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AN EXPERIMENTAL INVESTIGATION ON FLOW CHARACTERISTICS OF REFRIGERANT/OIL MIXTURE IN VERTICAL UPWARD FLOW

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ABSTRACT

Oil return from the evaporator to the compressor suction port is an important requirement. It is affected by the refrigerant/lubricant properties, gas velocities and piping geometry. The refrigerant R-134a has successfully replaced R-12 in household refrigerators and freezers. This paper describes a test method to estimate the mean oil film thickness and to observe the flow pattern in vertical upward flow in a R-134a suction line. The test facility to investigate a wide range of refrigerant and oil flow rates had been built. Three kinds of oils (mineral, two alkyl-benzenes) have been tested with R-134a in this facility. The results show an upward net oil flow for all oils investigated regardless of the miscibility between refrigerant and oil. The refrigerant and oil mixture flow as either churn flow or annular flow in the vertical upward suction line of the refrigeration system. The mean oil thickness and flow patterns are summarized for each case.

NOMENCLATURE

Roman Symbol

AB	Alkylbenzene
ASHRAE	American Society of Heating, Refrigeration and Air Conditioning Engineers
CFC	Chlorofluorocarbon
HCFC	Hydrochlorofluorocarbon
HFC	Hydrofluorocarbon
ISO	International Standards Organization
MFR	Mass Flow Rate
MO	Mineral Oil
MOFTR	Mean Oil Film Thickness Ratio
POE	Polyol Ester
R	Tube Ratio
VFR	Volume Flow Rate

Greek Symbol

δ	Oil Film Thickness

1. INTRODUCTION

In a refrigeration cycle, a small portion of oil circulates with the refrigerant through the cycle components while most of the oil remains in the compressor. The concentration of oil in the circulating refrigerant/oil mixture affects the refrigerant side heat transfer as well as the reliability of the compressor [1, 2]. The introduction of HFC refrigerants in the market as the replacement for CFCs and HCFCs has raised the issue of miscibility of the oil in the refrigerant. Though polyol-ester (POE) oils were introduced as the leading candidate oils for HFC refrigerants, POE oils pose some challenges: low reliability due to its high hygroscopicity as compared to the mineral oil, low refrigerant/oil mixture viscosity due to the high solubility of HFC refrigerant in POE oil and high cost [3, 4]. Therefore, other options using HFC refrigerants with immiscible oil or partially miscible oils such as alkybenzene (AB) and mineral oil (MO) are of interest. Although AB and MO are immiscible with HFC refrigerants, these oils are chemically stable and of lower cost. Research has been conducted to evaluate the oil return of HFC refrigerants with immiscible oils. Sundaresan and Radermacher [5] investigated oil return characteristics in residential heat pumps experimentally. The oil level in a compressor was measured for R-407C and R-22 with POE and MO. In the case of R-407C/MO, some amounts of oil were logged in the system outside of the compressor under ASHRAE test conditions. Sumida et al. [6] tested R-410A and AB to observe the flow pattern in the liquid line and to compare the cycle performance. This experiment showed that R-410A and the AB mixture had reliable oil return characteristics. An empirical correlation in upward flow for predicting MO return with R-12 and R-22 were studied by Jacobs et al. [7], but this study did not account for the viscosity change of oil and oil miscibility. However, Mehandale [8] conducted an experimental and analytical study of oil return failure conditions in single and two-phase regimes for HFC refrigerants with miscible and immiscible oil in a vertical tube. In spite of previous studies on experimental and analytical verifications of oil return characteristics by other investigations, the data is not sufficient to understand the influence of oil flow patterns and oil film thickness.

The worst scenario for oil circulation in a cycle is the case that a gas refrigerant/oil mixture flows upward in a vertical tube since the refrigerant has to overcome the gravitational force to carry the oil upward by the viscous force. The oil viscosity at the evaporator outlet is relatively higher than that of the condenser outlet because of lower solubility of the refrigerant in the oil. Thus, to investigate how much oil is stored in the system is an important issue. The objective of this study is to investigate the flow characteristics of specific refrigerant/oil mixtures experimentally in vertical upward flow under suction line conditions and to provide oil return characteristics such as mean oil film thickness for residential refrigerators and freezers.

