Investigation of Oil Retention in Residential Heat Pumps

Lorenzo Cremaschi
University of Maryland

Yun Ho Hwang
University of Maryland

Reinhard Radermacher
University of Maryland

INVESTIGATION OF OIL RETENTION IN RESIDENTIAL HEAT PUMPS

Lorenzo Cremaschi, Yunho Hwang[1], Ph.D., Reinhard Radermacher, Ph.D.

[1]Center for Environmental Energy Engineering
University of Maryland, College Park, MD 20742, USA
Tel.: 301/405-5247, Fax: 301/405-2025,
E-mail: yhhwang@eng.umd.edu [1]Author for Correspondence

ABSTRACT

In refrigeration and air-conditioning systems, oil migrates from the compressor to the remainder of the system. Thus, the working fluid is not only a refrigerant, but a refrigerant-oil mixture. While some oil leaves the compressor by forming an equilibrium mixture with the refrigerant, some is dragged as a result of very high refrigerant vapor velocity at the compressor discharge. The oil potentially clogs enhanced surfaces and in time forms a layer on all surfaces, which causes an undesirable additional pressure drop and heat transfer resistance. When a system runs with an immiscible refrigerant-oil mixture, using an oil separator at the compressor discharge line may solve the above problem. However, oil separators are costly and not always effective.

The purpose of this paper is to experimentally investigate the physics of oil retention and oil transport in all components of a vapor compression system. The oil retention volume was experimentally measured in the condenser, evaporator, suction and liquid line under realistic operating conditions of a system for a wide range of transport properties and mass fluxes. The test facility consisted of a residential heat pump designed for R22. The tests were carried out using an oil injection-extraction methodology. Refrigerants R22 and R410A with miscible lubricants have been investigated. The results show that the oil retention depends strongly on the oil concentration of the mixture and higher refrigerant mass fluxes lead to lower oil retention volumes in the test section. If the oil concentration increases from 1 to 8 wt.% for the R22 system the oil retention of MO increases from 2 to 28 mass % in the suction line and from 1 up to 6 mass % in the evaporator. The oil mass retained in the liquid line and in the condenser can rise up to 18 and 34 mass %, respectively. The oil retention volume is slightly different if the working fluid is R410A. For the given system, geometry and at fixed refrigerant mass flow rate, higher oil film viscosity leads to higher oil retention volume. For the R22 system, at fixed refrigerant mass flow rate, the pressure drops increase from 10 up to 40% in the suction line and from 1 up to 15% in the evaporator if the oil concentration increases from 1 wt.% to 8 wt.%.

