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Oil Retention and Pressure Drop in Horizontal and Vertical Suction Lines with R410A/POE

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ABSTRACT

In refrigeration systems a small amount of compressor lubricant is entrained in the refrigerant and circulated through the system, where some is retained in each component. The suction line to the compressor has the largest potential for oil retention. This paper presents results from an experimental apparatus that has been constructed to circulate POE (polyolester) oil and R410A at a controlled mass flux, OCR (oil in circulation ratio), and superheat, and to directly measure the pressure drop and mass of oil retained in horizontal and vertical suction lines. The bulk vapor velocity and overall void fraction are determined from direct mass and temperature measurements. The oil retention, pressure drop, and flow regimes near the minimum ASHRAE recommended vapor velocity condition are explored, in order to better understand and define these conditions.

1. INTRODUCTION

The oil holdup in components of a refrigeration system has been the focus of many studies over the last 40 years. The suction line of a refrigeration system, especially for large commercial or building systems, can be a major location of oil holdup. The low temperature and high quality inside of a suction line means the small amount of liquid will be very oil rich and have a high viscosity. A high velocity of refrigerant vapor is required to pull the oil through long suction lines, especially in vertical, upwards flow conditions. The demand for energy efficient building systems has pushed many innovations, such as variable speed compressors, to reduce power usage during low load conditions. Oil retention can especially be a problem during low-load conditions due to lower vapor velocities in the suction line. These problems are alleviated by the use of parallel risers and u-traps, but both of these solutions increase piping expense, increase pressured drop, and still may not solve oil return problems. A better understanding of suction line flow regimes and oil retention during low velocity conditions is necessary for development of better suction risers.

In 1968, Marc Jacobs published the first, and still most influential, paper about oil return in suction risers. He simulated the suction line of a refrigeration system by injecting oil at the bottom of a vertical pipe with sight glasses to monitor flow regimes. He decreased the refrigerant flow rates until he saw “flooding” in the sight glass, a churn/slug flow regime, which develops at the bottom of the tube as oil accumulates. He used visualization data to develop equation (1) to predict the minimum mass flux for sufficient oil return. (Jacobs *et. al.* 1968)

$$G = \left(j_g^{*1/2} \right)^2 \left[\rho_g g D (\rho_f - \rho_g) \right]^{0.5} \quad [1]$$

$$j_g^{*1/2} = .85 \text{ (empirically determined for R12 and 150 SUS oil)}$$

ρ_g = vapor density
 ρ_f = liquid density
 D = Pipe Diameter
 g = Acceleration due to Gravity

This relationship is used in the ASHRAE refrigeration handbook as the basis for suction riser sizing. The equation provides a simple solution to sizing suction risers, but omits factors such as oil retention and viscosity. In a real

system, oil will be returned at any flow condition as long as there is enough oil charge to satisfy the oil retention demands of the system components.

Some recent oil return studies have been completed at University of Maryland in a group lead by Reinhard Radermacher. Radermacher *et. al.* (2006) presented a method of calculating oil retention in suction lines based on a physical model of the liquid film and data from two of his students. This model predicts retention values different those measured in this experiment. These discrepancies may be due to the differing methods of oil injection used.

Mehendale and Radermacher (2000) experimented with vertical upward flows of refrigerant and oil in a suction line. Using visualization techniques similar to Jacobs, he determined when the liquid annulus began to reverse and flow downwards. He referred to this point of flow reversal as the “critical velocity.” His experiments determined this critical velocity for some mixtures, and he developed a physical model for determining the critical velocity based on his findings and previous interfacial friction factor relationships from Wallis (1969).