2. TEST SETUP

The refrigeration system of an upright freezer is modified to demonstrate and observe oil transport as shown in Figure 1. The test facility is equipped with two separate loops: a refrigerant loop and two oil loops. The refrigerant loop consists of a variable speed compressor, heat exchangers (evaporator, condenser), an expansion valve, and two sets of oil separators. The variable speed compressor was used to achieve a wide range of refrigerant mass flow rates. From the outlet of the evaporator, the refrigerant tube was extended vertically upward. A secondary refrigeration loop was installed to control the freezer compartment temperature, independent of the refrigerant and oil flow rates.

This vertical section represents the test section. Three sight tubes (ST1, ST2, ST3) were installed at the evaporator outlet. The oil flow was observed through these sight tubes. ST1 shows the oil stored at the bottom of the tube if the oil return fails. ST2 shows the oil flowing down to the evaporator below the oil injection port. ST3 shows the oil flowing upward above the oil injection port to the suction line. The oil flow patterns were monitored at the ST3 with a camcorder. The camcorder was installed inside the freezer compartment in order to monitor flow patterns without opening the freezer door.

Two oil loops were installed parallel to the refrigeration cycle. The first oil loop returns oil directly to the compressor. Oil leaving the compressor in the discharge line is separated by two oil separators connected in series, and then returned to the suction line. The second oil loop consists of a syringe pump, suction line oil separators and an oil storage tank. It provides oil to the test section for the oil return test. The separated oil is collected in a storage tank, which is also used to charge the syringe pump. The tank is equipped with a sight glass in order to measure the amount of returned oil.

The test facility was constructed inside an environmental chamber in order to maintain an ambient temperature of 23.9°C. The initial time delay and oil volume flow rate (VFR) returned from the test section to the oil storage tank was measured and compared with the oil VFR injected. When the returned oil VFR reaches steady state, the refrigerant/oil flow pattern was observed and recorded with the camcorder.