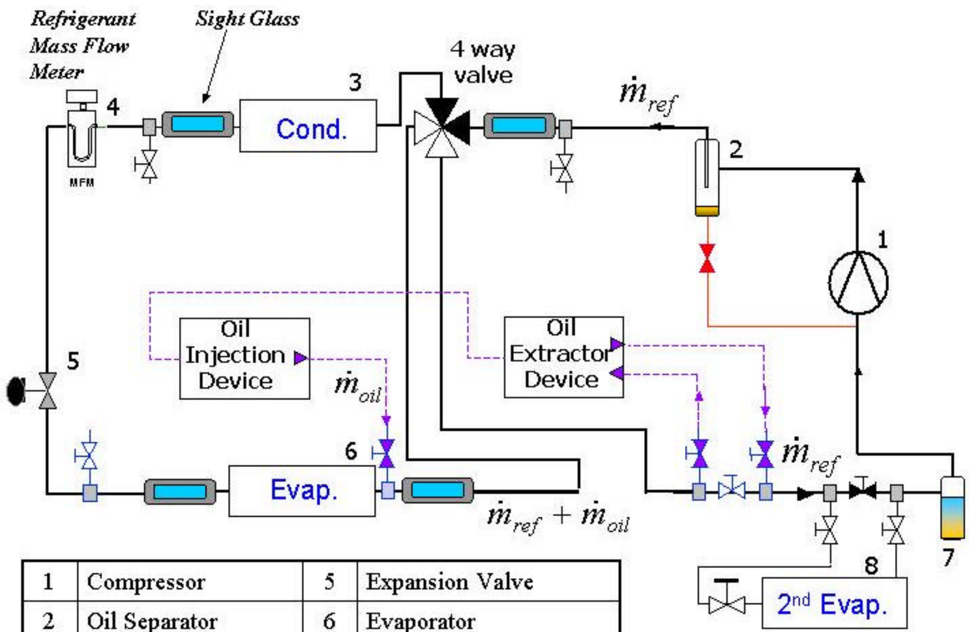
1. INTRODUCTION

In vapor compression systems some amount of oil is carried over with the refrigerant through the system. While the lubricant is necessary for the compressor, it causes an undesirable effect in the other components because it creates additional pressure drops and affects the heat transfer characteristics of the heat exchanger. Successful operation of the refrigeration system requires sufficient oil return into the compressor to avoid any potential problem due to lack of proper lubrication that may cause a compressor failure. Thus, a properly designed air conditioning system requires considerations of the oil transport characteristic in each component. The management of the oil initially charged into the compressor should take in into account that some amount of oil is retained in the system components and resides outside the compressor. This paper experimentally investigates the oil retained in the suction line, evaporator, liquid line and condenser of residential heat pumps using R22 and R410A as working fluids under realistic operating conditions. The oil used with R22 was blended white mineral oil (BWMO) that has a density of 882 kg/m^3 at 20ºC and viscosity of 110 cSt at 20ºC and 5.3 cSt at 100ºC. The oil used with R410A was ISO VG 32 poly ester oil, which is miscible with the refrigerant.

2. EXPERIMENTAL TEST SET UP

2.1 Test Facility

The schematic diagram of the oil retention test facility is shown in Figure 1. The indoor unit is located in a closed air-loop simulating indoor air conditions, while the outdoor unit is placed in an environmental chamber that simulates outdoor conditions. The test unit is designed for R22 and is rated 10 kW. The evaporator has five parallel passes, while the condenser has four parallel passes. A modified scroll compressor (1) with a sight tube and a sight glass was used. The sight tube allowed the liquid volume in the compressor to be monitored. A helical type oil separator has been placed at the compressor discharge to prevent oil flowing from the compressor to the test section. Four sight glasses allowed for visual monitoring of the oil flow, which was enhanced by using ultraviolet light and special fluorescent dye dissolved into the oil. An oil loop system stands next to the residential heat pump system. The oil injection and extractor devices are schematically shown in Figure 2. The extractor drains the oil through a u-shape tube into the oil level sensor vessel. In-stream thermocouples measure the bulk temperature of the liquid oil-refrigerant mixture entering the level sensor vessel, which was properly insulated to minimize heat conduction and temperature change effects. A capacitance probe measures the height of the mixture in the vessel by detecting the change in the dielectric constant between the electrode and the tank wall. The sensor has been accurately calibrated using oil-refrigerant mixtures in various solubility levels.



1	Compressor	5	Expansion Valve
2	Oil Separator	6	Evaporator
3	Condenser	7	Accumulator
4	Mass Flow Meter	8	Flush Evaporator