Cremaschi *et. al.* (2005) continued the experiments using the same facilities as Mehendale. Cremaschi took measurements of oil retention in the suction line as well as other system components. He used the injection-separation method, where oil is injected at the bottom of a pure refrigerant suction line. The oil was separated at the top of the suction line, and the time between the injection and separation was measured to determine the liquid velocity and retention rate. One downside to this method is that the injection of oil generates a non-equilibrium condition inside of the suction riser, because some refrigerant will be dissolving into the oil during the test. In addition, injection of oil into the vertical pipe does not simulate the entrance condition to a real system, where oil may be able to accumulate in the bottom. Cremaschi discussed trends for oil retention with changing OCR, mass flux, oil viscosity, and pipe diameter, and worked with Radermacher *et. al.* (2006) to develop the physical model for the oil annulus in a suction line.

Crompton *et. al.* (2004) studied oil retention in horizontal smooth and finned tubes with various refrigerant and oil mixtures. While the system is running at equilibrium, valves on both ends of the test section were closed simultaneously, and the test section was then removed and weighed. The refrigerant was then removed, and the test section was weighed again to determine the mass of oil retained. This method gives very accurate results via a direct measurement of oil retention. They developed a model for predicting oil retention in horizontal pipes for conditions with two-phase refrigerant.

2. SYSTEM SETUP

A system was constructed to circulate refrigerant and oil at controllable flow rates and thermodynamic conditions, to simulate the suction line of a typical R410A refrigeration system. A schematic of the system can be seen in figure 1. The fluids used in the test are R410A and nominally 32 cSt POE oil. The setup has one vertical, with upward flow, and one horizontal test section made of clear PVC, each of which is about 2 m long. There are valves on both sides of the test sections, which are closed simultaneously during steady state conditions to measure the mass of oil retained inside of the test sections. There are pressure taps at both ends of the test sections, which allows for pressure drop measurements.

A helical liquid separator at the exit of the vertical test section separates the vapor and liquid. The liquid, which is a mixture of oil and dissolved refrigerant, flows into the oil tank. The vapor flows into a 12-plate condenser, where it is completely condensed into liquid. The condenser operates in a counter-flow orientation with the cold side being ~5 °C water from a central chilled water system. The condensed refrigerant flows into a receiver made from a 2” inner diameter copper tube, and is then pumped through a small subcooler by a gear pump controlled by a variable frequency drive. The flow rate and density of the refrigerant liquid is measured with a MicroMotion CMF25 Coriolis flow meter. The accuracy and repeatability of the mass flow measurements are ±0.1% and ±0.05% of the flow rate, respectively. The accuracy of the CMF25 density measurement is ±0.5 kg/m³ and it is used to ensure the refrigerant is pure by comparison to pure refrigerant properties.

The oil is pumped from the oil tank and through a subcooler by another gear pump. The oil pump is driven by a fixed frequency AC motor, and the flow rate is controlled with a bypass valve. A MicroMotion CMF10 Coriolis flow meter measures the flow rate and density of the oil rich liquid before it is mixed with the pure refrigerant

stream. The accuracy and repeatability of the mass flow measurements are $\pm 0.1\%$ and $\pm 0.05\%$ of the flow rate reading respectively. The accuracy of the density measurement is $\pm 0.5 \text{ kg/m}^3$. A T-type thermocouple ($\pm 0.5^\circ\text{C}$) measures the temperature of the oil flow at the entrance to the flow meter. The concentration of refrigerant dissolved in the oil flow is calculated from the temperature and density of the oil mixture. The OCR at the inlet of the test section is controlled by adjusting the flow rate of the pure refrigerant stream and the oil stream. A typical OCR measurement with associated uncertainty would be 0.03 ± 0.0008 .

The refrigerant and oil streams are mixed and flow into a 12 plate counter-flow evaporator. The flow rate and temperature of the hot water in the evaporator are controlled, so the refrigerant and oil mixture can be held at the desired apparent superheat. Mixing the refrigerant and oil in the liquid phase before the evaporator emulates a real system and ensures that the liquid and vapor are very near equilibrium at the inlet of the test section. We believe this method is more realistic than injection of oil alone into the vertical pipe with pure refrigerant vapor flowing upwards. In laboratory systems where pure oil is artificially injected into the suction pipe, the liquid phase cannot be in equilibrium, and refrigerant will immediately begin dissolving into the oil. This results in changes in the liquid properties along the test section, and could potentially skew the results. A 50 diameter long development length is placed before the horizontal test section inlet, to ensure thermal and hydrodynamic development. The concentration of oil in the liquid phase is dependent on the temperature and saturation pressure of the flow, both of which remain within $\pm 3\%$ or $\pm 1^\circ\text{C}$ of the set value during a test.

