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ABSTRACT

This paper presents an experimental investigation of transient refrigerant and oil migration in a residential heat pump water heater (HPWH) system. In the experiments, R134a is paired with POE 22 oil. The Quick Closing Valve Technique (QCVT) is employed to localize the refrigerant and oil into each section of the system. The Remove and Weigh Technique (RWT) is then applied to measure the trapped refrigerant mass in the sections, with an uncertainty about 0.17% of the total refrigerant charge. The retained oil mass in each section, except for the compressor, is determined by the Mix and Sample Technique (MST), of which the uncertainty is about 0.15% of the total oil charge. Five experiments are conducted to cover a full heating-up of five hours. The experimental data shows that the most of refrigerant is in the heat exchangers. The inventory of the refrigerant generally decreases in the evaporator and increases in the condenser during the heating-up. The measurements also indicate that most of the oil stays in the compressor. The retention of the oil generally increases in the evaporator and it first decreases then increases in the condenser.

1. INTRODUCTION

In most vapor-compression refrigeration systems, oil is added into the compressor for lubrication. However, it is inevitable that a portion of oil escapes from the compressor and circulates throughout the system with refrigerant. The presence of the circulating oil affects the performance of the heat exchangers and the reliability of the compressor. Therefore, the study of refrigerant and oil migration in the system is of great significance.

Over the years researchers have developed various ways to experimentally study refrigerant and oil migration. One of the commonly used methods is the Quick-Closing Valve Technique (QCVT). In this method, the refrigerant and oil would be trapped into the section of interest by simultaneously closing two valves at the ends. The mass of the trapped refrigerant and oil is then obtained by different secondary procedures. Peuker and Hrnjak (2010) applied this method to study the refrigerant and oil migration in an automotive A/C system in steady and transient stop-start states. In their study, the tapped mass of refrigerant was measured by the Remove and Weigh Technique (RWT), in which the refrigerant was recovered by liquid nitrogen and then weighted. Their results showed that an uncertainty of 0.4% regarding the total refrigerant mass was reached. Jin and Hrnjak (2012) used the same methods (QCVT and RWT) to explore the steady distribution of two different refrigerants (R134a and R1234yf) pairing with oil PAG46 in an automotive A/C system. The deviation of the refrigerant distribution measurements was concluded to be 2% in their work. Björk [4] proposed another method to quantify the trapped refrigerant. In this method, the trapped refrigerant is expanded into a large vessel in which the superheat state is reached. Then the mass is calculated by the internal volume of the vessel and the pressure-volume-temperature (P-V-T) relationship of refrigerant. Björk (2005) compared this method with the RWT and found the deviation between these two secondary procedures was ranging from 1%~5%.

Non-intrusive measuring method, also known as the On-Line Measuring Technique (OLMT), quantifies the refrigerant mass in a section by placing it on a scale and directly measuring its weight while the system is still running. Miller (1985) applied this method to measure the migration in the outdoor unit of a 3-ton R22 split-system air-to-air heat pump. The results showed that the accuracy was about 0.05 kg.

Various methods have been developed to quantify the distribution of oil in the vapor-compression systems. For non-intrusive measurements, Shedd and Newell (1998) developed an optical technique to measure the in-tube oil film thickness. In this method, a light beam was reflected by the interfaces of the oil film flowing in a transparent tube. The thickness of the oil film could be calculated based on the reflected pattern on the outside of the tube wall. Xu and Hrnjak (2017) applied this method to measure the oil film thickness in the compressor discharge line. They also developed a video processing method to quantify the oil droplet sizes and velocities in annular-mist flow in the compressor discharge line. They concluded that their method gave a good agreement with the traditional sampling method. Lee et al. (2011) used injection-extraction method to investigate the oil retention in each component of a CO_2/PAG 46 A/C system. In their experiments, oil was injected at the inlet of a component and separated at the outlet with an oil separator. The oil retention was the difference between the mass of the oil injected and extracted. Cremaschi (2004) applied this technique on a residential A/C system and estimated the relative error of this method be 12%.

Peuker and Hrnjak (2010) developed the Mix and Sample Technique (MST) to determine the trapped oil mass in the sections after applying the QCVT. Jin and Hrnjak (2012) employed this method to study the oil distribution in an automobile A/C system and an uncertainty of 2.5% was reported in their work.