Figure 1: Schematic Diagram of the Oil Retention Test Facility

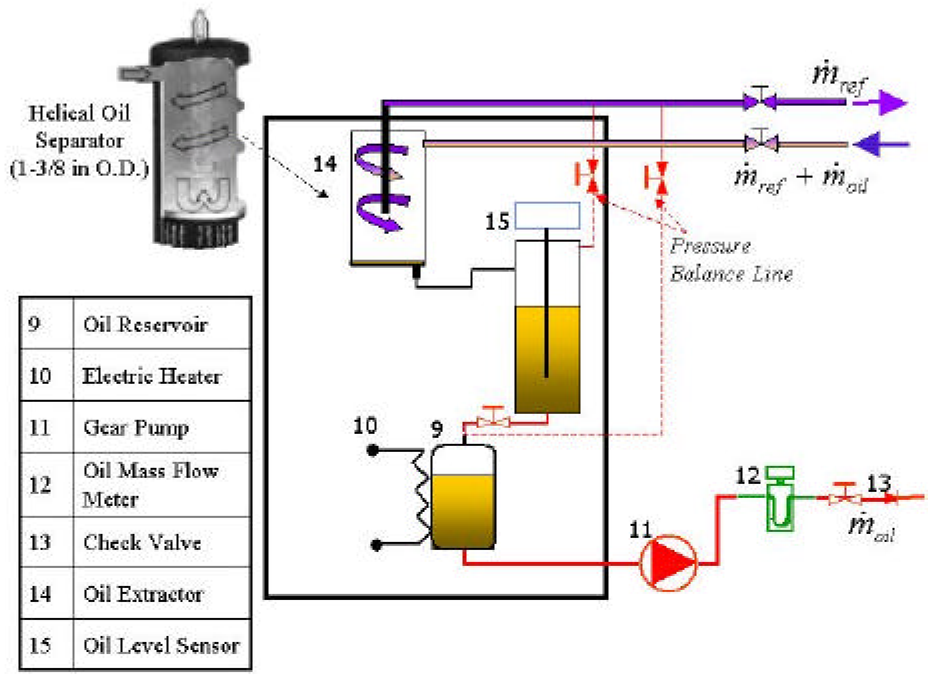


Figure 2: Schematic Diagram of the Oil Injection and Extraction Device

2.2 Test Procedure

The experimental test procedure is similar to that used by Lee (2002) during oil retention investigations in CO_2 air conditioning systems. In order to measure the oil retention in a specific component of the system, the oil volume injected in the test section and the rate of increasing oil volume inside the oil level accumulator at the end of the test section were measured. The following variables have been changed to perform a parametric study:

- OCR from 0.7 to 8 wt.%
- Refrigerant mass flow rate from 42 up to 77 g/s
- Refrigerant and oil pair: R22 with BWMO and R410A with POE oil.

From the preliminary test the operating limitations of the experimental test facility determined the range of the refrigerant flow rate. With fixed displacement compressor and RPM, closing the metering expansion valve reduces the refrigerant flow rate and affects the cycle temperatures and pressures. In particular, if air side conditions are kept constant a decrease of refrigerant mass flow rate leads to an increased superheating at the evaporator outlet. Thus, the refrigerant mass flow rate decreases due to reduction in refrigerant density along the test section. While the outdoor air side conditions were kept constant at the ASHRAE B conditions, the indoor air side conditions were varied slightly during the parametric study. The refrigerant charge and the indoor air side conditions were changed to maintain similar temperatures and pressures in the test section while varying the refrigerant mass flow rate.

Before each test, the system was flushed by running the compressor for about an hour and collecting the residual oil in the extractor. Then the refrigerant path to the flush evaporator was opened while the path to the main evaporator was shut. Thus liquid refrigerant collected the oil residual in the test section. Once the oil was drained from the level sensor tank, the test started. The gear pump injected the oil in to the injection port at specified flow rate. By aim of sight glass tubes the mixture flow was visualized. If the oil was injected in the liquid line through the condenser outlet port it formed a homogeneous mixture. Whereas, it formed an annular thin film on the pipe wall if it was injected in the suction line through evaporator outlet port. The oil is carried over with the refrigerant along the test section and after few minutes it was separated at the extractor and collected in the oil level sensor accumulator. Meanwhile the oil level in the sensor vessel was monitored on line and the rate of increased oil was recorded. Figure 3 shows a typical example of an oil retention test. Pressures and temperatures were measured both at the injection and extraction ports so solubility effects could be accounted for. The solid line with circles represents the oil amount injected at a given time, while the dashed line with triangles represents the mixture of oil and refrigerant that is extracted. In Figure 3, after 5 minutes the pump was shut off and the oil injection port was closed promptly by the closing action of the check valve. Most oil residual is collected within 10 minutes after the injection is completed. Additionally, the amount of refrigerant dissolved in the oil was taken into account as well.

The efficiency of the extractor was 99% when the OCR was equal or greater than 5 wt.%. It reached approximately 80% at OCR of 2 wt.% and it dropped below 50% if the OCR was less than 1wt.%. After taking this effect also into consideration, the solid line with squares was plotted, which represents the actual oil collected in the extractor.