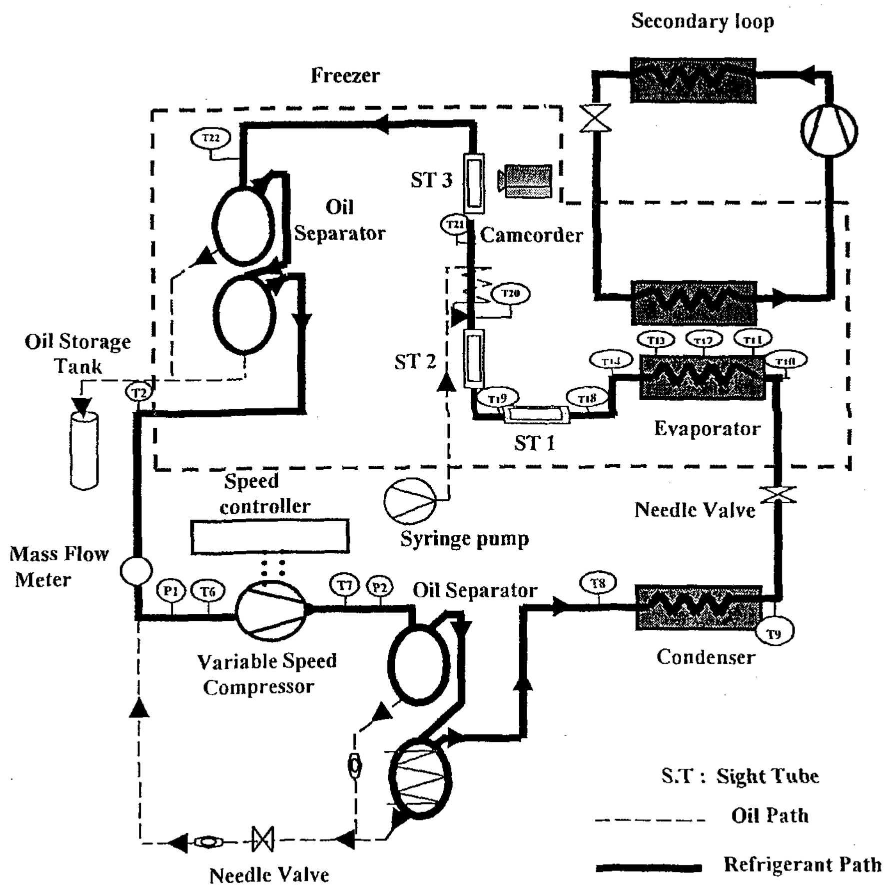


Figure 1. Schematic of Test Facility

3. EXPERIMENTAL PROCEDURE

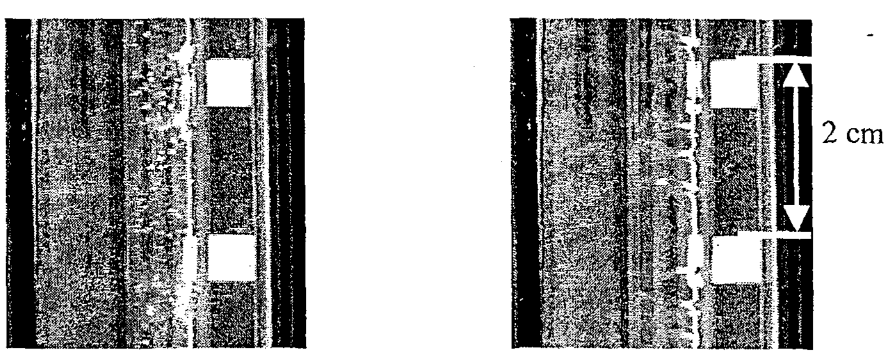
First, the expansion valve was controlled to maintain the temperature of the freezer compartment at −15°C as specified in the "ANSI/AHAM Standard for Household Refrigerators and Freezers" [9] at the given refrigerant MFR. Once steady state was achieved, the oil was injected to the lower end of the test section by the syringe pump. Oil flow rate was known from the setting of the syringe pump. Meanwhile, the oil flow pattern in the sight tube was monitored through the camcorder. The mean oil film thickness in the test section was calculated by integrating the oil flow rate difference between injected and returned quantities over time.

In this study, three kinds of oils were tested with R-134a: AB ISO 8, AB ISO 10 and MO ISO 10. The oil concentration that is defined as the ratio of MFR of oil and the refrigerant/oil mixture is varied from 0.1 to 5 %. For each oil, three different refrigerant MFR's and three different oil VFR's were investigated: refrigerant MFR (0.10, 0.38 and 0.58 g/s); oil VFR (4, 12 and 20 ml/hr). When the oil was changed from one test series to another, the refrigerant and oil in the system were removed and flushed with new oil by charging the new oil and running the cycle for one day.

4. RESULTS

Flow Pattern

Within the range of refrigerant MFR and oil VFR investigated in this study, only two flow patterns were observed: churn flow and annular flow [10,11]. Figure 2 shows the difference of flow pattern between churn and annular flow. When the refrigerant MFR is 0.1 g/s, the flow pattern is churn flow for all oil VFR's and oil types. In churn flow, the oil film on the wall flows downward, accumulates and eventually forms a "bridge". The bridge essentially is a plug that is pushed upward by the refrigerant vapor. The plug disintegrates into oil film waves and droplets. The flow pattern just above the test section shows droplets moving upward after they are broken from the liquid film. In churn flow, the oil film can be seen on the wall and moving upward or downward alternating in a more or less regular pattern. Oil film thickness on the wall is relatively thicker than in other cases due to the unstable flow of oil. For other refrigerant MFR cases (0.37 and 0.57 g/s), the flow pattern was annular flow for all oil types. In the annular flow pattern, the oil film on the wall flows upward at a range of velocities in wavy form. The distance between waves measured in Fig 2 decreases as refrigerant MFR or oil VFR increase. For all tests performed, no oil was found at the lowest sight tube (ST1). This means the net oil flow moves upward even for the case of the churn flow that at times exhibits a counter current flow between the central gas stream moving upward and the oil on the wall moving downward. This phenomenon can be explained as follows: the momentum flux of oil is much smaller than that of the refrigerant.