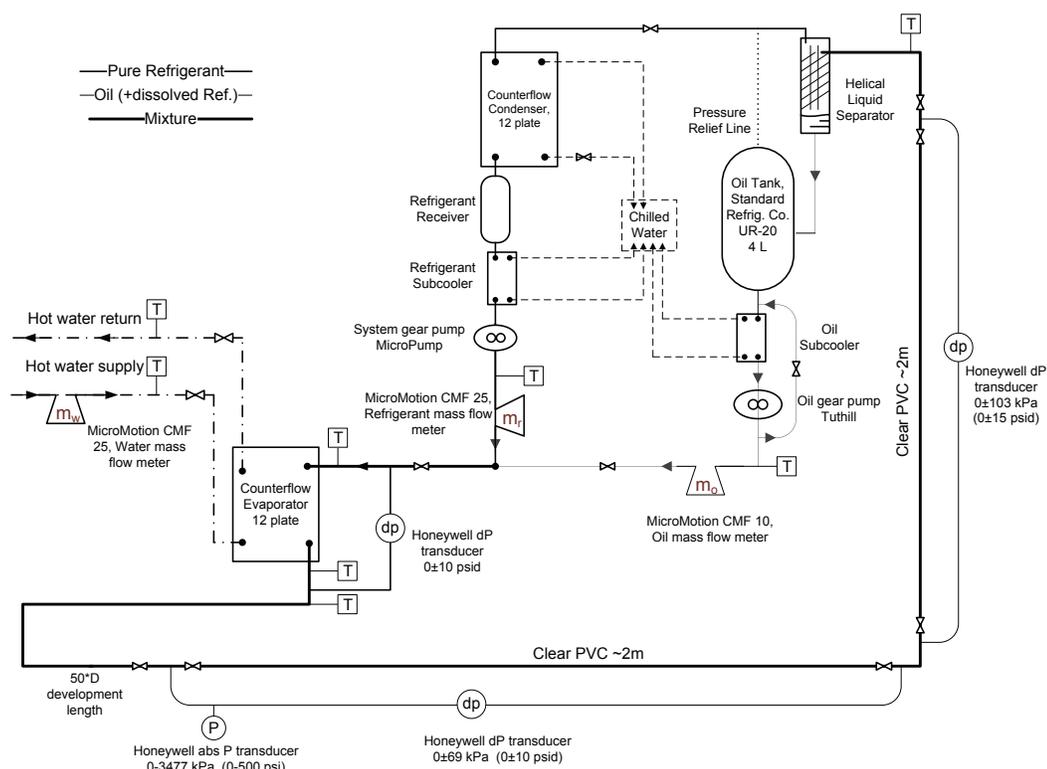


Figure 1. System Schematic

The saturation pressure is measured at the inlet to the horizontal test section by a Honeywell THE-CR absolute pressure transducer, with a range 0 to 3477 kPa and accuracy $\pm 8.6 \text{ kPa}$. The pressure drop across the horizontal test section is measured with a Honeywell Z differential pressure transducer, having a range $0 \pm 69 \text{ kPa}$ and accuracy $\pm 0.1 \text{ kPa}$. The pressure drop across the vertical test section is measured with a Honeywell Z differential pressure transducer, with a range $0 \pm 103 \text{ kPa}$ and accuracy $\pm 0.26 \text{ kPa}$.

Outputs from all thermocouples, pressure transducers, and Coriolis flow meters are read by a Yokogawa HR1300 data-logger. The data-logger interfaces with a computer running a LabView program to display and record all

measured data. Important parameters, such as OCR from the flow rate, density, and temperature, are displayed in real time.

