2012

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ABSTRACT

An experimental investigation of oil retention and pressure drop characteristics for R1234yf, R134a and R410A with POE 100 is presented, for horizontal and vertical suction lines of 10.2 mm internal diameter. Conditions of operation include a saturation temperature of 13 °C and a superheat of 15 °C, with the superficial vapor velocity and the Oil in Circulation Ratio (OCR) both varied in the range of 1-6 m/s and 1-5 % respectively. The effect of lubricant viscosity on oil retention and pressure drop is also presented by comparing results with those of POE 32, under the same conditions of operation.

1. INTRODUCTION

The lubrication requirements of compressors in typical refrigeration systems necessitate the presence of oil. Flow visualizations have indicated that this oil is forced out of the compressor, either by forming an equilibrium mixture with the refrigerant vapor, or due to the high momentum of the refrigerant vapor. Thus the effect of oil on the system performance has been the topic of study for several years. Of particular interest are the issues of oil retention and pressure drop, especially across the compressor suction lines. The conditions of low temperature as well as high quality in the suction lines leads to a high viscosity of the oil-rich liquid film, which in turn translates into high oil retention and pressure drop at these sections. These are important observations that have to be taken into account while designing and sizing vertical suction lines. Part-load conditions of operation as well as conditions of low mass flux are characterized by extremely high oil retention. This is because these conditions have low refrigerant vapor velocity, which does not possess sufficient momentum to transport oil across suction lines. In the interest of designing better vertical suction lines and thereby improving system performance, understanding and quantifying oil retention is essential.

Jacobs *et al.* (1968) conducted oil retention experiments in vertical suction risers, in order to verify the minimum tonnage requirements required for oil transport, as was reported in the ASHRAE Handbook (1973). An increase in oil accumulation in the suction line, with decreasing refrigerant mass flux was observed through a sight glass, thus indicating reduction in oil transport. This was continued until the test section was flooded, where no oil was transported. Thus an analytical correlation was proposed - based on these visual observations – to predict a critical mass flux known as the Jacobs mass flux, below which no oil transport was observed. It was recommended that vertical suction risers be designed based on this mass flux, with the authors providing modified tonnage requirements for the same. Though this work was highly influential in initiating studies on oil retention, it was observed that the proposed correlation did not take into consideration the effect of liquid film viscosity and OCR.

Mehendale and Radermacher (2000) looked at annular film flow reversal in an 8 mm inside diameter vertical suction line. This work investigated the critical refrigerant mass flow fluxes at which the oil-rich annular film started reversing, both experimentally as well as theoretically, with extensive flow visualizations being conducted. Experiments were performed with miscible and immiscible refrigerant-oil mixtures, with oil injection-separation methodology being employed. It was observed that these critical mass flux limits were higher than the Jacobs mass flux. An analytical model was developed in order to determine the critical mass flux for lubricant return, for which the Wallis (1969) interfacial friction factor correlation was used. Parametric variation of the model showed that the critical refrigerant mass flux should decrease with an increase in film viscosity. As noted by Sethi and Hrnjak (2011), the Wallis correlation has been found to be unsuitable for very large as well as very small liquid film thicknesses.

Cremaschi et al. (2005) conducted experimental oil retention investigations in both horizontal and vertical suction lines, using the method of oil injection-separation. The effect of lubricant density, viscosity as well as mass flux on the oil retention was characterized by considering various refrigerant/oil mixtures. It was observed that a decrease in suction line diameter led to an increase in the mass flux, and an increase in mass flux led to a decrease in oil retention. Vertical suction lines were always found to possess higher oil retentions due to gravitational effects. The liquid mixture viscosity was found to be an important factor which affects oil retention in suction lines, with higher viscosity mixtures exhibiting higher retentions, since they have a greater resistance to be transported by the refrigerant vapor.

Zoellick and Hrnjak (2010) performed experimental investigations on oil retention and pressure drop in 7.1 mm and 18.5 mm internal diameter horizontal and vertical test sections. The effects of superheat, OCR and refrigerant mass flux on oil retention and pressure drop were studied, for which a mixture of R410A/POE 32 was used. Direct measurement technique - similar to that used by Crompton *et al.* (2004) – was employed in measurements, which were also accompanied with flow visualization. They observed the flow regime to change from annular flow to churn flow regime when the mass flux was reduced to the Jacobs critical limit, which was accompanied by large oil retention.

Sethi and Hrnjak (2011) conducted oil retention and pressure drop experiments in 10.2 mm internal diameter horizontal, vertical and inclined suction lines. Refrigerant/oil mixtures considered were R134a/POE 32 and R1234yf/POE 100, with the effect of OCR, suction line inclination and refrigerant mass flux being studied. It was observed that the oil retention increased with an increase in OCR or decrease in refrigerant mass flux. It was also determined that inclined suction lines led to the highest oil retention, indicating that they should be avoided. Comparisons between R1234yf and R134a in terms of oil retention and pressure drop were also made.

