However, since the pressure drop across the oil extractor was too high at driving conditions (1800 RPM), the range of the compressor RPM tested was from 600 to 1450 RPM. The pressure was measured at the gas cooler inlet/outlet, evaporator inlet/outlet and extractor inlet to examine the oil retention effect on the pressure drops across the heat exchangers. To investigate the oil retention in the evaporator, the oil was injected both at the evaporator inlet and outlet using the gear pump. While the evaporator inlet pressure was kept at 4 MPa during all tests, the evaporator inlet vapor quality in this study was varied from 0.50 to 0.85 depending upon the refrigerant mass flow rate.

4. RESULTS

Figure 4 compares the oil retention volume at various oil circulation rates when the oil was injected before and after the evaporator. The lower fitted curve in Figure 4 shows the oil retention volume from the evaporator outlet to the oil extractor, which means the oil retention volume at the suction line, and the upper fitted curve represents the oil retention volume from the evaporator inlet to the oil extractor. Therefore, the oil volume retained in the evaporator can be determined by the difference between the two fitted curves.

Figure 5 shows the oil retention volume in the evaporator at various oil circulation rates up to 5 wt.%. In the case of the refrigerant mass flow rate of 14 g/s, the oil volume retained in the evaporator increased from 23 ml to

28 ml as the oil circulation rate increased from 1 to 5 wt.%. For the refrigerant mass flow rates of 20 g/s, the oil retention volume in the evaporator was increased from 8 ml to 16 ml, which is much less than that of the refrigerant mass flow rate of 14 g/s. When the refrigerant mass flow rate was further increased to 27 g/s, the oil retention volume was similar to the case of 20 g/s. This means that the minimum oil retention volume may exist in the evaporator.

The effect of the evaporator inlet vapor quality on the oil retention can be seen in Figure 6. As shown there, the larger volume of the oil is retained for the higher inlet vapor quality, 0.85 compared to 0.75. The local liquid viscosity in the oil rich film is responsible for the oil retention difference in the evaporator. Since the evaporation process is almost completed at the higher quality region, the liquid-phase oil/CO_2 solution would have less liquid CO_2, which will increase the local liquid viscosity. Moreover, since CO_2 solubility in the oil decreases as the increase of degree of superheating at the superheated region, the local liquid film viscosity is higher at the superheated region than at the lower quality region. Since a greater portion of the evaporator is in the high quality and superheated region for the higher inlet quality, the oil retention is higher in the evaporator.

The oil volumes retained in the heat exchangers for two refrigerant mass flow rates, 14 g/s and 20 g/s, are compared in Figure 7. For the refrigerant mass flow rate, 14 g/s, at 5 wt.% of oil circulation rate, the oil volume retained in the gas cooler was about 12 ml, which is quite small as compared to 28 ml in the evaporator. The reasons for the lower oil retention at the gas cooler are the lower oil viscosity and higher refrigerant mass flux at the gas cooler than at the evaporator. It is clear that the oil retention volume in heat exchangers decreases as the refrigerant mass flow rate increases, and the oil retention volume in the gas cooler is negligible in the case of the higher refrigerant mass flow rate.

Parameters affecting the oil retention at system components are shown in Table 1. Due to the higher refrigerant mass flux at the suction line, the oil film thickness ratio (δ/R) of the suction line is less than that of the evaporator. Since the internal volume of the suction line is larger than that of the evaporator, the oil retention volume at the suction line is larger than that at the evaporator in spite of higher oil film thickness ratio.