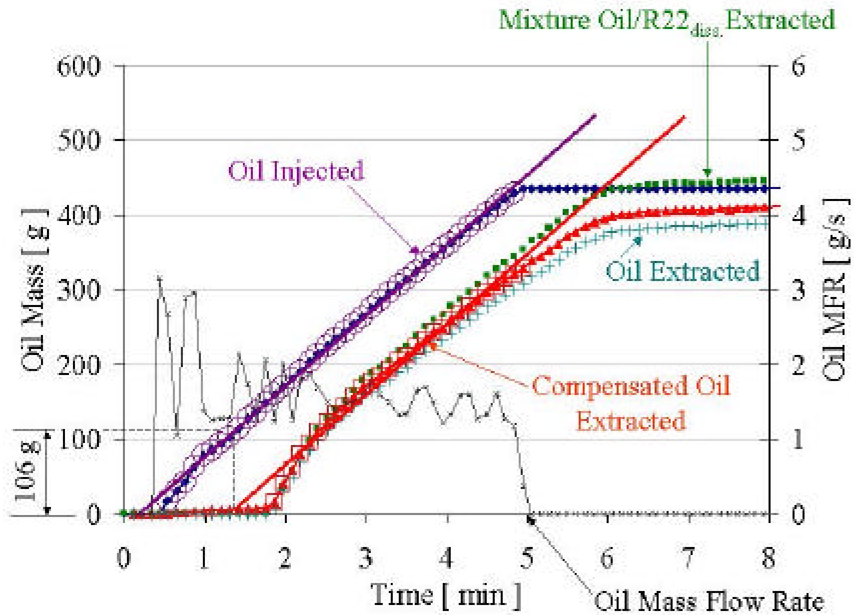


Figure 3: Example of Oil Retention

In steady state, the oil retention is defined as

$$\textit{Oil Retention [g]} = \textit{Oil Amount Injected [g]} - \textit{Oil Amount Extracted [g]} \qquad (1)$$

In order to compute a mean oil retention value correctly, it is important that the two lines of injection (circles) and extraction (squares) are in parallel and reach steady state for several minutes at least. The oil mass retained is found by taking the vertical difference between the two lines that represent the oil injection and extraction rates. The shift between the two slopes is constant during the injection period of the test. Finally the oil volume retained is defined as:

$$\textit{Oil Retention Volume [ml]} = \frac{\textit{Oil Retention Amount [g]}}{\textit{Average Density}\left[{}^{g}\!/_{ml}\right]} \qquad (2)$$

(Where the Average Density is the oil density averaged in time and space in the test section). Since the mass is a conservative property, it is more consistent to deal with mass rather than volume, especially when different system components are compared. The mass basis method produced a coherent set of results and the oil retention was converted in volume (ml) by simply dividing by an average oil density in the final step using equation 2.

3. EXPERIMENTAL RESULTS

3.1 Oil Retention in R22/MO Residential Heat Pump

This section describes the experimental results of oil retentions and pressure drops for the R22/MO heat pump system. Figure 4 represents the cumulative oil retention distribution in each component of a typical 10 kW cooling capacity R22 system. The suction line was about 14 meters long and its internal diameter was 19 mm. The overall length of the evaporator pipe was about 36 m while the liquid line was 19 m long. The large amount of oil retained in the condenser is due to its overall pipe length of about 70 m. The oil retention mass is given in both absolute value on the primary y-axis and percentage with respect to the initial mass of oil charged into the compressor in the secondary y-axis. If the OCR increases from 1 to 8 wt,% the oil retention in the suction line increases from 2% up to 28% of the initial oil charge. Only a few percentages of oil are retained in the evaporator while the cumulative oil retention in the liquid line, evaporator, and suction line can rise up to 40%. At OCR = 1 wt.% about 10% of the initial oil charged resides outside the compressor.