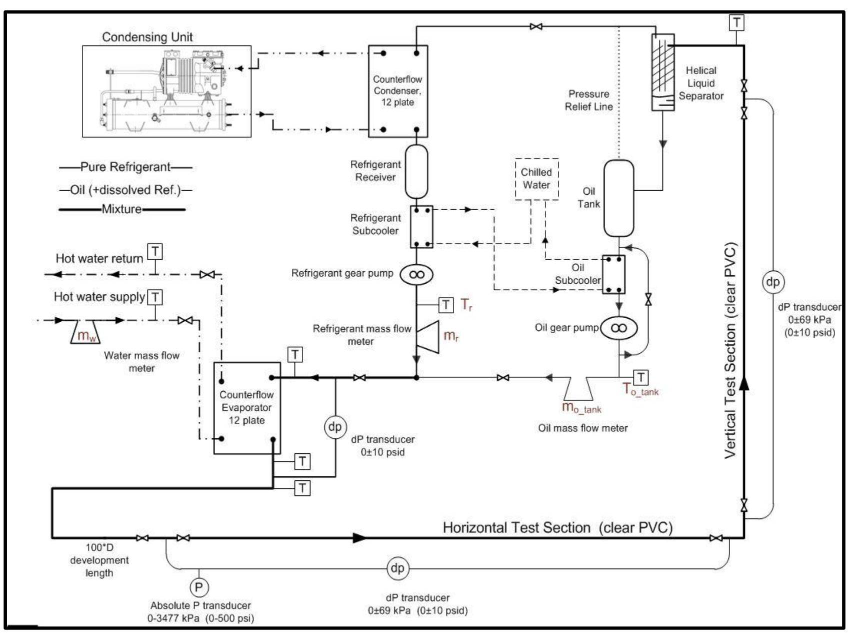

Figure 1. Schematic of experimental facility

With the European Union's Mobile Air-Conditioning Directive to use the low-GWP refrigerant R1234yf in automotive air-conditioning systems replacing R134a, there has been considerable interest in quantifying oil retention and pressure drop for R1234yf and comparing it with that of R134a, thus ascertaining the suitability of R1234yf in refrigeration and air-conditioning systems, including systems having long suction lines. The current work aims to present exactly this effort, by showing experimental results of oil retention and pressure drop using R1234yf and R134a refrigerants, with POE 100 lubricant being utilized. Tests were made in the same operating conditions as conducted by Sethi and Hrnjak (2011), who used POE 32 and comparisons were made with their data in order to capture the effect of lubricant viscosity on oil retention and pressure drop. Tests conducted in R410A with POE 32 and POE 100, served as baseline tests as well as data for further comparison.

2. EXPERIMENTAL FACILITY AND METHODOLOGY

Zoellick and Hrnjak (2010) developed a test facility to conduct experimental tests on oil retention and pressure drop in horizontal and vertical suction lines. The same basic facility was employed by Sethi and Hrnjak (2011), albeit some modifications were made. An R22 condensing unit was installed to increase the mass flux range over which data could be obtained, while existing test sections were replaced with clear PVC pipes of 10.2 mm internal diameter. The present work was conducted in the same apparatus, with only the range of the vertical differential pressure transducer being changed to (0±69) kPa, with an accuracy of ± 0.1 kPa. The testing procedure adopted was the same as that mentioned by Zoellick and Hrnjak (2010). Figure 1 represents the schematic of the test facility that was employed for all experimental measurements.

3. RESULTS

3.1 Experimental Data and Discussion

Experimental Tests were conducted using the following refrigerant/oil mixtures: R1234yf/POE 100, R134a/POE 100, R410A/POE 100 and R410A/POE 32. The lower limit of operation was maintained at the Jacobs critical mass flux, while the upper limit of operation corresponded to a superficial vapor velocity of 6 m/s for R1234yf and R134a, and 4 m/s for R410A respectively. Flow visualizations were also performed in order to capture the transition of flow regimes with variation in mass flux. Table 1 represents the test conditions for various experiments conducted.

Table 1. Test Conditions

Diameter : 10.2 mm **OCR** : (1-5)%		**Saturation Temperature** : 13 °C **Superheat** : 15 °C		**Oil** : POE 100, POE 32	
R1234yf (POE 100)		**R134a(POE 100)**		**R410A (POE 32 and POE 100)**	
Mass Flux	**Vapor Velocity**	**Mass Flux**	**Vapor Velocity**	**Mass Flux**	**Vapor Velocity**
kg/m^2-s	**m/s**	**kg/m^2-s**	**m/s**	**kg/m^2-s**	**m/s**
35 (Jacobs)	1.5	33 (Jacobs)	1.5	45 (Jacobs)	1.0
50	2.0	50	2.5	60	1.5
60	2.5	60	3.0	82.5	2.0
75	3.0	80	4.0	125	3.0
100	4.0	100	5.0	165	4.0
120	5.0	120	6.0		
145	6.0				