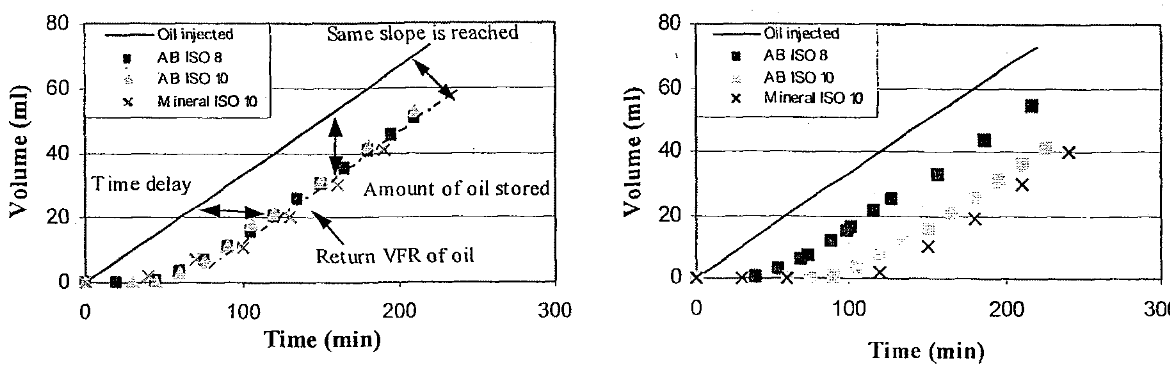
(a) Churn flow (b) Annular flow

Figure 2 Flow Patterns of Refrigerant and Oil Mixture

Therefore, the refrigerant provides enough shear force to transport the oil upward. It was observed that the oil on the wall flows down and reduces the cross sectional area when the flow pattern is churn flow. Then the viscous force of the refrigerant increases and finally pushes the accumulated oil layer so that the net oil flow moves upward. In this case, although the flow pattern is very unstable and shows oscillatory motion, in all cases there is a net upward oil flow.

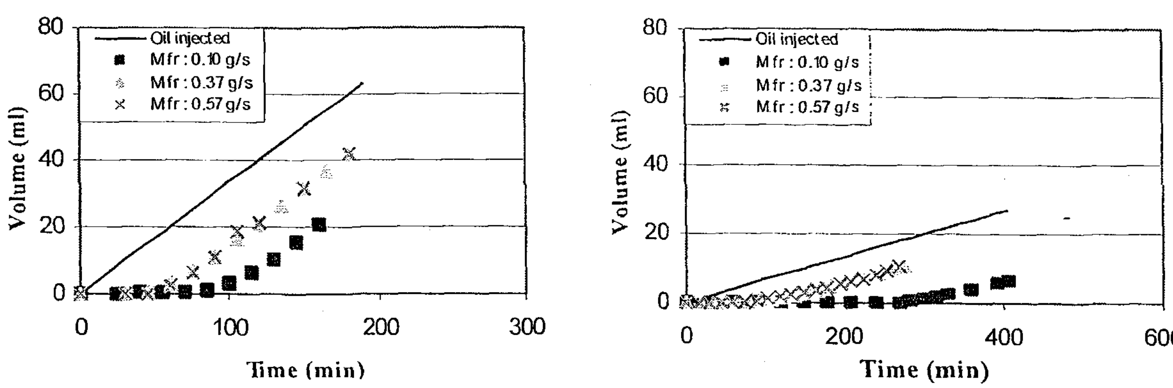
Mean Oil Film Thickness Ratio (MOFTR)

In this study, mean oil film thickness ratio (MOFTR) is defined as the mean oil film thickness (δ) relative to the inside radius of the tube (R). To determine MOFTR the internal tube volume is measured, including all tubes and sight tubes from the oil injection point to the oil storage tank. Then, the mean oil film thickness is calculated from the amount oil stored in the tube and the total internal tube volume.