3. TESTING PROCEDURE

The system is adjusted to the desired test conditions: flow rate, OCR, and superheat. The flow rate and OCR are adjusted by controlling the refrigerant pump speed and oil bypass valve opening. When running, during the transient period, the pressure drops across the test sections are monitored. Once the pressure drops maintain a steady value, the system is allowed to run for at least 5 additional minutes, to assure steady state operation. Data from all sensors is then recorded for the next 5 minutes. If any recorded conditions vary by more than 3% or 1°C during this period, the test run is discarded and condition re-run. Once the data is collected, the valves on either side of the test section are shut simultaneously, and the test sections are removed for weighing.

The test sections are removed from the system and the exterior is cleaned to remove any particles or oil. The tubes are then weighed on an electronic balance and the weight is compared that of the empty tubes. The accuracy of the balance is ± 0.03 g. This measurement represents the total amount of refrigerant and oil inside of the tube. The tube is then placed vertically and refrigerant vapor is slowly removed from the top of the tube until no bubbles can be seen coming out of the liquid oil. The procedure for venting the tube roughly follows the procedure outlined in ASHRAE standard 41.4. Once the refrigerant is removed from the test section, the test section is again weighed, to determine the mass of oil in the test section. The error of the oil measurement is ± 0.06 g, typically about 0.5% of the reading. From these measurements the quality inside of the pipe is calculated. Void fraction is determined from quality measurements and density calculated from pressure and temperature measurements.

The valves on either side of the test section allow for a direct measurement of refrigerant and oil inside of the suction line. This is much more accurate than the injection-separation method, which can only provide an indirect measurement of oil retention inside of the pipes.

4. RESULTS

Table 1 describes the test conditions. Two different pipe diameters were studied over a range of test conditions. The tests run with the 7.2 mm pipe were all above the minimum mass flux recommended by the Jacobs correlation, due to the minimum flow rate restriction of the system. The larger, 18.5 mm, pipe was used for testing a range of mass fluxes above and below the minimum recommended mass flux. High-speed videos of the flow regimes inside the clear pipes were recorded.

Table 1. Test conditions

Diameters:	7.2 mm	18.5 mm	
Qualities:	5° ΔT_{sh}	10° ΔT_{sh}	15° ΔT_{sh}
OCR	1%	3%	5%
Oil	POE ISO32 cSt		

D=7.2 mm		D=18.5 mm	
Vapor Velocity	Mass Flux	Vapor Velocity	Mass Flux
m/s	kg/m ² s	m/s	kg/m ² s
2.8	100	1.6	60
4	150	1.8	70
5	200	2	80
6.5	250	2.8	100
Jacobs kg/m ² s	42.9		59.8

At high mass fluxes, the film is annular and moving upwards, but it begins to fluctuate and even flow downwards as the mass flux decreases, as shown in Figure 2. The Jacobs limit is empirically linked to the point of flooding, where the downward flowing film dominates and oil accumulates in the bottom of the pipe, leading to a churn/slug flow regime. The left image shows the churn region in the bottom of the pipe, which changes to an annular flow with

downward moving film, and upward moving droplets at some height along the pipe. The height of this interface is dependent on the mass flux and OCR. In the annular section, some of the droplets will coalesce into the falling film, and the others will be transported up and out of the suction line. There is hysteresis in the annular/churn flow regime transition. The annular flow will transition to churn very close to the Jacobs limit, but higher flow rates are necessary for the transition from churn back to annular flow.