In this paper, the QCVT and the RWT, as well as the MST, are applied to a residential heat pump water heater (HPWH) system to investigate the transient refrigerant and oil migration during its heating-up.

2. EXPERIMENTAL SETUP

The experimental facility used in this study is instrumented on the base of a residential heat pump water heater system, which consists of a vapor-compression system and a 66-gallon water tank. The schematic of the experimental facility is given in Figure 1.
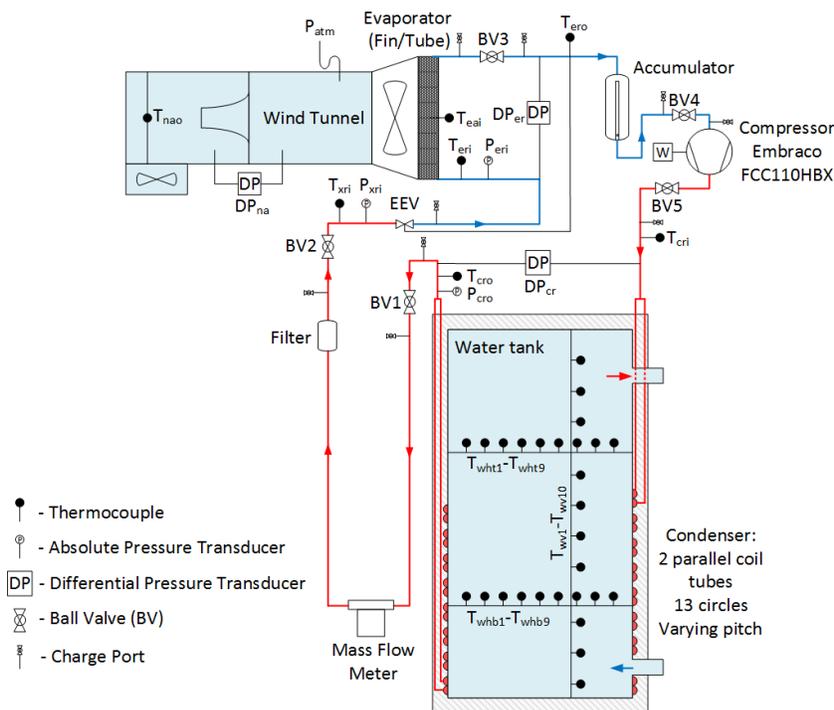
Figure 1: Schematic of experimental facility

In this HPWH, R134a is paired with oil POE 22. The evaporator is a fin-and-tube heat exchanger which has 2 circuits and 13 passes per circuit. The tube diameter is 7.9 mm. A low-side hosing reciprocating compressor, in which the housing cavity (where the lubricant oil is stored) is at the suction pressure, is used in this system. The condenser has two parallel aluminum coil tubes which are wrapped around the water tank. For a better contact with the tank wall, the coil tubes are designed to have a d-shaped across section.

The original design of this particular HPWH contains two immersed electric resistance heaters that operate in lieu of the heat pump system at high heat demanding. For the purpose of this study, the electric heaters have been removed, and the heating of water only relies on the vapor-compression system.

Type-T immersed thermocouples and absolute pressure transducers are installed at several key locations in the refrigeration loop to monitor the states of refrigerant. Two differential pressure transducers are also employed to measure the pressure drop across two heat exchangers. A Coriolis type mass flow meter is installed in the liquid line to measure the refrigerant mass flow rate. A wattmeter is connected to the compressor to record the power consumption. A wind tunnel is used to obtain the air side energy balance based on the air flow rate and temperature change cross the evaporator. On the water side, 28 thermocouples are put inside the water tank to monitor the temperature change during the heating-up, 10 of them are placed vertically along the centerline of the tank, with 10.16 cm interval; the rest are placed horizontally at two levels: 27 cm and 76.1 cm above the bottom. Each horizontal series has 9 thermocouples with 5.08 cm interval.

