International Refrigeration and Air Conditioning Conference

School of Mechanical Engineering

2014

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Yatim, Ardiyansyah S.; Cremaschi, Lorenzo; and Fisher, Daniel E., "Measurements of Oil Retention in a Microchannel Condenser for AC Systems" (2014). *International Refrigeration and Air Conditioning Conference.* Paper 1441.
http://docs.lib.purdue.edu/iracc/1441

Measurements of Oil Retention in a Microchannel Condenser for AC Systems

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ABSTRACT

In a refrigeration cycle, a small portion of the compressor oil circulates with the refrigerant flow through the cycle components, while most of the oil stays in the compressor. The presence of the lubricant affects the performance of heat exchangers by increasing the pressure losses and adding a thermal resistance to the heat transfer exchange process. The oil effects on microchannel heat exchangers are unique due to their relatively small scale geometry and manifold configuration. In this paper, oil retention in a microchannel type condenser was measured and its effects on heat transfer and pressure drop characteristics are presented. The heat exchanger was a 2 passes, aluminum louvered-fin type condenser that consisted of multiports rectangular microchannels with hydraulic diameter of 0.06 inch (1.7 mm). The refrigerant and oil flow rates were varied and actual operating conditions of an air conditioning condenser for R410A systems were replicated in laboratory. The refrigerant R410A and Polyolester oil mixture was studied at saturation temperature from 85 to 130 °F (29 to 54 °C) and two refrigerant mass flux that are common for a 4 ton nominal capacity AC system for residential applications. Oil mass fraction (OMF) in circulation with the refrigerant was varied from 0.5 to 5.6 in wt.%.

The results indicated that at OMFs of 0.5 wt.% to 1 wt.%, which are common ranges in typical air conditioning systems, the oil retention in the microchannel condenser was less than 5% of the microchannel condenser internal volume for all saturation temperatures and all mass fluxes studied in this work. The oil retained in the condenser increased if the OMF increased and it was measured up to 23% of the total microchannel condenser internal volume when the OMF was 5.4 wt. %. The superheated vapor refrigerant section of the condenser held small amount of oil due to high refrigerant vapor superficial velocities inside the microchannel tubes. At OMFs of 0.5 wt. % the heat transfer capacity of the coil was the same of that of oil free conditions. At high saturation temperature of 130 °F (54 °C) and high mass flux, the heat transfer capacity of the coil decreased as the OMF increased and some penalization of refrigerant-side heat transfer rate was observed at OMFs as low as 1 wt. %. If OMF increased to about 5 wt. % then the heat transfer capacity of the heat exchanger was penalized by up to 6% and the pressure drops across the condenser augmented up to 19% with respect to the oil free case.

1 INTRODUCTION

In an air conditioning system, a small portion of the oil circulates with the refrigerant flow through the cycle components, while most of the oil stays in the compressor. The compressor in a refrigeration system needs oil to prevent surface-to-surface contact, to remove heat, to provide sealing, to keep out contaminants, to prevent corrosion, and to dispose of debris created by wear (Vaughn, 1971). Most compressor mechanical failures are due to improper oil management that leads to a lack of proper lubrication inside the compressors in the field. This means taking into account the fact that oil might be missing from the compressor because it can be held up inside the heat exchangers during actual system operating conditions.

Oil retention is a complex function of fluid properties as well as geometry and configuration aspects. The circulating oil, which is missing from the compressor, can form a fairly homogeneous mixture with the liquid refrigerant or it can exist as a separate oil film inside the tubes and headers of the heat exchangers; the amount of oil is affected by the system conditions. Each heat exchanger in a refrigeration cycle has different oil retention characteristics, and large amounts of oil retention cause a decrease in heat transfer and an increase of pressure drop (Cremaschi *et al.*, 2005). As a result, proper oil management is necessary in order to improve the compressor reliability, increase the overall efficiency of the system, and minimize the system cost by avoiding to install oil separators at the compressor outlets and oil pumps and other auxiliary components for oil management.

Abundant literature can be found on oil and refrigerant flow inside simple geometries. Sundaresan and Radermacher (1996) studied oil return characteristics in residential heat pump systems using R22, R407C, and R410A with mineral oil (MO) and synthetic polyolester (POE) oils. From their experiments, they recommended the use of POE oils with new refrigerant blends such as R407C and R410A. Biancardi *et al.* (1996) conducted experimental and analytical efforts to determine the lubricant circulation characteristics of R134a/POE and R134a/MO pairs in a residential heat pump system and compared the behavior with a R22/MO mixture. The minimum flow rate for "the worst-case" scenario, in which the critical velocities occurred in the vertical vapor suction line, were determined by visual observations. They reported that minimum flow velocities ranging from 1.8 to 1.9 m/s (354 to 374 fpm) were required in the vertical upward suction lines when the system operated in the cooling mode. Oil return characteristic in vertical upward flows was also investigated in Mehendale and Radermacher (2000).