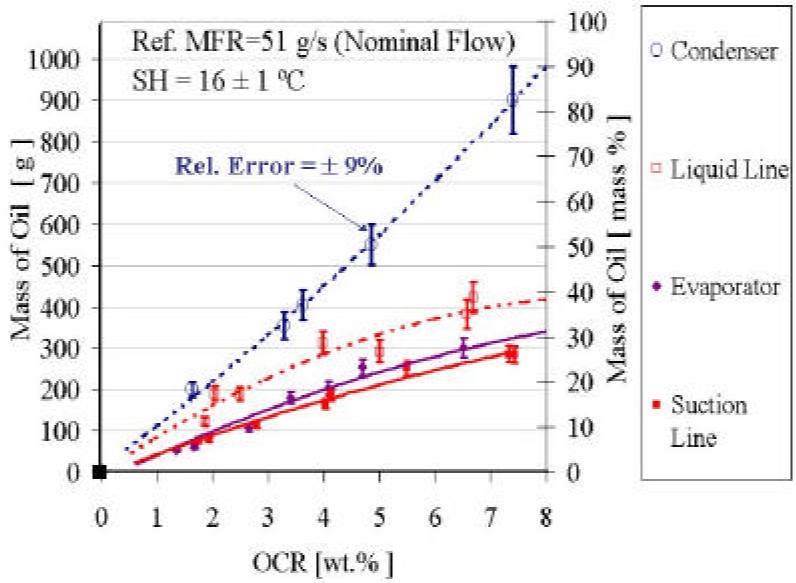


Figure 4: Oil Distribution in a R22 Heat Pump System at Nominal Flow Rate

Figure 5 shows the relation between the OCR and the cumulative oil retention mass in the suction line, evaporator, liquid line and condenser at various refrigerant mass flow rates. The cumulative percentage of oil present in the components with respect to the oil mass initially charged into the compressor is shown in the secondary y-axis of the charts. While the oil retention is strongly dependent on the oil concentration in the mixture it does not much affected by the refrigerant mass flow rate. However at higher refrigerant mass flow rates lower oil retention values have been observed. In the suction line an increase of refrigerant flow rate from 42 to 59 g/s led to a decrease of the oil retention of about 23% at OCR=1wt.% and about 28% at OCR=5wt.%. The flow in the liquid line was visualized using a sight glass tube located before the mass flow meter at the condenser outlet. The oil was rather homogeneously mixed with the liquid refrigerant and the oil retention did not depend on the refrigerant mass flow rate. The solid lines on the right graph of figure 5 represent the oil retention in the liquid line at various refrigerant mass flow rates. The results shows very similar oil retention characteristic at each flow rate.

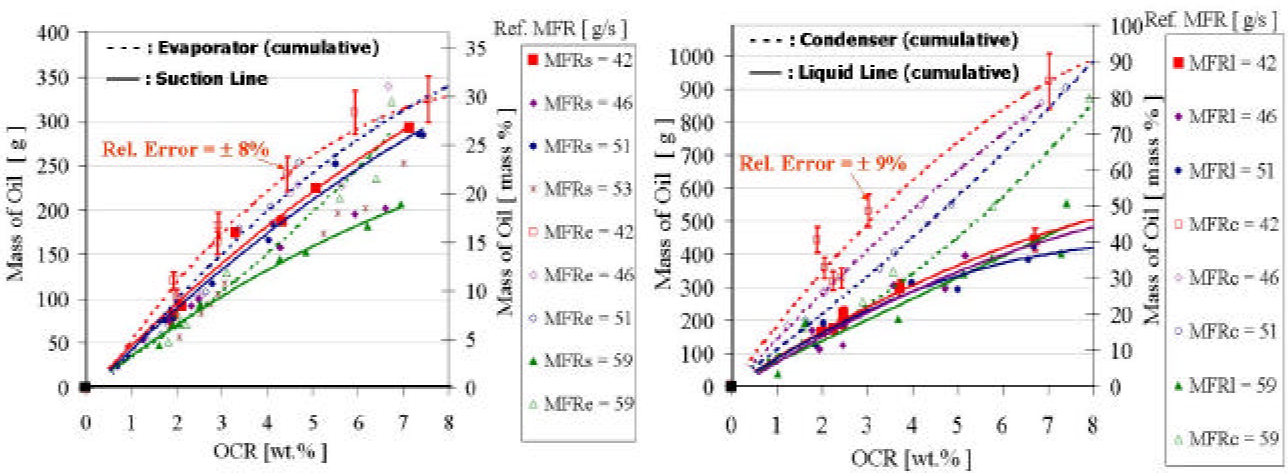


Figure 5: Cumulative Oil Retention in the Suction Line, Evaporator, Liquid Line and Condenser of R22 System