Figure 2 shows the variation of oil retention and pressure drop with the total mass flux for the case of R1234yf/POE 100, under different OCR conditions. Both quantities are represented in per unit length values. In general, an increase in oil retention was observed with a decrease in mass flux, since the refrigerant vapor possesses lesser momentum to transport the oil-rich mixture through the suction lines. In the case of the vertical suction line, a continuous increase in oil retention was observed, with the maximum oil retention occurring at the Jacobs critical mass flux of 35 kg/m^2-s. Interestingly in the case of the horizontal suction line, the oil retention was found to initially increase with a decrease in mass flux, but subsequently decreased when the mass flux was varied from 100 kg/m^2-s to 80 kg/m^2-s, stayed almost constant till 50 kg/m^2-s, after which it again increased. The decrease in oil retention was found to correspond with the transition in flow regime from annular flow to stratified wavy flow, where the oil film is found only at the bottom surface of the horizontal tube. Flow visualizations indicated the stratified oil film thickness to be almost the same at mass fluxes of 75, 60 and 50 kg/m^2-s, thus giving similar oil retention. In general, the pressure drop decreased with a reduction in mass flux, due to a decrease in the frictional pressure drop component. This was true for all mass fluxes in the horizontal suction line, while in the vertical suction line, the pressure drop progresses through a minimum value at 50 kg/m^2-s, after which it again increased at the Jacobs mass flux. Figures 3 and 4 show detailed horizontal and vertical visualizations conducted for R1234yf/POE 100 mixture. Variation of flow regime with mass flux, superficial vapor velocity and OCR are shown.

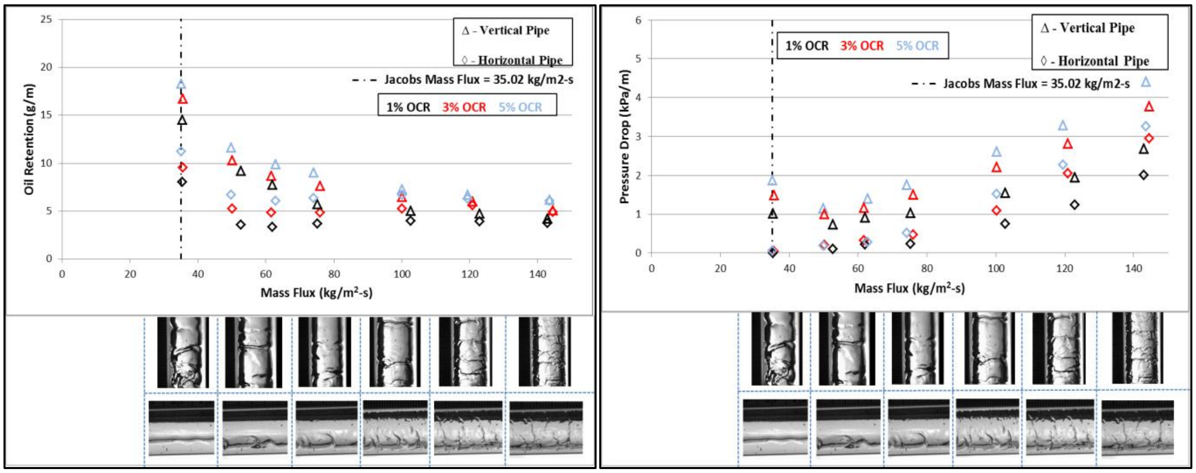

Figure 2. Variation of oil retention and pressure drop with total mass flux for R1234yf/POE 100

Visualizations indicated that in vertical suction lines, liquid film flow reversal occurred at 50 kg/m^2-s, after which the flow transitioned into the churn flow regime at the Jacobs critical mass flux, where the hydrostatic pressure drop component increased, thus leading to an increase in the overall pressure drop. Thus in the case of R1234yf, at 5% OCR, the horizontal suction line oil retention at a mass flux of 144 kg/m^2-s was observed to be 6.08 g/m, which increased to 6.32 g/m at 119 kg/m^2-s. Further reduction in mass flux to 100 kg/m^2-s led to increased oil retention of 6.76 g/m. At a mass flux of 74 kg/m^2-s, the oil retention reduced to 6.41 g/m. Subsequent reduction in mass flux to 63 kg/m^2-s and 50 kg/m^2-s yielded relatively constant oil retention values of 6.11 g/m and 6.76 g/m respectively.