In order to determine the oil retention volume, one option might be to measure the thickness of the oil film created during annular flow on the interior wall of a tube. Shedd and Newell (1998) proposed a non-intrusive, automated, optical film thickness measurement technique to be used with a wide range of fluids and flow configurations. Extensive experimental flow visualization in horizontal and vertical pipes was required and the oil film thicknesses were correlated with the oil mass flow rates, vapor velocity and pipe diameter. The technique requires optical access to the refrigerant flow and might not be practical for microchannel heat exchangers. Not only the tubes in microchannel heat exchangers are likely to be too small to provide accurate measurements of the oil film thickness by optical methods, but also creating an optical access to the tubes of a microchannel heat exchanger might interfere with the real operation of the heat exchanger during refrigerant condensation. Furthermore, the flow regime during refrigerant condensation in the actual air conditioning applications of the microchannel heat exchanger is mostly annular but the oil film thickness might not uniform along the heat exchanger refrigerant path.

While studies of oil return and oil transport in suction liners are quite numerous in the literature (Lee *et al.*, 2001;Radermacher *et al.*, 2006), measurements of oil retention in condensers for air conditioning and refrigeration systems are rather sporadic in the open domain of the state-of-the-art work (Youbi-Idrissi and Bonjour, 2008). Research focused on measuring the oil retention in fin-and-tube evaporators and condensers of air conditioning and refrigeration systems was reported by Cremaschi *et al.* (2005) and Radermacher *et al.* (2006). The refrigerants adopted in their works were R22, R410A, and R134a in combination with three different types of oils: mineral oil, polyolester (POE), and polyalkylene glycole synthetic lubricants. Oil retention was proportional and very sensitive to the oil mass fraction (OMF) of the refrigerant-oil mixture in heat exchanger. Oil retention was also observed to be proportional to the ratio of liquid film over refrigerant vapor viscosity. At constant refrigerant mass flux and OMF, an increase in oil film viscosity resulted on increased oil retention volume. The authors reported that for R410A-POE case an increased OMF from 1 to 5 in weight percentage (wt. %) caused the mass of oil held up in the condenser from 1 to 8% of the total mass of oil initially charged into the compressor. The corresponding scenario for R134a-POE mixture resulted on 15% oil retention at the condenser. The presence of the oil in the condenser caused the increase of pressure drop by 1.13 times compared to the oil-free condition. Reviews of published researches in oil effect during condensation were presented in Gidwani *et al.* (1998) and Shen and Groll (2005). Schlager *et al.* (1990) conducted experiments using R22 in combination with 150 to 300 SUS mineral oil in order to determine the effects of oil in smooth and micro-fin tubes during evaporation and condensation of refrigerant-oil mixtures. The parameters that affect the oil retention during condensation were OMF, viscosity, condenser inlet and exit conditions and saturation pressure. They reported that unlike evaporator, the decrease of heat transfer coefficient due to oil presence in the condenser was not strongly dependent on the mass flux.

The lubricant effects on microchannel heat exchangers are unique due to their relatively small scale geometry and manifold configuration. At the component level, experimental studies of oil effect on condensation heat transfer and pressure drop characteristics of R410-POE oil in a single microchannel tube were performed by Huang *et al.* (2010a) and Huang *et al.* (2010b). The authors found that the effect of the oil is most important at oil concentration of 3-5 wt. %. The presence of oil was found to always degrade the heat transfer coefficient. However, it is interesting to note that the frictional pressure drops with oil presence were less than that of pure refrigerant. The author argued that the decrease of pressure drop is influenced by the flow shift toward laminar with the presence of the oil. Works on the oil effects on refrigerant distribution in microchannel heat exchanger were recently reported in

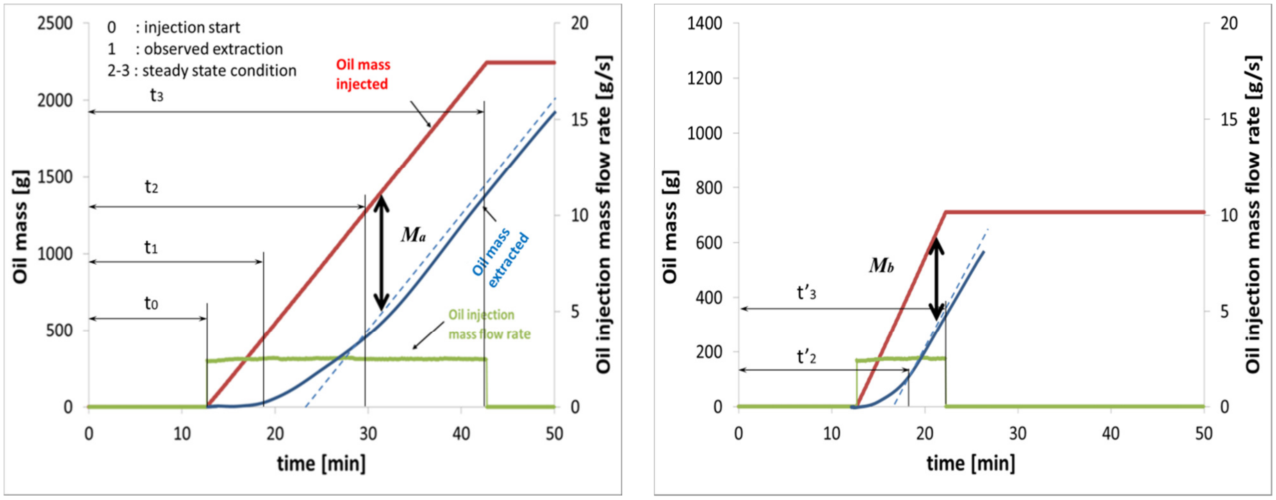
Li and Hrnjak (2013) and (Jin and Hrnjak, 2013;2014). The authors proposed a model for the refrigerant distribution, which was affected by the oil in circulation. The distributions were reported to be worse as the oil mass fraction increased up to 3%. However more uniform distribution was observed at higher oil mass fraction. The model, which used a thermodynamic approach originally proposed by Thome (1995), was able to predict the oil retention in microchannel condenser within 15% of error with respect to the measurements.