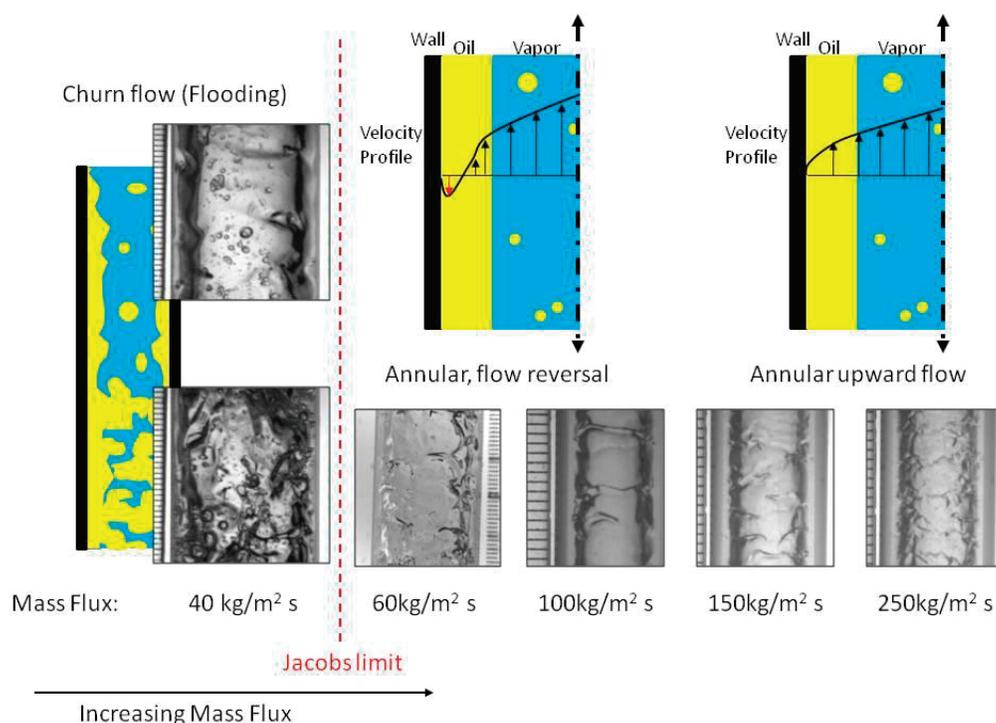


Figure 2. Flow Regime Visualization

Figure 3 shows the relationship between oil retention per inner surface area and total mass flux. The data for this figure was taken at a saturation pressure corresponding to a temperature of 12°C with 15° of superheat. The data for mass fluxes above 100 kg /m² s were taken in the 7mm ID pipe. In the annular regime, which occurs at high mass flux, the oil retention slowly decreases with increasing mass flux. This is due to the thinning of the oil film layer. For high mass fluxes, both the vertical and horizontal suction lines have annular flow, and therefore oil retention is very similar in both lines. As the mass flux is decreased, the vertical line begins to retain more oil than the horizontal line as the flow regime changes from annular to stratified in the horizontal line while remaining annular in the vertical line. OCR is shown through color in the figure. An increase in the OCR of 2% results in increased oil retention of almost 20% for most cases.

At 100 kg/m² s, retention data from the 7 mm tube and 18.5 mm tubes are compared to study the effect of tube diameter on oil retention. Since the flow is stratified with only some small waves in the horizontal pipe, an increase in diameter has very little effect on the oil retention. However, a large dependence on diameter can be seen in the vertical pipe. The increased amount of oil droplets in the larger diameter tube may explain some of the diameter effect.

The effect of increasing the OCR is consistent with both diameters, increasing the OCR by 2% results in about a 20% increase in oil retention. A similar trend is seen with the apparent superheat in the suction line. An increase in 5° apparent superheat results in an increase in oil retention by 15%. When the superheat was allowed to drop to 0° and some liquid refrigerant passed through the evaporator, the sudden drop in liquid viscosity caused almost all of the retained oil to be washed out of the vertical pipe. This transient effect was not quantified, but it may be an effective method of returning excessive retained oil from the suction lines.