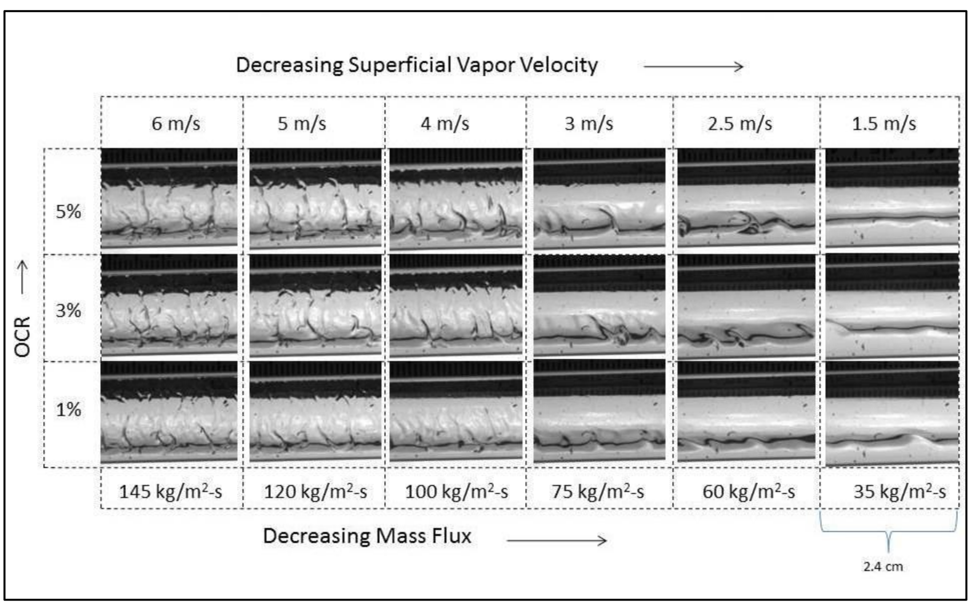

Figure 3. Horizontal Suction Line Flow Visualization of R1234yf/POE 100

Also, a higher OCR value gave higher oil retention. For instance, at a mass flux of 120 kg/m^2-s, the oil retention increased by 42% when the OCR was varied from 1% to 3%, while an oil retention increase of 60% was observed when the OCR was changed from 1% to 5%. At a lower mass flux of 50 kg/m^2-s, the oil retention increased by 48% when the OCR was changed from 1% to 3%, while an 89% change was observed when the OCR was varied from 1% to 5%. Thus at lower mass fluxes, the percentage increase in oil retention with increase in OCR is higher. The pressure decreased with reduction in mass flux. For instance, at 5% OCR, the horizontal suction line pressure drop decreased from 3270 Pa/m to 1520 Pa/m, when the mass flux was reduced from 144 kg/m^2-s to 100 kg/m^2-s. Also, an increase in pressure drop was observed with increasing OCR values. For instance, at 120 kg/m^2-s, the pressure drop increased from 1240 Pa/m to 2050 Pa/m when the OCR was changed from 1% to 3%, while the pressure drop increased up to 2280 Pa/m when OCR was changed to 5%.

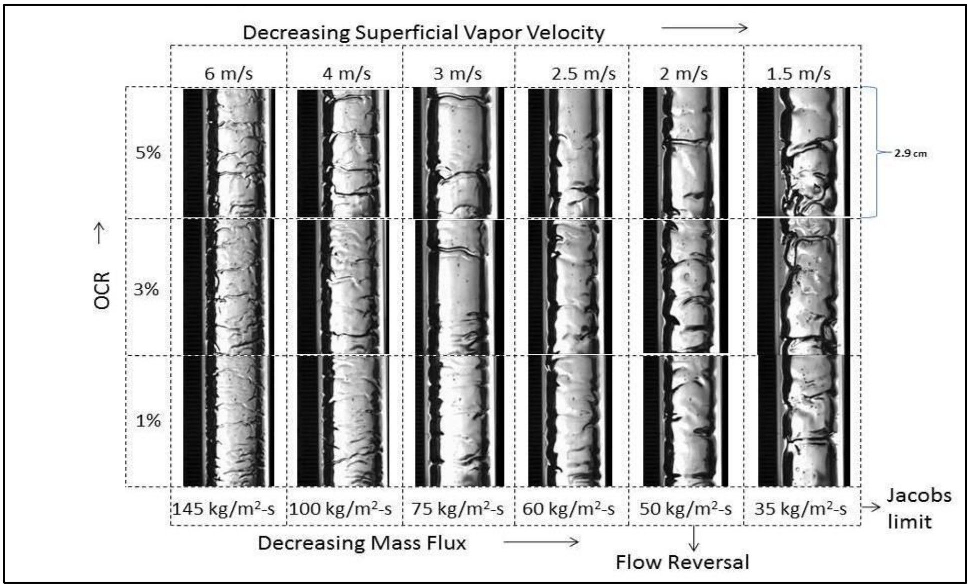

Figure 4. Vertical Suction Line Flow Visualization of R1234yf/POE 100

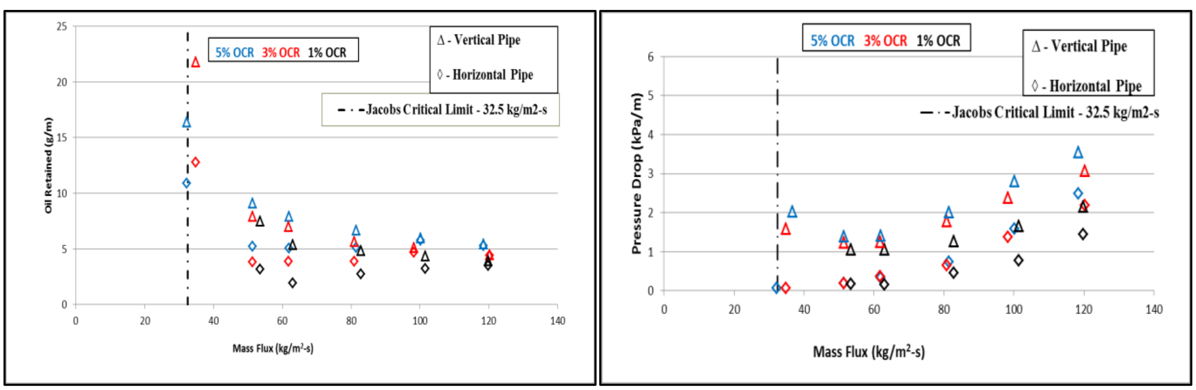

Figure 5. Variation of oil retention and pressure drop with total mass flux for R134a/POE 100