The summary of the state-of-the-art work above illustrate that, to the authors best knowledge, there are not any study that investigates the effect of oil retention on microchannel type condensers for air conditioning systems for stationary applications. This paper focuses on addressing this gap. The oil retention in a microchannel heat exchanger and its effect on heat transfer and pressure drop characteristics during condensation of refrigerant R410A and POE lubricant were measured and the findings are discussed in this paper.

2 EXPERIMENTAL METHODOLOGY, SETUP AND TEST CONDITIONS

2.1 Experimental methodology

The experiments were conducted by using boiler-pump type refrigerant closed loop in which the refrigerant was circulated by a gear pump. Oil was injected in the refrigerant loop by using a variable speed gear pump and the oil was purposely injected at two locations, namely the inlet and the outlet of the microchannel condenser (referred to as test section in this paper). The principle of the oil retention measurement procedure is illustrated in Figure 1. The amount of oil injected and extracted in and from the refrigerant loop were directly measured. The amount of refrigerant dissolved in the oil was taken into account both at the injection and extraction points based on the POE oil solubility that was estimated at measured pressure and temperature from Cavestri and Schafer correlations (2000). For several tests, measurements of solubility were also taken in the present work according to the ANSI/ASHRAE Standard 41.4-1996 (ASHRAE, 1996) in order to confirm the solubility estimated by the correlations. Referring to Figure 1(a), at the time of t_o, oil was injected at the inlet of the test section. The oil flowed through the test section and reached the oil separators where it was extracted from the system. The extracted oil was observed at the oil line sight glass at time of t_1 and by a sudden increase of the oil flow rate at the extraction point of the system. The injection and extraction flow rates becomes steady approximately at time t_2. It should be noted that refrigerant was also present in the oil flow that was extracted from the system and the solubility of the refrigerant in the oil was account for in order to obtain the amount of POE oil extracted from the refrigerant loop. It should be also emphasized that the extractor efficiency of separation ranges between 0.7 and 0.99 and it was considered in order to obtain the total amount of oil that entered the oil extractor. From time t_2 to time t_3, the average difference between the oil mas injected and the oil mass extracted from the refrigerant loop resulted in the oil mass that was held up in the microchannel condenser plus all connecting pipelines between the condenser and the oil separators. This mass is referred to as M_a in Figure 1(a).



(a) (b)

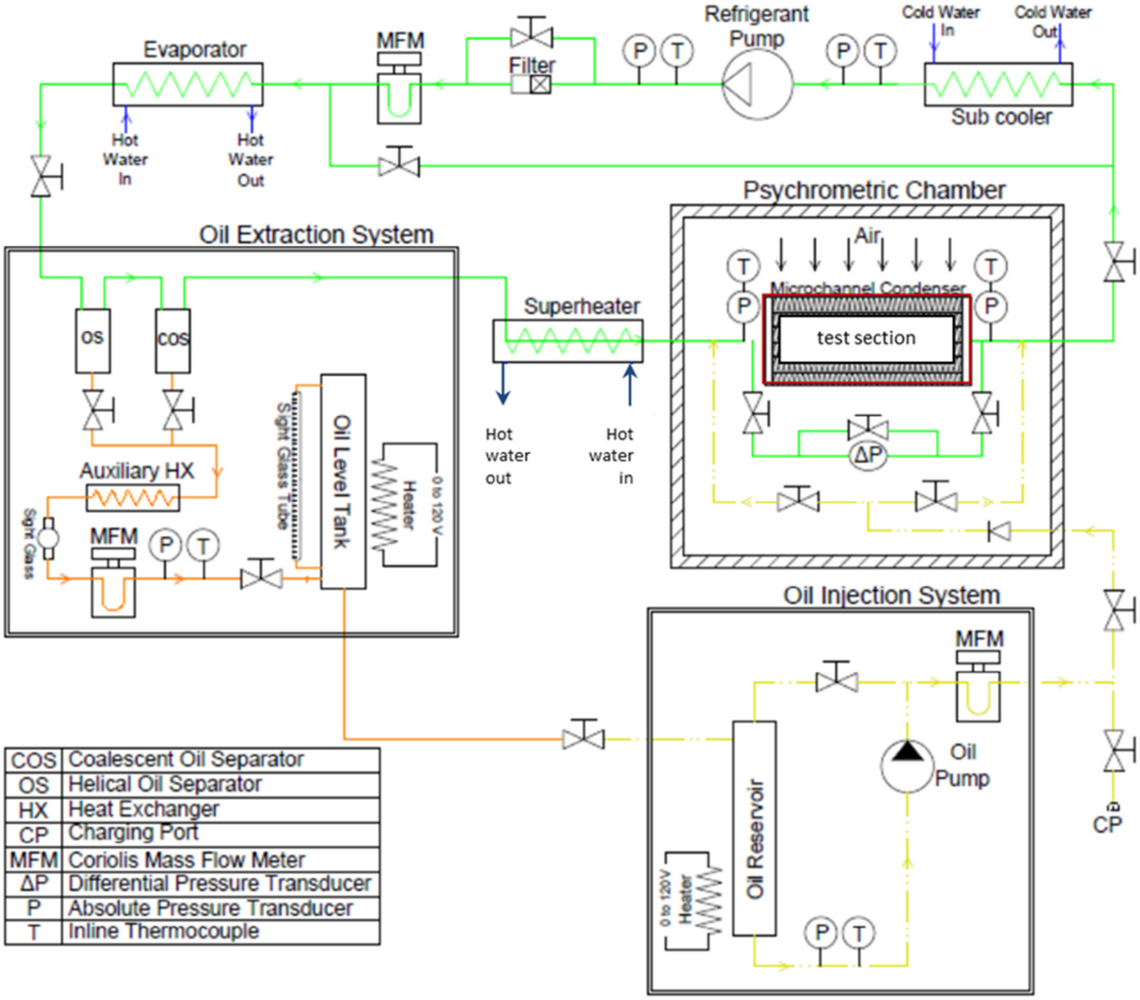
Figure 1: *Oil retention measurement at inlet (a) and at outlet (b) of the test section*