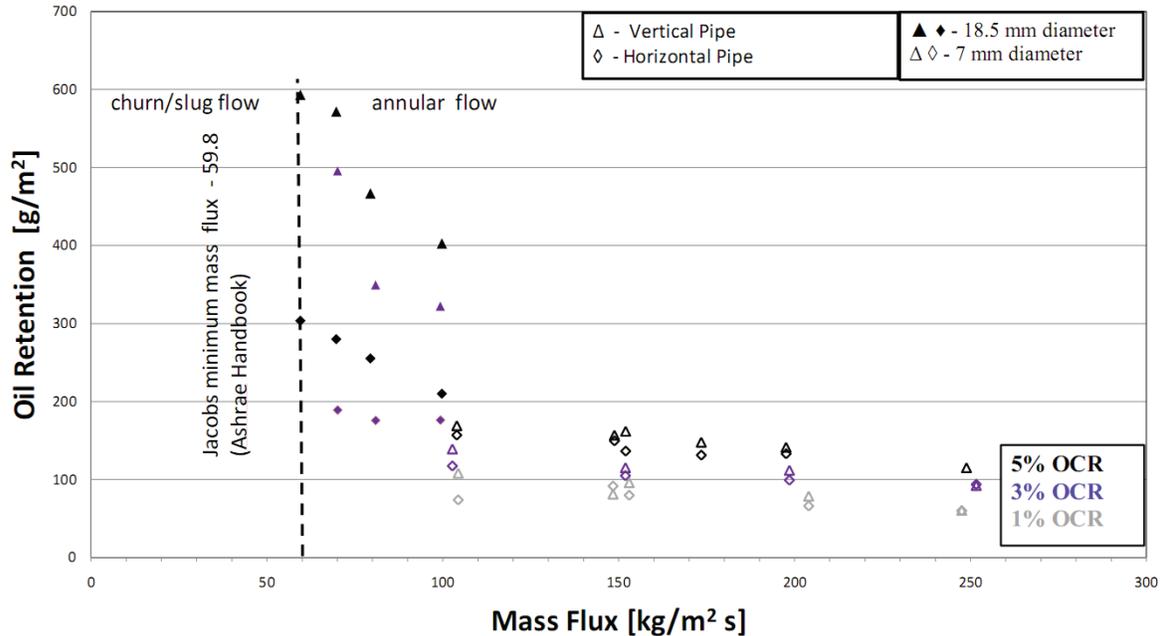


Figure 3. Oil Retention

Figure 4 shows the pressure drop per unit length in the vertical and horizontal suction lines. The data for this figure was also taken at a saturation pressure corresponding to a temperature of 12°C with 15° of superheat. In the high max flux conditions shown in the diagram, which is the annular regime, interfacial friction dominates the pressure drop. In this region, increases in flow rate will increase the Reynolds number, and thus increase the overall pressure drop. Pressure drop measurements from test conditions without oil are shown on the figure along with the Friedel prediction for two phase flow. The accuracy of the pressure drop sensors was verified by these no-oil tests before tests were run with oil.