Figure 6 shows the pressure drop penalty factor in the suction line and evaporator of a R22 heat pump system. The pressure drop penalty factor (PDPF) is defined as

$$\textbf{PDPF}\ [-] = \frac{DP\big|_{OCR=x\,wt.\%}^{component(i)}}{DP\big|_{OCR\approx 0\,wt.\%}^{component(i)}}$$

where i = 1is the suction line and i = 2 is the evaporator.

If the OCR increases up to 8 wt.% the pressure drop increases about 40% in the suction line and 15% in the evaporator with respect to the case of OCR≈0 wt.%, i.e., no oil is injected in the test section. A more significant increase of pressure drop occurred in the suction line rather than in the evaporator. This may be due to less mutual solubility between the refrigerant core and the oil film in the suction line, which leads to higher values of liquid film viscosity. At OCR= 1 wt.% the PDPF in the suction line increases by 10% while in the evaporator the PDPF increases less than 2%.

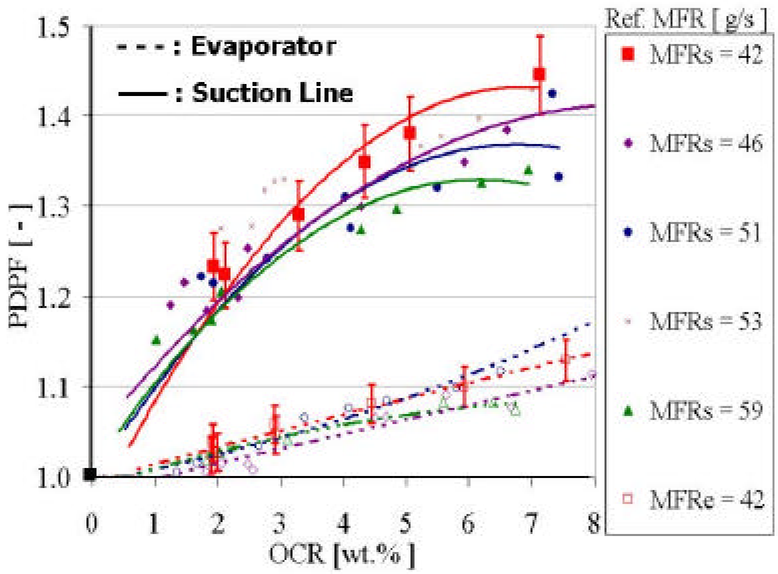


Figure 6: Pressure Drop Penalty Factor in the Suction Line and Evaporator of R22 System

Table 1 summarizes the oil retention experimental results of the R22 heat pump system. The values represent the oil retention mass per unit length of tube in each component. As shown here, the suction line is the most critical component with the highest values of oil retention per unit length.

Table 1: Summary of Oil Retention in R22/MO Heat Pump System

Component	OR Min	OR Max	I.D.	Length	Min OR/unit length	Max OR/unit length
Suction Line	35 g (3 mass %)	270 g (25 mass %)	19 mm	14 m	2.5 g/m	19.3 g/m
Evaporator	5 g (0.5 mass %)	110 g (10 mass %)	8 mm	36 m	0.1 g/m	3.0 g/m
Liquid Line	45 g (4 mass %)	110 g (10 mass %)	8 mm	19 m	2.4 g/m	5.8 g/m
Condenser	70 g (6 mass %)	440 g (40 mass %)	8 mm	70 m	1.0 g/m	6.3 g/m
Overall System	155 g (14 mass %)	930 g (85 mass %)	-	139 m	-	-