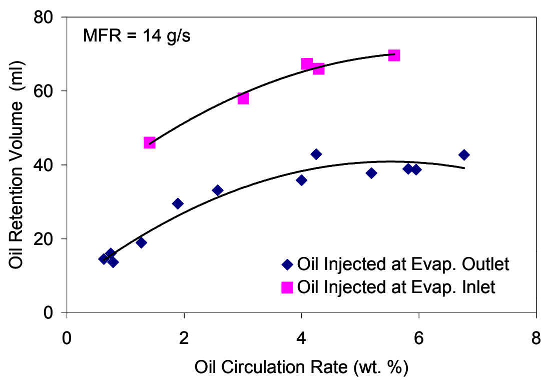

Figure 4 Oil Retention Volume

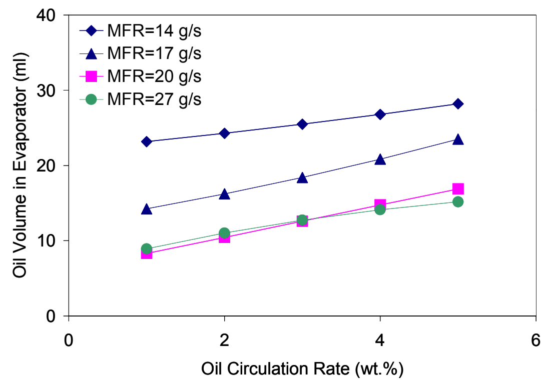

Figure 5 Oil Retention in the Evaporator

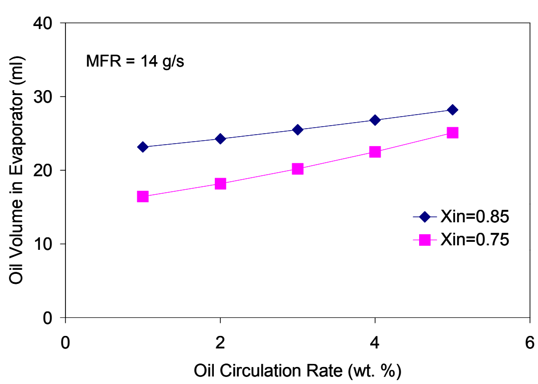

Figure 6 Effects of Inlet Vapor Quality on Oil Retention of Evaporator

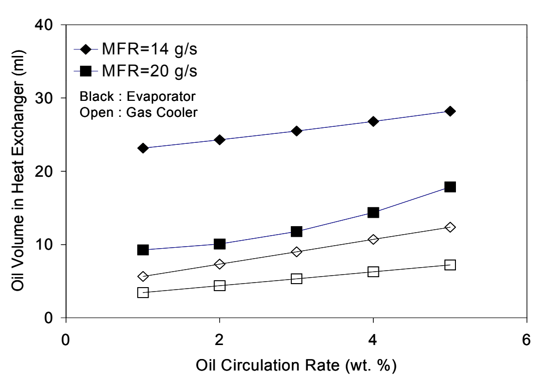

Figure 7 Oil Retention in Heat Exchangers

Table 1 Summary of Test Condition (MFR_{ref}=14g/s)

Component	Refrigerant mass flux (kg/m^2s)	δ/R	Internal volume (ml)	Oil retention volume (ml)
Suction line	290	0.12	176	41
Evaporator	70	0.19	80	28
Gas Cooler	110	0.04	165	12

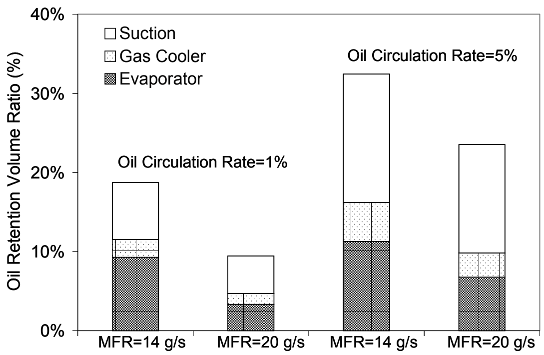

Figure 8 Oil Distributions in the System

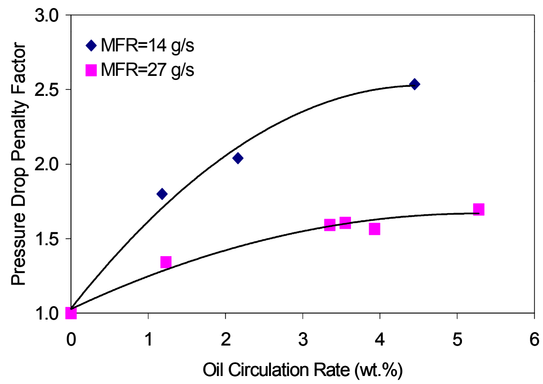

Figure 9 PDPF at the Evaporator

The oil distribution in the system is shown in Figure 8 for two different oil circulation rates and refrigerant mass flow rates. The oil retention volume ratio in the heat exchangers and suction line is defined as the ratio of the oil retention volume in the system components to the oil volume charged initially in percentage. For the refrigerant mass flow rate, 14 g/s, 9 to 11% of the total oil volume was retained in the evaporator under 1 to 5 wt.% of oil circulation rates. On the other hand, only 2 to 5% of the total oil volume was retained in the gas cooler. In the suction line, a relatively higher oil volume was retained compared to the evaporator and gas cooler: 7 to 16% and 5 to 14% of the total oil volume were retained for the refrigerant mass flow rates 14 g/s and 20 g/s, respectively. As a result, 30% of the total oil volume was retained in the evaporator, the gas cooler, and the suction line for the refrigerant mass flow rate 14 g/s, at 5 wt.% of oil circulation rate. It is expected that the oil, which is retained in neither the heat exchangers nor the suction line, would stay in either the oil separator or the accumulator in the refrigeration system. Minimizing the length of the suction line could reduce the oil retention amount at the suction line.

The pressure drop penalty factor (PDPF) of the evaporator is shown in Figure 9 for two different refrigerant mass flow rates. For the refrigerant mass flow rate 27 g/s, the PDPF increased up to 1.7 at 5 wt.% oil circulation rate. The PDPF of the lower refrigerant mass flow rate, 14 g/s, was 65% higher than that of refrigerant mass flow rate 27 g/s because of the larger oil retention in the evaporator. Basically, the gas refrigerant/oil mixture flows in the tube can be divided into two different flow regimes: high-speed gas refrigerant flow at the core and viscous flow of liquid oil film along the wall. The interfacial shear stress depends upon the difference between the refrigerant gas velocity and liquid oil film velocity. These velocities can be varied by the oil amount retained in the tube. Thus, the pressure drop, which is the function of the interfacial friction factor, is affected by the oil retention in the tube. This reasoning agrees with the empirical correlation [10], which shows that the increase of the interfacial friction factor increases by the increase of oil film thickness.

5. CONCLUSIONS

The oil retention volume in heat exchangers and suction lines was experimentally investigated through the oil injection-extraction method. As a result, the oil distribution in a CO_2 automotive air-conditioning system was found. From the experimental results and observations, the following conclusions were obtained:

- The oil retention volume in the evaporator increases as the oil circulation rate increases and the refrigerant mass flow rate decreases.

- However, the oil retention volume in the evaporator does not change when the refrigerant mass flow rate is higher than 20 g/s.
- Higher inlet vapor quality in the evaporator results in higher oil retention since a greater portion of the evaporator is in the high quality and superheated region.
- The oil volume retained in the gas cooler is smaller than in the evaporator because of the lower oil viscosity and the higher refrigerant mass flux as compared to those at the evaporator.
- 10% of the oil initially charged stays in the heat exchangers and the suction line for the higher refrigerant mass flow rate, 20 g/s, at 1 wt.% of oil circulation rate.
- Higher oil retention results in higher pressure drop.

ACKNOWLEDGMENTS

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