To implement the QCVT in this system, 5 manually operated ball valves are installed into the refrigerant loop, which divide the system into 5 sections: the condenser, the liquid line, the evaporator, the accumulator and the compressor. To be clarified, the liquid line in the original HPWH system is much shorter than its current length. It has been artificially prolonged to accommodate the space of the instruments. Two charge ports are also added at two ends of each section for the secondary procedures of the refrigerant/oil retention measurements.

The entire experimental facility is placed in an environmental chamber where a PID-controlled heater is used to provide the required heat to this HPWH system and maintain the ambient temperature relatively constant at 25 $^{\circ}$C.

In this study, the charge of the refrigerant is selected to maximize the Coefficient of Performance (COP) and the charge of the oil is kept the same as initial charge of the compressor.

Following the method developed by Peuker and Hrnjak (2010), the QCVT and the RWT, as well as the MST, are used to investigate the transient refrigerant and oil migration during the heating-up of the HPWH. For this HPWH unit, it takes around 5 hours to heat a full tank of water from an initial temperature of 25 $^{\circ}$C to 50 $^{\circ}$C with the ambient temperature fixed at 25 $^{\circ}$C. Therefore, in this study, 5 experiments have been conducted after the HPWH running for 1~5 hours. For each experiment, the refrigerant and oil retention in all 5 sections have been determined. After each experiment, the system would be cleaned by the flushing machine and recharged with the same amount of refrigerant and oil for the next test.

To test the accuracy of the MST, several verification experiments have also been conducted. In these experiments, a known quantity of the oil is added into a vessel to simulate the oil retained in a section. Then, the MST is applied to obtain the oil quantity in the vessel, and the measured oil mass is then compared with the original charge. 5 tests have been conducted to cover a possible range of the oil retention in reality. The results are given in Figure 2. Within the tested range, the deviation between the charged oil mass and measured oil mass is less than 0.4 g. Overall, it can be concluded that MST is capable to measure the oil retention in the section with an acceptable accuracy. 0.4 g is also taken as the uncertainty of MST.

It is also crucial to know the internal volume of each section since it directly indicates how much physical space each section has to contain the refrigerant/oil. Two methods are applied to determine the internal volume of the sections: the Liquid Refrigerant Method and the Isothermal Gas Method. The basic principle of these two methods is similar: the section is filled with a known quantity of a fluid and the internal volume is then calculated based on the mass and the density calculated from the equilibrium temperature and pressure. In the Liquid Refrigerant Method, subcooled R134a is used, while in the Isothermal Gas Method, vapor CO_2 is chosen. The measurement results are given in Figure 3. The internal volumes obtained using these two methods agree with each other (deviation < 5%), thus the average values of these two methods are used.
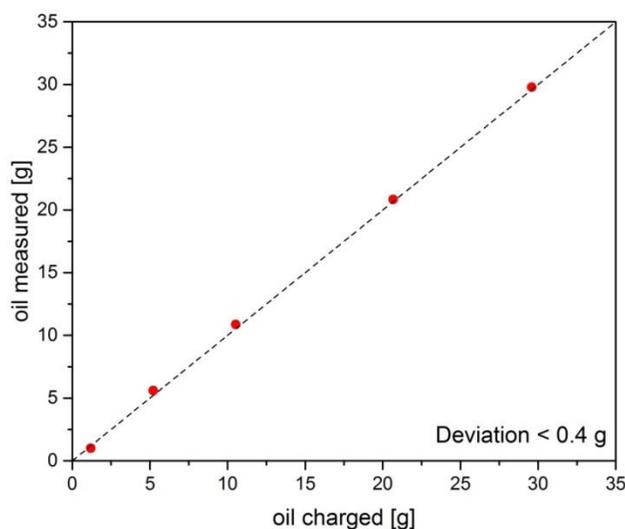
**Figure 2:** Verification tests of the Mix and Sample Technique (MST)
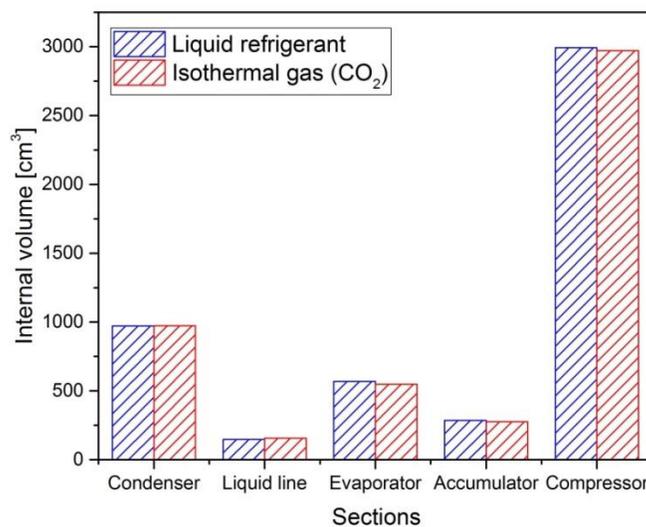
Figure 3: Measurements of internal volume by two methods