3.2 Oil Retention in R410A/POE Residential Heat Pump

This section describes the oil retention experimental results of the R410A/POE heat pump system. Figure 7 shows the relations between OCR and the cumulative oil mass retained in the suction line, evaporator, liquid line and condenser at various refrigerant flow rates. The system components were not modified with respect to the previous refrigerant. Thus the geometry and length of the pipes were invariant. The evaporation and condensation pressures of the R410A system were higher than those of the R22 system. At fixed outdoor air side conditions the refrigerant flow rate increased in the range from 46 up to 77 g/s. The thermophysical proprieties, solubility and miscibility of the refrigerant and oil mixture were different determine the liquid film viscosity. In the suction line an increase of refrigerant flow rate from 46 to 77 g/s led to a decrease of the oil retention of about 18% at OCR=1wt.% and about 10% at OCR=5wt.%. The PDPF for the suction line and evaporator have similar trend of those seen for the R22 system. At OCR=1.5 wt.% the PDPF increased about 18% in the suction line and less than 2% in the evaporator while at OCR=5wt.% the PDPF increased about 33% in the suction line and 9% in the evaporator.

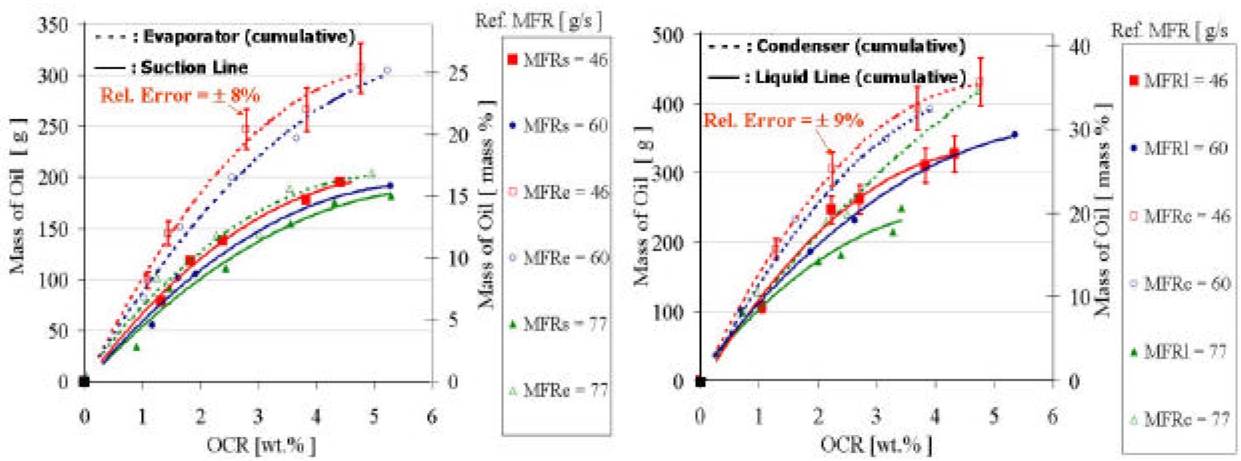


Figure 7: Cumulative Oil Retention in Suction Line, Evaporator, Liquid Line and Condenser of R410A/POE System

3.3 Comparison of Oil Retention between R22 and R410A Residential Heat Pump

Figure 8 presents a comparison of the oil retention volume between R22 and R410A systems. The 19 mm I.D. suction line is considered in the figure. The oil retention volume in the figure is an average value per unit length of pipe. The results are plotted versus the OCR, which ranges from 0.7 to 5.5 wt.%. The dotted area represents the oil retention volume for R410A/POE mixture, while the area in solid vertical line includes the oil retention experimental results of the R22/MO mixture. R410A/POE mixture has higher oil retention volume at low OCRs but lower oil retention volume at OCR greater than 5 wt.%. R410A/POE mixture has higher oil film viscosity but also higher refrigerant mass flux. The balance between oil film viscous force and refrigerant core inertia force depends on the oil film thickness. Viscous forces seem to be a predominant factor at low OCRs. At a similar flow rate, the oil retention volume of R410/POE mixture is higher than R22/MO because of higher liquid film viscosity.