In vertical suction lines, oil retention was observed to increase consistently with a decrease in mass flux. At an OCR of 5%, the oil retention was observed to be 6.23 g/m at a mass flux of 144 kg/m^2-s, which increased to 7.33 g/m when mass flux was decreased to 100 kg/m^2-s. Further reduction in the mass flux up to 74 kg/m^2-s led to oil retention of 9.07 g/m. The flow reversal point of 50 kg/m^2-s was characterized by an oil retention of 11.65 g/m, which was a 18% increase in oil retention observed at 63 kg/m^2-s. The Jacobs critical mass flux was characterized by the churn flow regime, as observed from the flow visualization studies conducted. At this mass flux, the oil retention was a very high value of 18.31 g/m. Similar to the horizontal suction line, an increase in OCR yielded an increase in oil retention. At a mass flux of 120 kg/m^2-s, the oil retention increased by 27% when the OCR was varied from 1% to 3%, while an increase in 41% was observed when the OCR was changed from 1% to 5%. On lowering the mass flux to 75 kg/m^2-s, the oil retention increased by 33% when the OCR was altered from 1% to 3%, while an increase in oil retention of 57% was observed when the OCR was altered from 1% to 5%. The pressure drop was found to decrease up to the flow reversal point, beyond which it again increased due to change in flow regime. For instance, at an OCR of 3%, the pressure drop decreased from 3790 Pa/m to 2820 Pa/m when the mass flux was changed from 144 kg/m^2-s to 121 kg/m^2-s. Further decrease in mass flux to 76 kg/m^2-s yielded a pressure drop of 1510 Pa/m. At 50 kg/m^2-s, the pressure drop was 1010 Pa/m, which increased to 1490 Pa/m at 36 kg/m^2-s. Similar results for R134/POE 100, R410A/POE 100 and R410A/POE 32 are shown in Figures 5, 6 and 7.

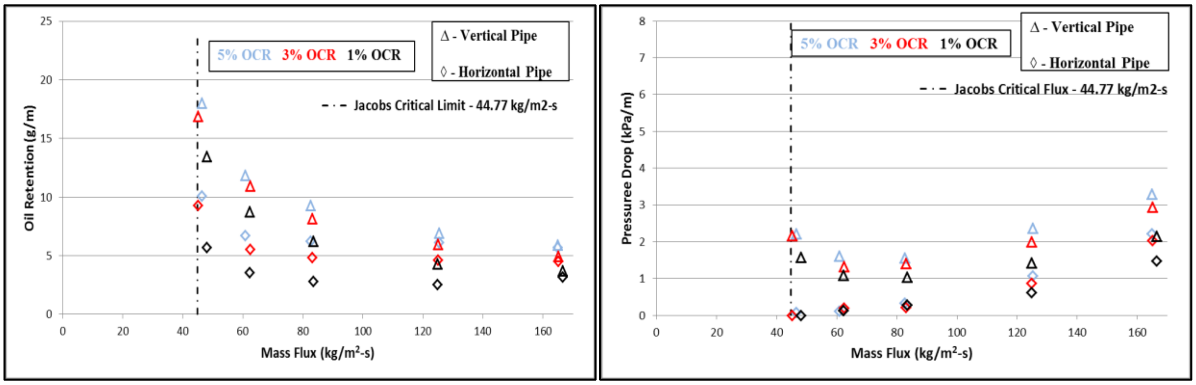

Figure 6. Variation of oil retention and pressure drop with total mass flux for R410A/POE 100

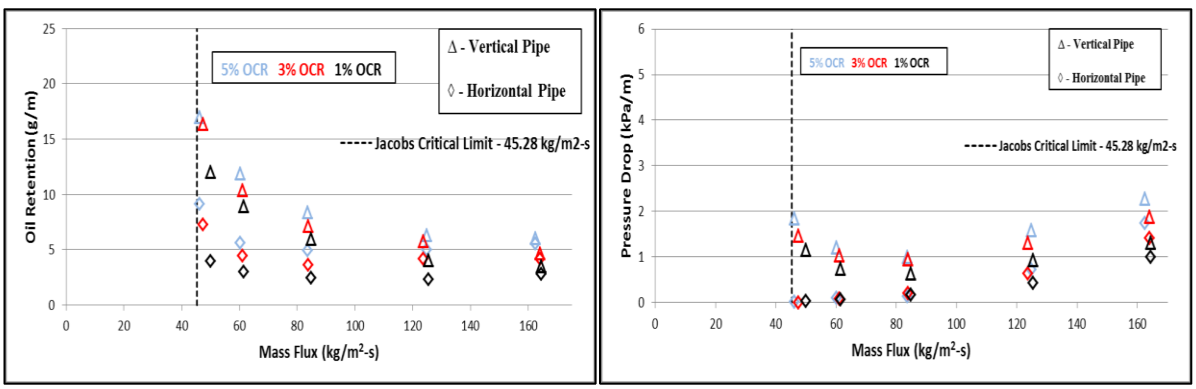

Figure 7. Variation of oil retention and pressure drop with total mass flux for R410A/POE 32