3. RESULTS AND DISCUSSION

3.1 Refrigerant Distribution

The transient refrigerant distribution is shown in Figure 4. It can be seen in the Figure 4 that the refrigerant distribution among 5 sections is similar at different time instants (1~5 hours). Generally speaking, the condenser has the highest refrigerant retention ($\approx$60%) due to its largest internal volume and a moderate void fraction. The liquid line has the smallest internal volume among all 5 sections, but it retains the second largest refrigerant mass ($\approx$20%) because it contains only liquid refrigerant. It's worth noticing that this liquid line section does not exist in the original HPWH unit, which means a real commercial product does not contain this part of refrigerant. The evaporator has a moderate internal volume and void fraction, which makes about 14% of refrigerant retained in it. Although the compressor has the largest internal space, only less than 7% of total refrigerant is found in it since the majority of the compressor internal volume is occupied by superheated vapor refrigerant. But there is still a portion of liquid refrigerant dissolved in the oil, and reserves as the refrigerant-oil mixture in the compressor. Accumulator is found to have the smallest amount of refrigerant in 5 sections. This means under the selected charge, the accumulator is not used as storage of refrigerant, but functions to avoid liquid going into the compressor.

Figure 4 also reveals the transient migration of the refrigerant among 5 sections during the 5-hour's heating-up. It seems that the refrigerant retention in the liquid line, the accumulator and the compressor keeps a relatively constant value during the heating-up. This is because in these three sections, the refrigerant is almost single-phase, of which the density does not change too much during the heating-up. P-h diagram during the heating-up of this HPWH system, given in Figure 5, may help explain the change of refrigerant retention in two heat exchangers. More detailed description of the system performance could also be found in Li and Hrnjak (2018). In the evaporator, the refrigerant generally decreases with the time. This is because the inlet quality of the evaporator increases during the heating-up and that makes more internal volume occupied by vapor refrigerant. On the contrary, the condenser seems to hold an increasing refrigerant mass with the time. Actually, it can be observed in the P-h diagram, with the elevation of the condensation pressure, the superheated region and subcooled region are both increasing during the heating-up. At the same time, the density of vapor refrigerant is also increasing with the time. Therefore, there are two factors which increase the refrigerant retention (increased subcooled region, higher vapor density), and one factor that decreases the refrigerant retention (increased superheated region). The ultimate refrigerant retention change in the condenser is the collective outcome of these factors.
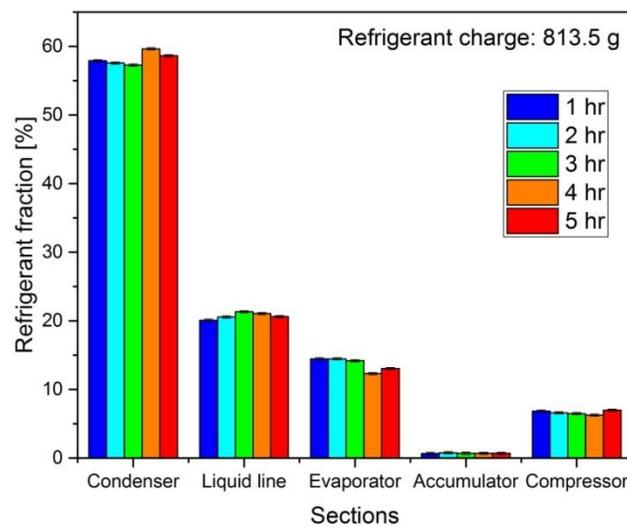
Figure 4: Refrigerant distribution in time during the heating-up
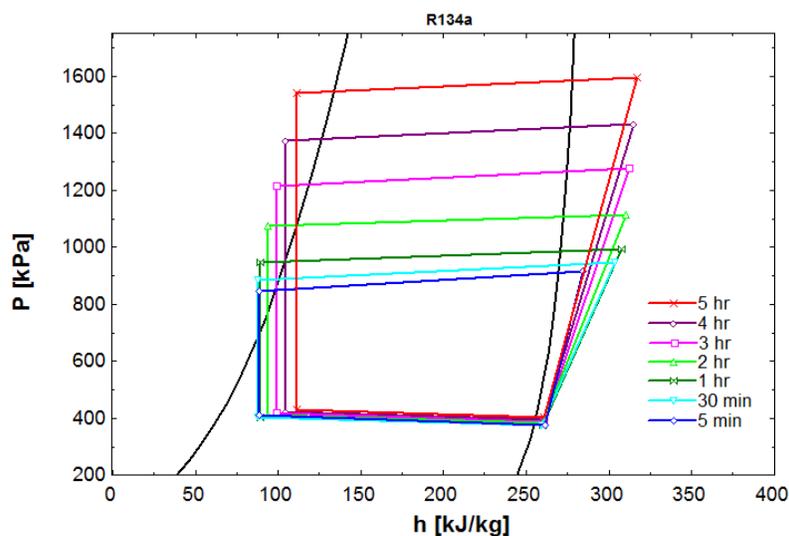
**Figure 5:** P-h diagram of the heating-up