Similar procedure was then conducted at the outlet of the condenser as shown in Figure 1(b). From the new time t'$_2$ and t'$_3$, the average difference between the oil mas injected and the oil mass extracted from the refrigerant loop resulted in the oil mass that was held up in all connecting pipelines between condenser outlet and the oil separators. This mass is referred to as M_b in Figure 1(b). Since the flow rate, pressure and temperature of the refrigerant loop were the same during the two tests, the difference between the two amounts of oil masses resulted in the oil mass that was retained in the test section, $M_{oil,retention}$, that is:

$$M_{oil,retention} = M_a - M_b \tag{1}$$

2.2 Experimental setup

A schematic of the test set up for the oil retention measurements is shown in Figure 2.



COS	Coalescent Oil Separator
OS	Helical Oil Separator
HX	Heat Exchanger
CP	Charging Port
MFM	Coriolis Mass Flow Meter
ΔP	Differential Pressure Transducer
P	Absolute Pressure Transducer
T	Inline Thermocouple

Figure 2: *Experimental test setup and instrumentation for measuring oil retention in microchannel condenser, heat transfer rate and pressure drop with and without oil (boiler-pump refrigerant loop is shown at the top, oil extraction system is shown at the bottom left and oil injection system is shown at the bottom right)*

The microchannel heat exchanger was installed in a laboratory small-scale boiler pump refrigerant loop that controlled the refrigerant saturation temperature and the refrigerant flow rate. From the refrigerant pump, the refrigerant flowed through a Coriolis mass flow meter and then was directed to a tube-in-tube evaporator coil to achieve vapor superheated conditions at the inlet of the oil extraction system. The evaporator coils were heated by water and had a dedicated control. From the evaporator coils the refrigerant circulated through the oil extraction system. The oil extraction system consisted of two customized refrigerant oil separators that were placed in series, a mass flow meter and oil tanks. The first oil separator was of large capacity and it separated the main oil stream from the refrigerant flow. A second oil separator was installed downstream to remove all residual oil, when present. The oil that was extracted from oil separators was then stored in the oil tanks equipped with level sight glass indicator. Through the refrigerant line from of the oil separators, the refrigerant was directed to a plate heat exchanger that worked as superheater to control the degree of superheated vapor at the inlet of the microchannel condenser. The condenser was installed inside a thermally controlled enclosure and the inlet air temperature and velocity were regulated by a large-scale climate control psychrometric chamber (Cremaschi and Lee, 2008). Pressure transducers and inline thermocouples were installed to monitor the refrigerant conditions and a dedicated differential pressure transducer was used to measure the refrigerant side pressure drop. From the test section, the refrigerant (and oil when present) was circulated back to the pump through a large sub-cooler. In addition, an hydraulic accumulator was installed in the refrigerant line to limit pressure fluctuations during oil injection and extraction processes.