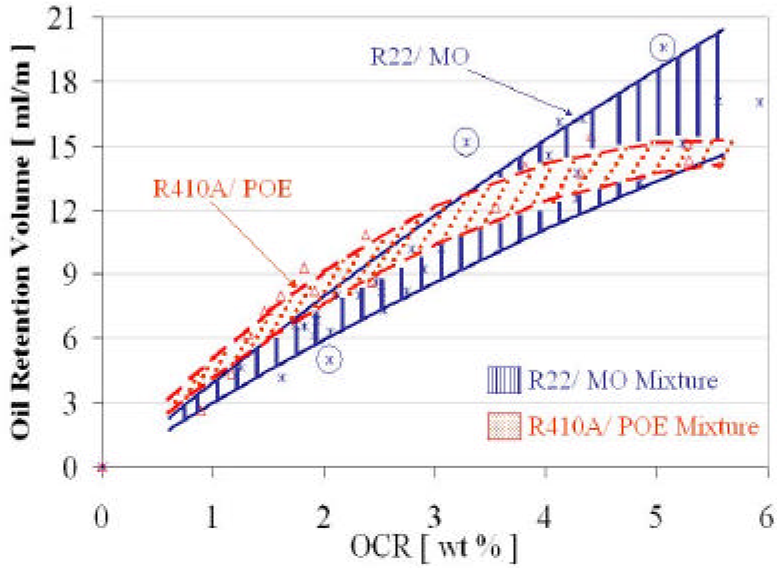


Figure 8: Comparison of the Oil Retention Volume in the Suction Line for R22 and R410A Systems

Table 2 compares the oil retention volume per unit length of tube for the R22/MO and R410A/POE mixtures in each component of the system. The results show that the R410A/POE mixture has higher oil retention volume in the evaporator but lower oil retention volume in the liquid line and condenser.

Table 2: Oil Retention Summary for R22/MO and R410A/POE Heat Pump Systems

Component	Oil Ret. Vol. R22/MO System [ml/m]		Oil Ret. Vol. R410A / POE System [ml/m]	
	OCR = 1 wt.%	OCR = 5 wt.%	OCR = 1 wt.%	OCR = 5 wt.%
Suction Line	3.9	18.6	5.0	15.2
Evaporator	< 0.2	1.4	1.0	3.0
Liquid Line	2.5	7.9	1.7	2.2
Condenser	1.6	6.2	0.6	3.0

4. CONCLUSIONS

The following conclusions can be drawn from the current work:

- The oil retention in R22 and R410A system depend strongly on the oil circulation ratio (OCR).
- Higher refrigerant mass flux leads to lower oil retention in the suction line, evaporator, and condenser. In the liquid line, the oil and refrigerant are homogeneously mixed and the oil retention does not depend on the refrigerant mass flow rate. In the suction line, which is the most critical component, an increase of refrigerant flow rate from 42 to 59 g/s produces an average decrease of oil retention volume of about 26% for R22/MO systems. In R410A/POE systems an increase of refrigerant flow rate from 46 to 77 g/s causes the oil retention to decrease of about 15% in average.
- If the OCR increases from 1 to 5 wt.% the cumulative oil retention in the R22 system components increases from 10% up to 50 mass % of the initial oil charged inside the compressor.
- R410A/POE mixture behaved similarly to the R22/MO mixture. In general the higher liquid film viscosity leads to higher oil retention volume. R410A heat pump systems have usually higher refrigerant mass fluxes that prevent oil from accumulating in the system at higher oil concentration values.

NOMENCLATURE

OR	Oil Retention
OCR	Oil Circulation Ratio
PDP	Pressure Drop Penalty Factor
$DP\big\|_{OCR=x wt.\%}^{component(i)}$	Pressure Drop in the component (i) at $OCR=x\ wt.\%$
$DP\big\|_{OCR\approx 0\ wt.\%}^{component(i)}$	Pressure Drop in the component (i) at $OCR \leq 0.5\ wt.\%$ (i.e., no oil injection)
BWMO	Blended White Mineral Oil
VG	Viscosity Grade
POE	Poly Ester Oil
ISO	International Organization for Standardization
MFR	Mass Flow Rate
e	evaporator
c	condenser
l	liquid line
s	suction line

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