With the data in Figure 4, as well as the pressure and temperature measurements during the tests and the internal volume, the average liquid fraction in each section, which is the ration of the liquid occupied volume and the total internal volume, can be calculated. In each section, the measured refrigerant mass can be expressed as the sum of liquid refrigerant and vapor refrigerant in Equation (1):

$$\left[\rho_{vap} \cdot \alpha + \rho_{liq} \cdot (1 - \alpha)\right] \cdot V = M_{ref,section} \tag{1}$$

The densities in Equation (1) are approximated by the saturated vapor and liquid density of the refrigerant at the average pressure.

$$\rho_{vap} \approx \rho_{sat,vap}(P_{avg}); \ \rho_{liq} \approx \rho_{sat,liq}(P_{avg}) \tag{2}$$

The average liquid fraction in each section can be calculated by solving Equation (1) and (2). The results are shown in Figure 6. As described above, the refrigerant in the liquid line, the accumulator and the compressor is almost single-phase. In Figure 6, the liquid fraction of these sections is either 100% (the liquid line) or near 0% (the accumulator and the compressor). For two heat exchangers, the change of liquid fraction accords with the change of refrigerant retention during the heating-up. In the evaporator, the liquid fraction decreases with the time, which corresponds to an increasing inlet quality; in the condenser, the liquid fraction increases with the time and that means the increase in subcooled region is dominant over the increase in superheated region.
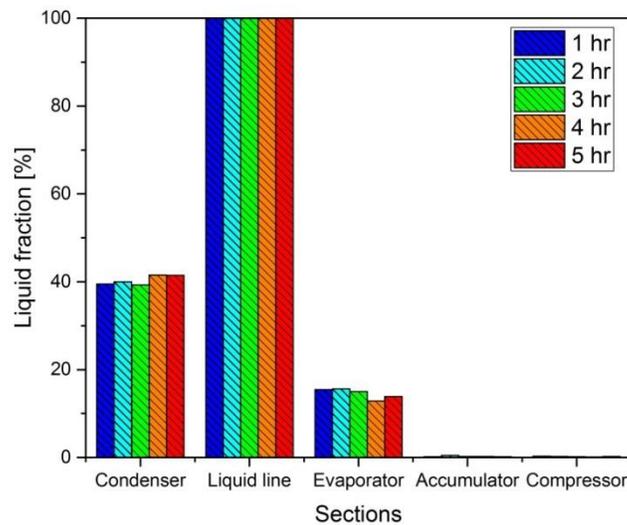
Figure 6: Liquid fraction (1- α)