The experimental setup included an oil injection system, indicated at the right bottom side of Figure 2. The oil inside the oil reservoir was heated by an electric band heater to adjust the temperature of the oil close to the temperature of the refrigerant entering the test section. The reservoir was connected to the vapor section of the refrigerant loop and refrigerant vapor under high pressure was used to pressurize the oil. The temperature and pressure data of the oil reservoir were measured to determine the solubility of refrigerant in the oil reservoir. The solubility values were also experimentally verified with samples taken from the oil reservoir according to the ASHRAE standard (ASHRAE, 1996). From the reservoir, oil was injected into the test section using a variable speed gear pump coupled with a variable-frequency drive. Additional fine tuning of the oil flow was provided by a bypass metering valve. A Coriolis mass flow meter was used to measure the oil mass flow rate. When lubricant was injected to the test section, it formed a mixture with refrigerant and circulated through the test section, the sub-cooler, the refrigerant pump, and to the evaporator coils. Then the oil entered the oil separators where it was divided from the refrigerant stream and extracted from the refrigerant loop. The heat transfer capacity of the microchannel condenser was measured from the air side and the air flow rate was measured and calculated according to the ANSI/ASHRAE 41.2 Standard (ASHRAE, 1987). Baseline tests were conducted by measuring the heat transfer rates and pressure drops of the microchannel condenser for the nominal refrigerant flow rates, saturation pressures, and degree of superheated vapor at the inlet of the condenser. Additional tests were run for flow rates and saturation pressures slightly above and slightly below the nominal values so that the heat transfer capacity and pressure drop of the condenser with refrigerant only (i.e., no oil) were characterized at nominal conditions and in the neighbor of the nominal conditions. During the tests with oil, the performance of the condenser in oil free conditions were obtained by double interpolation of the baseline data based on flow rate and saturation pressure. This double interpolation procedure served to normalize the heat transfer and pressure drop data with and without lubricant to the same saturation pressures and flow rates, which is key in order to isolate and quantify the effects of oil retention on the heat transfer and pressure drop characteristics of the microchannel condenser.

A heat balance between refrigerant and air side was conducted when the refrigerant outlet was subcooled and the air side measurements (primary method) agreed with the refrigerant side measurements (secondary method) within ±5%. The uncertainty of the measurements was calculated based on an error propagation analysis described by Taylor and Kuyatt (1994) and the uncertainty results are summarized in Table 1.

Table 1: Experimental uncertainties

Parameter	Symbol	uncertainty
Pressure	P	±0.65 psi (4.5 kPa)
Pressure difference	ΔP	±0.03 psi (0.21 kPa)
Temperature	T	±0.1 °F (0.05 °C)
Mass flow rate	$\dot{m}$	±0.10 %
Air volume flow rate	CFM	±0.4 %

Parameter	Symbol	uncertainty
Oil mass fraction	OMF	0.1 %
Oil retention volume	ORV	2.7 %
Pressure drop factor	PDF	2.0 %
Heat transfer factor	HTF	4.3 %

2.3 Test Conditions

The test conditions are summarized in Table 2. The microchannel condenser was a 48 inch width by 36 inch height (1.2 by 0.9 m) aluminum louvered-fin type heat exchanger. The microchannel condenser consisted of 2 passes, referred as condenser and subcooler passes with 69 and 32 microchannel tubes, respectively. Each microchannel tube had multiple rectangular ports with an hydraulic diameter of 0.06 inch (1.7 mm). The refrigerant-oil mixture tested was R410A and ISO VG 32 Mixed Acid Polyolester (POE) oil at saturation temperatures ranging from 85 to 130 °F (29 to 54 °C) and refrigerant flow rates of 400 and 600 lb/hr (0.05 and 0.08 kg/s), referred as low and high flow rates, respectively. The corresponding mass fluxes for condenser and subcooler sections of the microchannel heat exchangers are indicated in Table 2. The oil mass fraction (OMF) in the refrigerant-oil mixture flow rate was varied from 0 to 5.6 in wt.%. The degree of inlet superheated vapor were controlled to 65 °F (36 °C) for all tests. At the condenser pass, the refrigerant liquid phase Reynolds number (Re) ranged from 1,200 to 2,500 and the refrigerant vapor phase Re ranged from 7,900 – 13,900. For the subcooler pass, the liquid refrigerant phase Re ranged from 2,500 – 5,500 and the refrigerant vapor phase Re ranged 16,600 – 32,600. Thus the liquid phase flow was mostly laminar and the vapor refrigerant flow was always turbulent.

Table 2: Test conditions for the microchannel condenser

Test Label	T_{sat} °F (°C)	$\dot{m}$ lb/hr (kg/s)	$G_{condenser}$ $lb_m/ft^2\cdot s$ ($kg/m^2\cdot s$)	$G_{subcooler}$ $lb_m/ft^2\cdot s$ ($kg/m^2\cdot s$)	OMF (wt.%)
A	85 (29)	low	16 (80)	36 (173)	From 0 up to 5.6
B	105 (41)				
C	130 (54)				
D	85 (29)	high	24 (120)	53 (260)	
E	105 (41)				
F	130 (54)				

3 EXPERIMENTAL RESULTS

3.1 Data Reduction

The amount of oil carried over with the refrigerant in the microchannel heat exchanger is referred to as the oil mass fraction (OMF) and in steady state conditions, was calculated as follow:

$$OMF = \frac{\dot{m}_{oil}}{(\dot{m}_{oil}+\dot{m}_{ref})} \times 100 \tag{1}$$

The amount of oil retention was calculated from the measured oil retention mass, $M_{oil,retention}$, as follow:

$$OR = \frac{M_{oil,retention}}{\rho_{oil@20\,°C}} \tag{2}$$

Where ρ was the density of the oil at reference temperature of 68 °F (20°C). The oil retention inside the microchannel heat exchanger was measured according to the procedure described in the experimental setup and calculated by equations (1) and (2). The normalized oil retention volume, ORV_N, was calculated as the ratio of the oil volume retained in the heat exchanger to the internal volume of the microchannel condenser, including the headers, $MCHX_{volume}$, as follows:

$$ORV_N = \frac{OR}{MCHX_{volume}} \tag{3}$$

The amount of oil retained in the test section can result in flow restriction for the refrigerant flow, hence affecting the pressure drop. The lubricant also increased the viscosity of the liquid phase. The combined effects on pressure drop were estimated by measuring the pressure drop in the test section at specific mass flow rates and OMFs. The mixture's pressure drop at the measured OMF, $\Delta p_{with\ oil}$, was compared to the corresponding pressure drop for refrigerant-only flow through the test section at the same mass flow rate and at the same saturation pressure. The double interpolation of the pressure drop baseline data yielded to the pressure drop without oil of $\Delta p_{with\ no\ oil}$. A pressure drop factor (PDF) was used to quantify the effect of lubricant on the refrigerant side pressure drop of the condenser and it was defined as follows:

$$PDF = \frac{\Delta P_{with\ oil}}{\Delta P_{with\ no\ oil}} \tag{4}$$

Similarly, a microchannel condenser heat transfer capacity factor, HTF, was used to quantify the effect of lubricant on the refrigerant side heat transfer rate of the condenser. HTF was calculated based on the heat transfer capacity measured during tests with oil, $\dot{Q}_{with\ oil}$, and the corresponding capacity in case of refrigerant only flow (i.e. no oil) at the same mass flow rate and at the same saturation pressure. The double interpolation of the heat transfer rate baseline data yielded to the heat transfer capacity without oil of $\dot{Q}_{with\ no\ oil}$. The HTF resulted as follows:

$$HTF = \frac{\dot{Q}_{with\ oil}}{\dot{Q}_{with\ no\ oil}} \tag{5}$$

The experimental results of oil retention, pressure drop factor and heat transfer factor of refrigerant R410A and POE oil mixture in microchannel condenser are presented and discussed in the next sections. The findings are summarized in figures 3 to 5 as a function of oil mass fraction (OMF) for each test condition, represented by open and full symbols and legend A to F according to Table 2.

3.2 Oil Retention

The oil retention volume for each saturation temperature and mass flux are presented in Figure 3. The results indicated that the oil retained in the condenser was strongly depended on the OMF. The oil retention volume increased if the OMF increased and it was up to 23% of the total microchannel condenser internal volume when the OMF was 5.4 wt. %. At OMFs of 0.5 wt.% to 1 wt.%, which are common ranges in typical air conditioning systems, the oil retention in the microchannel condenser was less than 5% of the condenser internal volume for all saturation temperatures and all mass fluxes. The effects of mass flux are indicated in Figure 3 by full symbols for low mass fluxes (cases A, B, and C) and the corresponding open symbol for high mass fluxes (cases D, E and F). Figure 3 shows that the effects of mass flux were negligible at OMF lower than 2 wt. %. As OMF increased above 2.5 wt. %, the effects of mass flux showed different trends at the three saturation temperatures. The impact of mass flux on oil retention volume is significant at medium saturation temperature of 105 °F (41 °C) as represented by cases B and E in the figure. The oil retention volume increased by almost 3 times as mass flux increased from low to high. For low saturation temperature of 85 °F (29 °C) (see series A and D) and high saturation temperature of 130 °F (54 °C) (see series C and F) the mass flux did not have a measurable effect on oil retention and the data of each pair of series belonging to the same saturation temperature were within the experimental uncertainty. At low mass flux, the oil retention volume was found to be maximum at low saturation temperature of 85 °F (29 °C). As the saturation temperature increased to 105 °F (41 °C), the oil retention decreased. Then the oil retention volume increased back at high saturation temperature of 130 °F (54 °C). For the high mass flux cases, the oil retention volumes for low and medium saturation temperatures were similar as indicated by the open symbols for series D and E in Figure 3. However, lower oil retention occurred when the saturation temperature increased to 130 °F (54 °C). This non-linear behavior observed on the oil retention volumes may be attributed to different flow regimes established in the microchannel condenser tubes when oil was present. The properties of the liquid mixture and the exit quality of the refrigerant and oil mixture varied. Thus, the oil retained in the condenser seemed to be proportional to the amount of liquid refrigerant present inside the heat exchanger during the condensation process.

3.3 Pressure Drop Factor

The pressure drops factor (PDF) of refrigerant R410A and POE oil mixture in microchannel condenser are shown in Figure 4. By definition, the PDF is equal to 1 at OMF equal to 0, that is, when no oil is present in the condenser. Figure 4 indicates that the PDF increased as the OMF increased. Up to 19 % increase of pressure drop were measured at high T_{sat} of 130 °F (54 °C). The increasing pressure drop with oil presence can be attributed to the higher refrigerant-oil liquid mixture viscosity compared to that of liquid refrigerant, which caused an increase on shear stress and of the frictional pressure drop. The effects of oil presence was also important for annular flow encountered in the microchannel tubes as the increase of mixture viscosity has been reported to increase the shear stress pronouncedly for annular flow regime compared to that of other flow regimes (Shao and Granryd, 1995). Another reason for the pressure drop increase can be attributed to flow restriction effects to the superheated vapor refrigerant at the inlet section of the microchannel condenser.