(a) Refrigerant MFR: 0.57 g/s (b) Refrigerant MFR: 0.10 g/s

Figure 3. Effect of Oil Type on Volume of Oil Returned (Oil VFR: 20ml/hr)



(a) Oil VFR: 20 ml/hr (b) Oil VFR: 4 ml/hr

Figure 4. Effect of Refrigerant MFR on Volume of Oil Returned (AB ISO 10)

The test results for each refrigerant and oil combination are shown in Figure 3. Figure 3 indicates the volume increase of returning oil for the fixed oil VFR injected and refrigerant MFR. Figure 3 (a) shows additional details for clarification. A solid line indicates the oil volume injected to the tube over time. A dotted line indicates the amount of oil returned at the separator outlet. These two lines are linear and parallel to each other after an initial time delay. The horizontal distance between these two lines indicates a time delay for the oil injected to return to the oil separator. A vertical distance between these two lines means the oil volume stored in the tube. Therefore, the time delay from the start of the test till the slope of the returned oil becomes the same as the slope of the oil injected indicates a period of oil accumulation in the tube. This time delay was caused by the oil filling the tube from the injected point to the low pressure oil separator. After the initial time delay, oil flow reached its steady state. The difference between the volume of oil injected and the volume of oil returned determines the volume of oil that is stored in the tube. As the volume of the oil stored in the tube increases, the oil return time delay increases. Figure 3 shows the oil volume returned for two different refrigerant MFR's. At high mass flow rates the amount of oil stored is similar regardless of oil viscosity and oil type. On the other hand, for low refrigerant MFR the oil stored is influenced by the oil viscosity and oil type. In the case of AB, the time delay of the low viscosity oil is less than that of the high viscosity oil.

Figure 4 shows the returned oil volume for two different oil VFR's. The returned oil volume of AB ISO 10 was almost the same for the given oil VFR only when the refrigerant MFR was either 0.37 or 0.57 g/s. When the refrigerant MFR was 0.10 g/s, the MOFTR in churn flow was 2–3 times higher than for the other cases. This phenomenon also occurs in the case of MO ISO 10. However, in AB ISO 8, the MOFTR does not change with the refrigerant MFR at any oil flow rate. Thus, the effect of viscosity occurs only under low MFR conditions in which churn flow can be observed.

Table 1 shows the MOFTR for refrigerant-oil combinations. These results indicate that the oil that has a poor miscibility and higher viscosity creates a thicker oil film in the tube and delays oil return. Especially when the refrigerant MFR is low, the MOFTR gets higher as the oil viscosity increases. At high refrigerant MFR (0.57 g/s) the MOFTR is not influenced by oil type and viscosity as compared to the other MFR's (0.10, 0.37 g/s), but the MOFTR increases as the oil VFR increases. The MO has higher MOFTR as compared to AB under the same condition.

Table 1 Test Results

Oil VFR (ml/hr)	Ref. MFR (g/s)	Flow Pattern	Mean Oil Film Thickness Ratio (δ/R)			Reynolds Number of Refrigerant		
			AB ISO 8	AB ISO 10	MO ISO 10	AB ISO 8	AB ISO 10	MO ISO 10
4	0.10	Churn	0.05	0.17	0.23	2.7×10^3	3.5×10^3	4.1×10^3
	0.37	Annular	0.05	0.06	0.20	1.0×10^4	1.1×10^4	1.5×10^4
	0.57	Annular	0.05	0.06	0.08	1.6×10^4	1.6×10^4	1.6×10^4
12	0.10	Churn	0.11	0.25	0.44	3.0×10^3	4.3×10^3	7.6×10^3
	0.37	Annular	0.09	0.12	0.25	1.1×10^3	1.2×10^4	1.7×10^4
	0.57	Annular	0.11	0.11	0.14	1.7×10^4	1.7×10^4	1.8×10^4
20	0.10	Churn	0.16	0.3	0.40	3.1×10^3	4.4×10^3	6.0×10^3
	0.37	Annular	0.16	0.16	0.27	1.3×10^3	1.3×10^4	1.7×10^4
	0.57	Annular	0.17	0.15	0.20	2.0×10^4	2.0×10^4	2.2×10^4