To further analyze the refrigerant retention in two heat exchangers, the liquid and vapor refrigerant mass fraction (with respect to the total charge) during the heating-up has been estimated by Equation (3) and (4) below, and given in Table 1.

$$\rho_{vap} \cdot \alpha \cdot V = M_{ref,vap} \tag{3}$$

$$\rho_{liq} \cdot (1 - \alpha) \cdot V = M_{ref,liq} \tag{4}$$

According to the estimation in Table 1, in the evaporator, the vapor refrigerant mass increases and liquid refrigerant mass decreases with the time. This agrees with two previous observations: inlet quality increases and liquid fraction decreases during the heating-up. In the condenser, the vapor refrigerant mass also increases with time. This indicates that the increase in the vapor density at a higher condensation pressure compensates the decrease in void fraction. The liquid refrigerant mass in the condenser is estimated to first decrease then increase with the time. This may be the outcome of compromise between the increasing liquid fraction and a varying liquid density.

Table 1: Estimated liquid and vapor refrigerant distribution in heat exchangers

| Time [hr.]	Condenser		Evaporator	
	$M_{ref,vap}$ [%]	$M_{ref,liq}$ [%]	$M_{ref,vap}$ [%]	$M_{ref,liq}$ [%]
1	3.39	54.52	1.02	13.46
2	3.72	53.86	1.02	13.45
3	4.41	52.87	1.06	13.13
4	4.68	54.98	1.08	11.23
5	5.24	53.40	1.09	11.98

3.1 Oil Distribution

Table 2 shows the oil distribution in the HPWH unit during the heating-up. The results are also given in percentage of the initial total charge. It can be seen that most of the oil still stays in the compressor during the 5-hours' heating-up. Only less than 4% of the oil escapes from the compressor. The escaped oil is mainly distributed in two heat exchangers and the accumulator. A very small portion of oil ($< 0.2\%$) is found in the liquid line. With the refrigerant and oil retention data in the liquid line, the system OCR (Oil Circulation Rate) at different time points can be calculated. The calculated OCR for this system is ranging from 0.25% to 0.29%.

To analyze the transient migration of oil in the system, a bar graph, shown in Figure 7, is used to present the data in Table 2, but the oil retention in the compressor is excluded due to its large scale. It can be clearly seen from the Figure 7 that, during the heating-up, the evaporator holds more and more oil. But for the condenser, the oil retention seems to decrease at the first three hours, and later increase. Both the refrigerant and oil mass in the liquid line are relatively constant, and that leads to an almost constant system OCR. The accumulator serves as a separator to avoid liquid refrigerant entering the compressor. Its complex geometry may contribute to an irregular change of retained oil mass in it.

Table 2: Oil distribution [%]

Time [hr.]	Condenser	Liquid line	Evaporator	Accumulator	Compressor
1	1.38	0.17	0.89	0.91	96.65
2	1.28	0.16	0.99	0.87	96.70
3	0.99	0.17	1.00	0.96	96.88
4	1.10	0.17	1.21	0.73	96.79
5	1.28	0.16	1.31	0.92	96.33
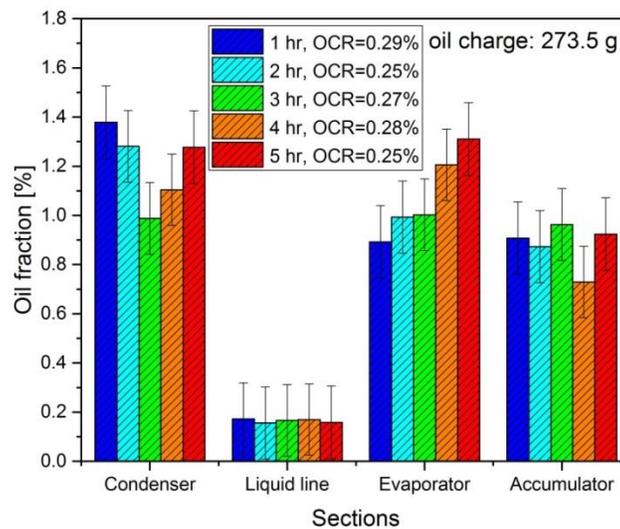
Figure 7: Oil distribution in time during the heating-up