As indicated in Figure 4, the pressure drop increased if the refrigerant mass flux increased although with different magnitude based on the saturation temperature of the refrigerant. If OMF was above 2 wt. % the pressure drop augmented significantly with the increase of refrigerant mass flux at high saturation temperature, as shown by the series C and F in Figure 4. At saturation temperature of 130 °F (54 °C), the PDF at low mass flux (see series C) was approximately 1.1 at OMF of 3 wt. % and it increased to about 1.2 for the corresponding high mass flux case (see series F). This behavior did not occur at saturation temperatures of 85 and 105 °F (29 and 41 °C) for which the PDFs at OMF of 3 wt. % for low and high mass fluxes were within the experimental uncertainty.

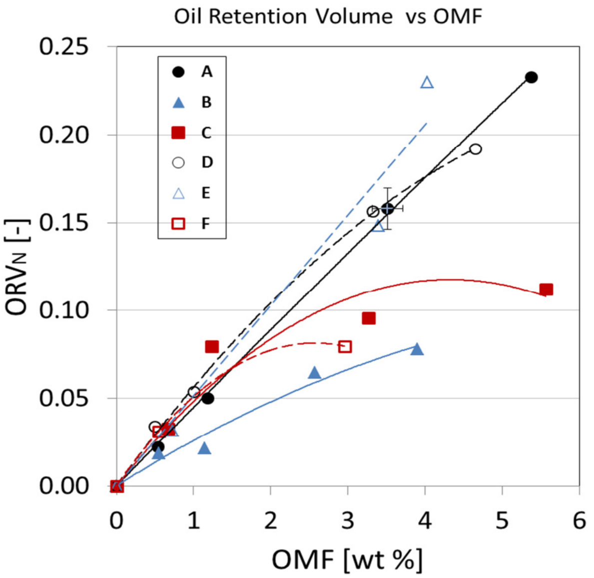


Figure 3: *Oil retention volume (ORV_N) as a function of oil mass fraction (OMF), saturation temperature, and mass flux*

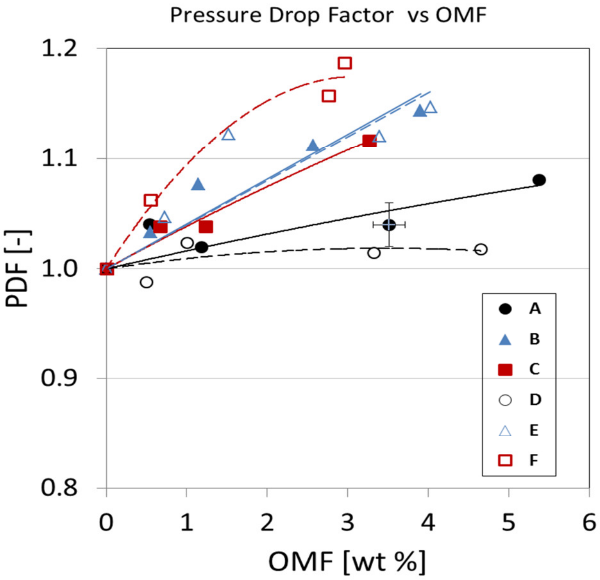


Figure 4: *Pressure drop factor (PDF) as a function of oil mass fraction (OMF), saturation temperature, and mass flux*

Thus, it is interesting to note that at high saturation temperature, the effect of refrigerant mass flux became dominant even though the viscosity of R410A-POE oil mixture was lower. This could be due to conditions of immiscibility of the refrigerant and oil mixture at higher saturation temperature for the superheated section of the condenser. In addition, the section of the condenser with superheated vapor increased at high saturation temperature of 130 °F (54 °C) because R410A was nearer to its critical point temperature of 163 °F (72.8 °C). Thus, the condenser reject less heat in the two phase region and more heat in the superheated region when compared to condensation at saturation temperatures of 85 and 105 °F (29 and 41 °C). Because the desuperheating section in the condenser increased when the saturation temperature approached 130 °F (54 °C), the flow restrictions effects of the lubricant were more severe due to higher refrigerant vapor superficial velocities in the condenser. This could explain why the PDF increased significantly at higher saturation temperature of 130 °F (54 °C) when the mass flux increased from low to high.

3.4 Heat Transfer Capacity Factor

The heat transfer capacity factor of R410A and POE oil mixture during condensation in microchannel heat exchanger is summarized in Figure 5. At OMFs of 0.5 wt. % the heat transfer capacity of the coil was the same of that of oil free conditions and the measured HTFs with oil were within the experimental uncertainty. At high saturation temperature and high mass flux, indicated with the series F, the HTF decreased as the OMF increased and some penalization of heat transfer was observed at OMF as low as 1 wt. %. For medium saturation temperature of 105 °F (41 °C), indicated with the series B and E in Figure 5, the heat transfer factor capacities seemed to decrease if OMF was above 2 wt.% and the HTFs were independent from the mass flux conditions. For medium saturation temperature and at OMF of 3 wt. % the HTF was about 0.97. It is interesting also to note that at low saturation temperature, the presence of oil seemed to increase the heat transfer capacity of the coil, although not in monotonic fashion. This means that the heat transfer capacity at saturation temperature of 85 (29°C) increased if the OMF