3.2 Effect of Lubricant Viscosity on Oil Retention and Pressure Drop

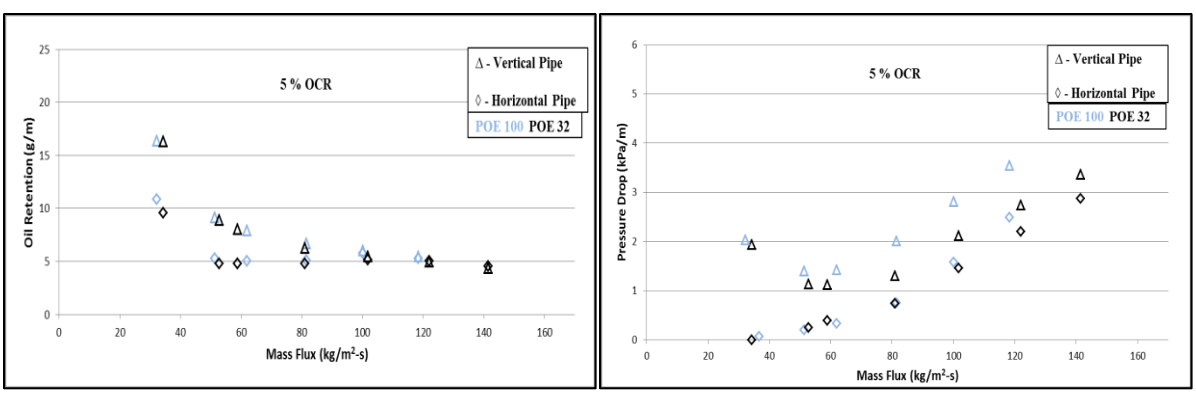

Figure 8. Effect of lubricant viscosity on oil retention and pressure drop for R134a at 5% OCR

Figure 8 compares oil retention and pressure drop using POE 100 and POE 32 in R134a, at 5% OCR. On using POE 100, it was observed that oil retention was 5-14 % higher in horizontal suction lines, while a maximum variation of 11% was observed in vertical suction lines. The horizontal pressure drop increased by 2-13 % while large variations were observed in the vertical suction line, in the order of 20-50 %. These variations are predominantly due to increased liquid film viscosity in the case of POE 100, as a result of which at the same mass flux, there is increased viscous resistance for the oil to be transported by the refrigerant vapor. The vertical suction line pressure drop appears to be the worst affected parameter with the percentage variation increasing with increasing mass flux. But based on oil retention results, the effect of POE 100 in comparison to POE 32 is only marginally different, which seems to indicate that the refrigerant/oil liquid mixture viscosity - which has a dominating effect on oil retention than the pure lubricant viscosity – should be close to each other for both lubricants. Similar results were obtained for 3% and 1% OCR values.

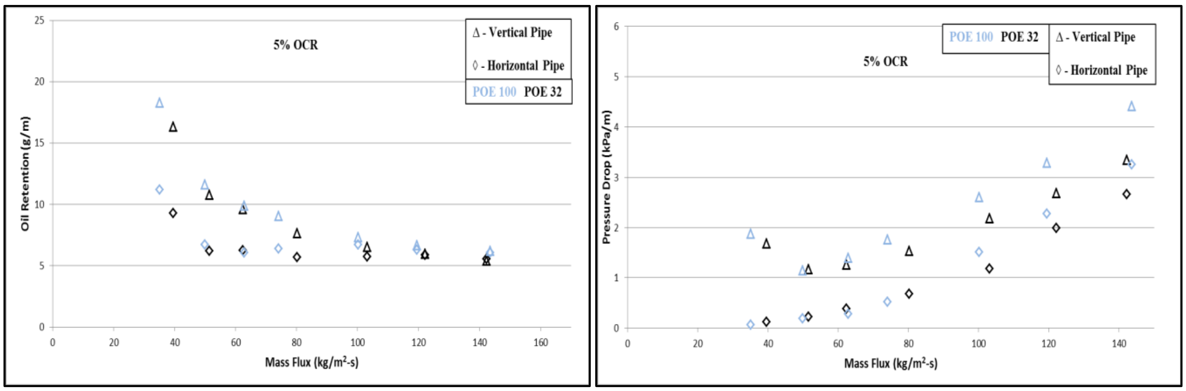

Figure 9. Effect of lubricant viscosity on oil retention and pressure drop for R1234yf at 5% OCR

Similar trends were observed in the case of R1234yf and R410A as well, as shown in Figures 9 and 10 at the same OCR of 5%. For R1234yf, the maximum increase in oil retention for POE 100 in the horizontal and vertical suction lines was observed to be 21% and 18% respectively. The horizontal and vertical pressure drops showed maximum variations of 27% and 32% respectively, with POE 100. Similarly in the case of R410A, POE 100 led to a maximum increase in oil retention in horizontal and vertical suction lines by 26% and 11% respectively. The pressure drop varied in horizontal and vertical suction lines by a maximum of 27% and 58% respectively.