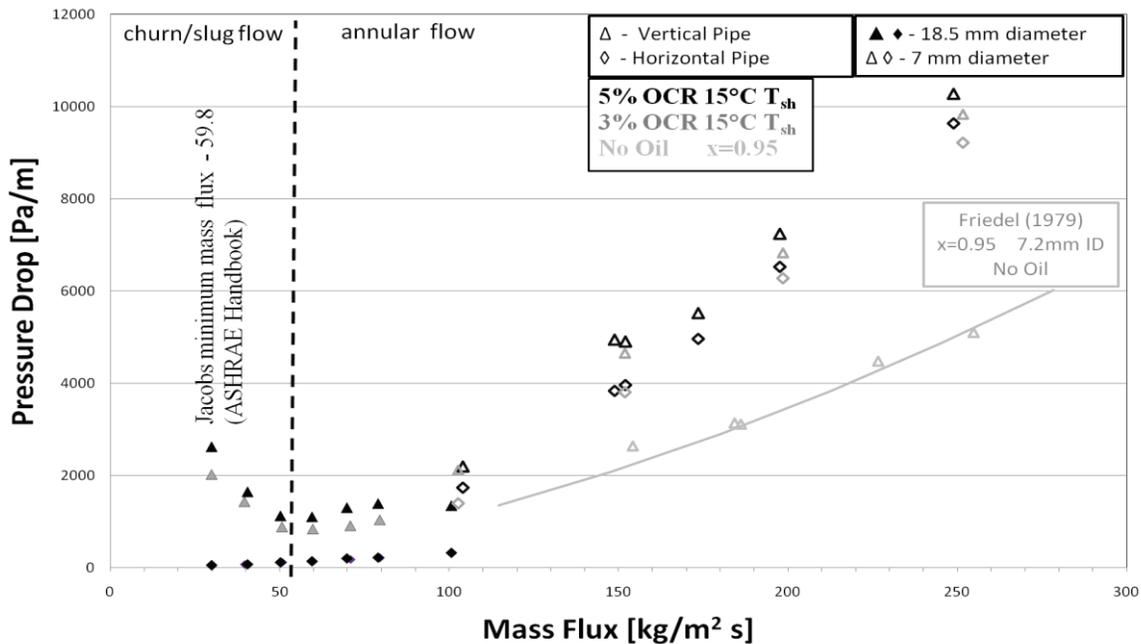


Figure 4. Pressure Drop

As the flow rates approach the Jacobs limit, the pressure drop in the vertical tube reaches a minimum at the transition to the churn regime. Below this mass flux, pressure drop becomes dominated by the hydrostatic force of the liquid column. The churn region increases in height with decreasing mass flux, therefore the hydrostatic force, and consequently the pressure drop, will also increase. The horizontal tube maintains stratified flow below the Jacobs limit, thus pressure drop continues to decrease with decreasing mass flux.

Changes in the OCR have a small effect on the pressure drop in the annular regime, causing a slight thickening of the liquid film. An increase in the OCR by 2% will increase the pressure drop by less than 10%. Increasing the OCR has no measurable effect on pressure drop once the horizontal pipe transitions to the stratified regime. When the vertical pipe transitions to the churn regime, an increase in the OCR will noticeably increase the height of the churn region, and thus it will also increase the pressure drop.

5. CONCLUSIONS

- Oil retention increases substantially when mass flux is below the Jacobs limit. In order to avoid the churn flow regime and excessive oil holdup, it is recommended to maintain system conditions above the Jacobs limit at all times.
- The OCR has a significant effect on the oil retention in the suction line. Increasing the OCR by 2% leads to a 20% increase in oil retention. An oil separator at the exit of the compressor may be a feasible method to reduce overall OCR if oil retention was problematic in a system.
- The vertical suction line tends to retain 10% more oil than the horizontal line when both pipes are in the annular flow regime. However, once the horizontal line transitions to stratified flow the difference becomes more apparent. Near the Jacobs limit, the vertical suction line retains twice as much oil as the horizontal line.
- It may be pertinent to calculate the Jacobs limit using $j_g^{*1/2} = 0.9$ for R410A and POE 32, to ensure operation in the annular upwards flow regime.
- A 5°C increase in apparent superheat causes a 15% increase in oil retention in the superheat range studied. At higher superheats more refrigerant is evaporated from the liquid, which increases the mass fraction of oil in the liquid, and thus the viscosity. Higher viscosity liquids will form a thicker film on the tube wall, and retain more oil.
- If the superheat is lowered and a small amount of liquid refrigerant is allowed to pass through the evaporator, the oil retained in the suction line is quickly washed out by the low viscosity liquid refrigerant. This may be an effective method for returning oil, by reducing the evaporator capacity for a short time to allow the temperature to reach saturation.
- There is some hysteresis in the transition to the churn flow regime. The transition from annular to churn flow occurs at a lower mass flux than the transition from churn back to annular flow.

NOMENCLATURE

G	mass flux	(kg/m ² s)		
j*	normalized velocity	(m/s)	Subscripts	
ρ	density	(kg/m ³)	g	vapor
g	gravity	(m/s ²)	f	liquid
D	pipe diameter	(m)		
OCR	oil in circulation ratio			
ΔT _{sh}	apparent superheat			

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