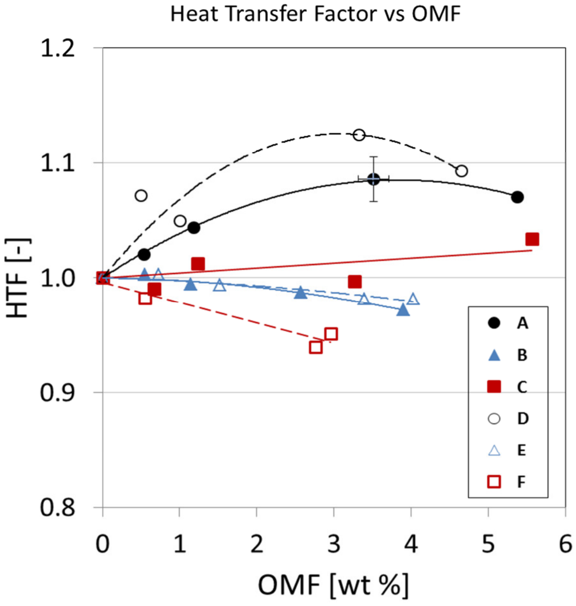


Figure 5: *Heat transfer capacity factor (HTF) of the microchannel condenser as a function of oil mass fraction (OMF), saturation temperature, and mass flux*

increased up to about 3 wt. %, and then the heat transfer capacity started to decline when the OMF increased further. The effects of mass flux in heat transfer capacity indicated different tendencies which were dependent on saturation temperature. At low saturation temperature, the HTF was slightly higher for high mass flux compared to that of low mass flux as depicted in Figure 5 for series A and D. On the other hand, at high saturation temperature (see series C and F), the HTFs had opposite trends: the heat transfer capacity of the coil was basically unaffected by the oil for high saturation temperature of 130 °F (54 °C) and low mass flux (see series C) while it decreased if the mass flux was high (see series F). At saturation temperature of 105 °F (41 °C), the HTFs were not affected by the mass flux. The HTFs decreased if the saturation temperature increased and OMF and mass flux were constants. The degradation of heat transfer capacity can be attributed to the augmentation of the liquid mixture viscosity of refrigerant-oil mixture compared to that of refrigerant. The higher viscosity, along with the higher surface tension of the liquid refrigerant-oil mixture might reduce the molecular and thermal transport within the condensate liquid mixture at the wall of the microchannel tube; hence decreasing the condensation heat transfer coefficient. It should be also emphasized that the trends seen in Figure 5 for the saturation temperatures are the combined results of variation in heat transfer in the superheated, two-phase, and sub-cooled sections of the condenser and with the test methodology of the present work, each individual contribution cannot be isolated and quantified.

4 CONCLUSIONS

This paper investigates the effect of oil retention on the heat transfer capacity and pressure drop of a microchannel condenser. Refrigerant R410A and POE lubricant were studied at saturation temperatures of 85, 105, and 130 °F (29, 41 and 54 °C). The results indicated that the oil retained in the condenser was strongly depended on the OMF. At OMFs of 0.5 wt.% to 1 wt.%, which are common ranges in typical air conditioning systems, the oil retention in the microchannel condenser was less than 5% of the microchannel condenser internal volume for all saturation temperatures and all mass fluxes studied in this work. The oil retention volume increases if the OMF increases and it was measured up to 23% of the total microchannel condenser internal volume when the OMF was 5.4 wt. %. The superheated vapor refrigerant section of the condenser held small amount of oil due to high refrigerant vapor superficial velocities that carried the lubricant inside the microchannel tubes.

At OMFs of 0.5 wt. % the heat transfer capacity of the coil was the same of that of oil free conditions. At high saturation temperature of 130 °F (54 °C) and high mass flux, the heat transfer capacity of the coil decreased as the OMF increased and some penalization of refrigerant-side heat transfer rate was observed at OMFs as low as 1 wt. %. If OMF increased to about 5 wt. % then the heat transfer capacity of the heat exchanger was penalized by up to 6% and the pressure drops across the condenser augmented up to 19% with respect to the oil free case. The increases of pressure drop were consistent with larger amount of oil retained in the microchannel condenser if the OMF increased. At low saturation temperatures of 85 °F (29 °C) and high mass flux, the heat transfer capacity of the coil increased if the OMF increased up to 3 wt. % and then it started to decline.

NOMENCLATURE

Symbol	Meaning	Unit	Symbol	Meaning	Unit
ΔP	pressure drop	Psi (kPa)	ORV	oil retention volume	(-)
G	mass flux	lb/ft^2.s (kg/m^2.s)	PDF	pressure drop factor	(-)
HTF	heat transfer factor	(-)	$\dot{Q}$	heat transfer	Btu/h (W)
$M_{oil,retention}$	mass of oil retention	lb (g)	T	temperature	°F (°C)
$\dot{m}$	mass flow rate	lb/h (kg/s)	**Subscript**		
OMF	oil mass fraction	wt.%	sat	saturation	
OR	oil retention	ft^3(m^3)	ref	refrigerant	

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ACKNOWLEDGEMENTS

The authors gratefully acknowledge funding and support from the American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE), as well as the help of the Project Monitor Subcommittee Members and ASHRAE Technical Committee TC 8.4 Air-to-refrigerant Heat Transfer Equipment. The authors would also like to thank you Pratik Deokar, a graduate student from Oklahoma State University, for the help with construction and calibration of the experimental setup.