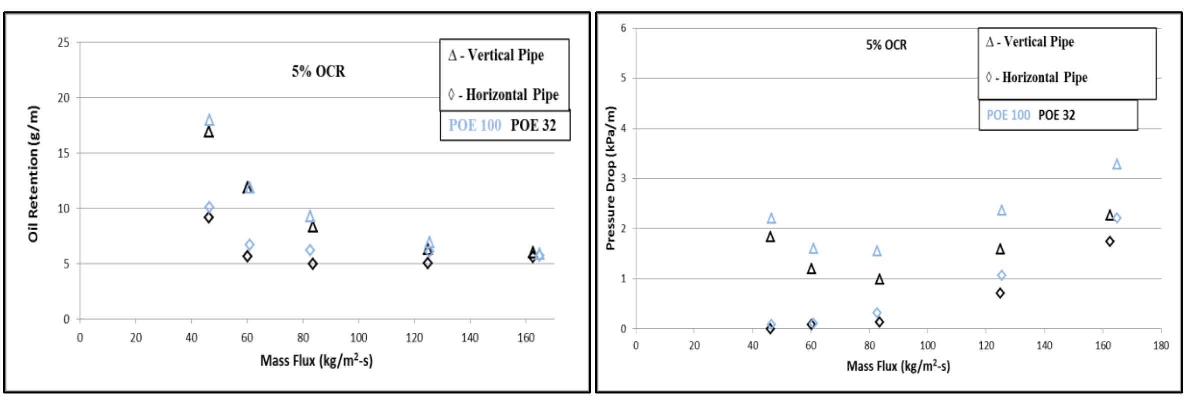

Figure 10. Effect of lubricant viscosity on oil retention and pressure drop for R410A at 5% OCR

3.3 Comparison of Oil Retention and Pressure in Different Refrigerants

Figure 11 shows the variation of oil retention and pressure drop for different refrigerants at 5% OCR, when the same POE 100 lubricant is employed for same superficial vapor velocity. Figure 12 shows the same trend in the case of

POE 32. It must be noted that at the same operating conditions, the vapor density of R410A is greater than that of R1234yf, which is in turn marginally greater than that of R134a.

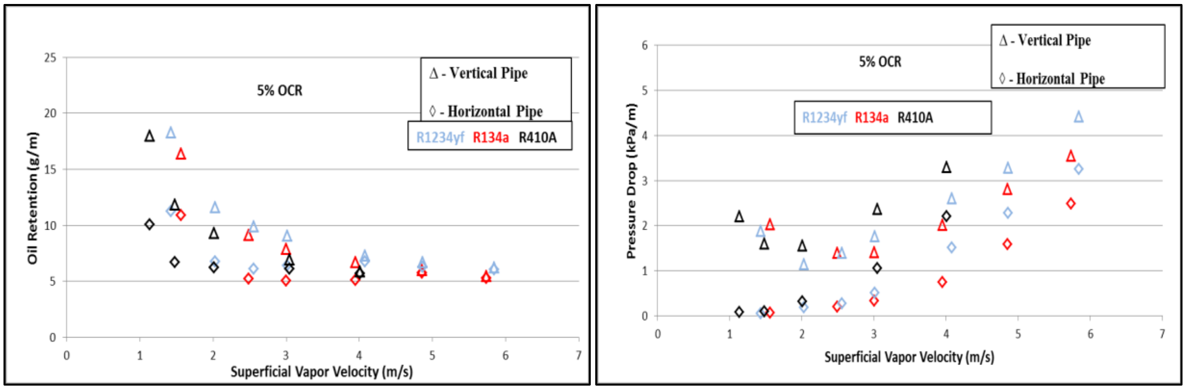

Figure 11. Effect of refrigerant type on oil retention and pressure drop for POE 100 at 5% OCR

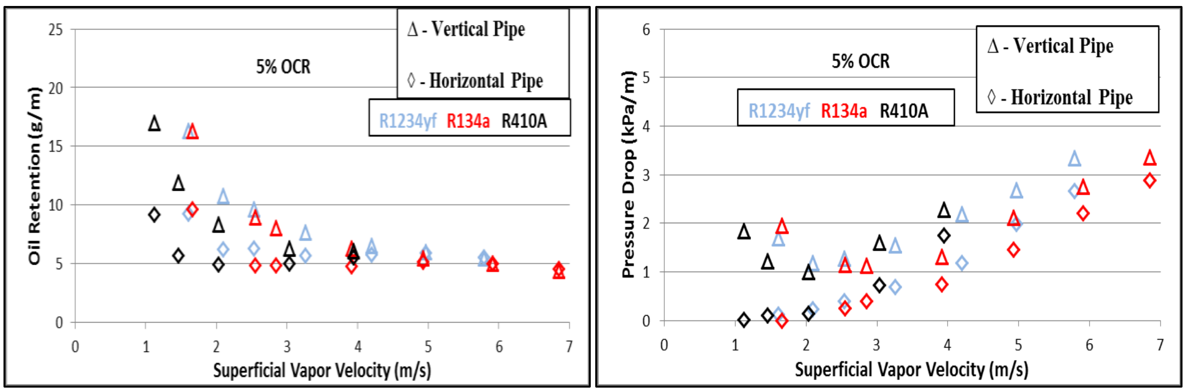

Figure 12. Effect of refrigerant type on oil retention and pressure drop for POE 32 at 5% OCR