5. CONCLUSIONS

From the experimental results and observations, the following conclusions are obtained:

(1) A new test protocol to estimate the volume stored in the tube and the MOFTR in the tube has been developed.

(2) The oil volume stored in the tube and MOFTR for the given oil VFR behaves in the following ways :

- AB ISO 8 is not sensitive to the refrigerant MFR's.
- AB ISO 10 is only sensitive at the lower refrigerant MFR.
- MO ISO 10 is very sensitive to the refrigerant MFR's.
- The order is (highest to lowest film thickness):
  MO ISO 10 > AB ISO 10 > AB ISO 8.

(3) The oil that has poor miscibility and high viscosity causes a larger oil volume stored in the tube and a higher MOFTR. Especially when the refrigerant MFR is low, the high viscosity oil leaves more oil in the tube.
(4) Under high refrigerant MFR, the influence of oil type and viscosity is not dominant.
(5) For the lowest refrigerant MFR, the flow patterns of all oils are churn flow.
(6) The net oil flow moves upward for the tests performed in this study.

Although the net flow moves upward, it is recommended that the churn flow pattern be avoided because the oil on the wall moves downward and could possibly cause oil return failure especially in heat exchangers depending on the design.

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REFERENCES

[1] ASHRAE, 1998, *ASHRAE Handbook, Refrigeration*, American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, GA., p. 7.6.
[2] Kruse, H.H. and M. Schroeder, 1984, *Fundamentals of Lubrications in Refrigerating Systems and Heat Pumps*, ASHRAE Transactions, Vol. 90, Part 2B, pp. 763-783.
[3] Daniel E. Kramer, 1999, *Why Not Mineral Oil*, ASHRAE Journal, Vol. 41, No. 11, pp. 55-61.
[4] Muir, E.B., 1994, HFC replacement for R22, *CFC's The Day After,* Proceedings of IIR Conference, Padova, Italy, pp. 249-257.
[5] Sundaresan, S.G. and R. Radermacher, *1996, Oil Return Characteristics of Refrigerant Oils in Split Heat Pump Systems*, ASHRAE Journal, Vol. 38, No. 8, pp. 57-61.
[6] Yoshihiro Sumida, Masahiro Nakayame, Sou Suzuki and Susumu Kawaguchi, 1998, *Alkylbenzen for Split Air Conditioner with R-410A Part 2: Oil Return Characteristics*, Proceedings of 1998 International Refrigeration Conference at Purdue, pp. 471-476.
[7] Jacobs, M., F. Scheidemann, S. Kazem, and M. Macken, 1976, *Oil transport by refrigerant vapor*, ASHRAE Transactions, Vol. 81, No. 2, pp. 318-329.
[8] Mehandale, S.S., 1998, *Experimental and Theoretical Investigation of Annular Film Flow Reversal in a Vertical Pipe*, University of Maryland, College Park, MD, Ph.D. Dissertation.
[9] ANSI/AHAM, 1988, American National Standard for Household refrigerators/ Household Freezers, ANSI/AHAM HRF-1-1979, Association of Home Appliance Manufacturers, Chicago, IL.

[10] Wallis G., 1969, *One Dimensional Two-Phase Flow*, McGraw-Hill Book Company, New York, NY.
[11] Whalley, P.B., 1987, *Boiling, Condensation, and Gas-Liquid Flow*, Oxford University Press, NY.