It is observed that at the same superficial vapor velocity, R410A has lesser oil retention than R134a and R1234yf. Due to its higher vapor density, R410A vapor will possess a larger momentum in comparison to R134a and R1234yf at the same operating conditions. This higher momentum has the capacity to transport a larger quantity of oil in the suction lines, thus leading to low oil retention in both horizontal and vertical suction lines. On the other hand, this higher momentum leads to a higher pressure drop in the annular flow regime for R410A at the same vapor velocity, as seen in Figure 11 and 12 respectively. Figure 11 shows that for the case of POE 100 at 5% OCR, R1234yf has greater oil retention than R134a in the suction lines. This again translates into a higher pressure drop for R1234yf in comparison to R134a.

From Figure 11 corresponding to 5% OCR in POE 100, the oil retention in the horizontal suction line for R1234yf is about 26% more than that of R134a, while it was 15% in the vertical suction line. Also, large increase in suction line pressure drops were also observed, with the horizontal pressure drop increasing by 57% and the vertical pressure drop increasing by 24% respectively in R1234yf, at 3 m/s superficial vapor velocity. Also, R410A was observed to possess lower oil retention that R134a and R1234yf, while the horizontal pressure drop doubled and the vertical pressure drop increased by 35% respectively, at the same vapor velocity of 3 m/s.

From Figure 12, one can see that oil retention is similar for R134a and R1234yf in POE 32, for same conditions of superficial vapor velocity. At a velocity of 1.5 m/s, R410A has a 40% decrease in oil retention in comparison to R134a and R1234yf. Also, it was noticed that R1234yf had a 20-30 % increase in oil retention at the same vapor velocity, in comparison to R134a. This has implications in the context of using R1234yf as a drop in replacement for R134a, since it has a higher pressure drop. Also, it was observed that R410A had much higher suction line pressure drop in the annular flow regime, with the pressure drop increasing by (5-50)% in comparison to R1234yf.

4. CONCLUSIONS

The following salient conclusions were made based on the various experiments and flow visualizations conducted and comparisons made:

- It was observed that the flow regime in the horizontal suction line was annular at high mass fluxes, which transitioned into stratified wavy flow regime as the mass flux was reduced. Visualizations indicated that this transition occurred at a superficial vapor velocity of around 4 m/s for large OCR values.
- Flow visualizations also indicated that the flow regime in vertical suction line was annular for all mass fluxes above the Jacobs critical limit. Flow reversal was noticed when the mass flux was reduced to 50 kg/m^2-s for R134a and R1234yf and at 60 kg/m^2-s for R410A. The Jacobs critical limit was characterized by a churn flow regime.
- It was observed that when the mass flux was reduced, oil retention in the vertical suction line continuously increased. The horizontal suction line was characterized by an initial increase in oil retention, followed by a decrease in retention, which remained constant with further reduction in mass flux. This was due to the change into the flow regime from annular to stratified wavy, where the film thickness was observed not to vary much with mass flux decrease.
- It was noted that the horizontal pressure drop decreased continuously with drop in mass flux. In the vertical suction line, the pressure drop decreased initially, passed through a minimum point and increased again, with reduction in mass flux. This minimum point coincided with the flow reversal mass flux, after which it increased in the churn flow regime due to increase in hydrostatic pressure drop.
- It was observed that at the same mass flux and the same refrigerant, the oil retention increased by 0-30 % when the more viscous POE 100 was used in the place of POE 32. Horizontal pressure drop increased by 0-30 % while vertical pressure showed steep increases of 0-60 %. It may also be observed that refrigerant/lubricant mixture property has preceding importance over pure lubricant properties.
- At the same superficial vapor velocity in POE 100, it was observed that R1234yf had higher oil retention and pressure drop values in comparison to R134a.
- In POE 32 and at the same superficial vapor velocity, it was noticed that R1234yf and R134a had similar oil retention, while a 20-30 % increase in pressure drop was observed in R1234yf. These results show that using R1234yf in the place of R134a as a drop-in replacement would definitely lead to a reduction in system performance.
- It can also be seen that R1234yf shows larger variation in oil retention and pressure drop in comparison to R134a for POE 100, while the variation is observed to be smaller in the lower viscosity lubricant, POE 32.

NOMENCLATURE

GWP	Global Warming Potential
ISO	International Organization for Standardization
OCR	Oil in Circulation Ratio
POE	Polyol Ester Oil

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ACKNOWLEDGEMENT

The authors would like to thank the sponsor members of the Air Conditioning and Refrigeration Center for their financial support as well as Creative Thermal Solutions for lending various equipment used in the experiments.