To explain the oil retention change in two heat exchangers, following analysis could be helpful. To start with, it is important to assume that oil always flows with the liquid refrigerant as a homogeneous refrigerant-oil mixture. Therefore, the velocity of the oil is the same as the velocity of the liquid refrigerant. The next assumption in this analysis should be no oil is stationary and all oil is flowing with the liquid refrigerant. With these two assumptions, the retained mass of the oil in a section can be estimated by the oil mass flow rate multiplying the time needed for one oil molecule to flow through the entire section.

$$M_{oil} = \dot{m}_{oil} \cdot \Delta t_{oil} = \dot{m}_{oil} \cdot \frac{L_{section}}{\bar{v}_{oil}} = OCR \cdot \dot{m}_{total} \cdot \frac{L_{section}}{\bar{v}_{liq}} \tag{5}$$

Here, $\dot{m}_{total}$ is the total mass flow rate of refrigerant and oil; $L_{section}$ is the length of the section; $\bar{v}_{oil}$ and $\bar{v}_{liq}$ is average velocity of the oil and liquid refrigerant, and they should be the same according to the assumptions above. Since in this HPWH system, the OCR and $\dot{m}_{total}$ are relatively unchanged during the heating-up, the oil retention in a section is mainly determined by the average velocity of the liquid refrigerant (or liquid mixture). The average liquid velocity can be expressed as following:

$$\bar{v}_{liq} = \frac{\dot{m}_{total} \cdot (1 - x_{mix})}{\rho_{liq,mix} \cdot A \cdot (1 - \alpha_{mix})} \tag{6}$$

Here, A is the cross-sectional area of the tube; $\rho_{liq,mix}$ is the density of liquid refrigerant-oil mixture; x_{mix} is the vapor quality of mixture which takes oil into the consideration:

$$x_{mix} = \frac{\dot{m}_{ref,vap}}{\dot{m}_{ref,liq} + \dot{m}_{ref,vap} + \dot{m}_{oil}} \tag{7}$$

It is worthy noticing that due to the existence of liquid refrigerant-oil mixture, the vapor quality of mixture x_{mix}, is always less than 1, even in the superheated region. Therefore, the Equation (7) is valid throughout the entire heat exchanger. Furthermore, the void fraction of mixture α_{mix}, is usually the function of vapor quality x_{mix}, if other conditions are given. Many void fraction models have been proposed in the literature which correlate α and x. But none of them takes the existence of the oil into the consideration. Nevertheless, the models developed for the pure refrigerant can still be used here to qualitatively explain the oil retention change in the heat exchangers. Applying a void fraction model, for example, the model developed by Rouhani and Axelsson (1970), that is in form of:

$$\alpha = \frac{x}{\rho_{vap}} \left\{ C \left[\frac{x}{\rho_{vap}} + \frac{1-x}{\rho_{liq}} \right] + \frac{1.18}{G_{ref}} \left[\frac{\sigma_{ref} g (\rho_{liq} - \rho_{vap})}{\rho_{liq}^2} \right]^{0.25} \right\}^{-1} \tag{8}$$

where $C = 1 + 0.2(1 - x)$, and assuming the density of liquid refrigerant-oil mixture $\rho_{liq,mix}$ does not change too much, one would see that with x_{mix} varying from 0 to 1, the average liquid velocity $\bar{v}_{liq}$ first increases then decreases. That means in a heat exchanger, the oil is most likely accumulated at the subcooled region ($x_{mix} = 0$) and superheated region ($x_{mix} \sim 0$) due to the low liquid velocity. Therefore, during the heating-up, the superheated region is increasing in the evaporator, and that explains the increased oil retention in the evaporator. For the condenser, both superheated region and subcooled region are increasing with the time, but the oil retention in the condenser decreases at first 3 hours then increases. This might be explained by the fact that with an increasing condensation temperature, less refrigerant is dissolved in the oil and the density of liquid refrigerant-oil mixture $\rho_{liq,mix}$ is decreasing. That increases the liquid velocity and counteracts the expansion of the superheated and subcooled region.

4. SUMMARY AND CONCLUSION

Transient refrigerant and oil migration in a residential heat pump water heater system has been experimentally investigated. The Quick Closing Valve Technique is employed to localize the refrigerant and oil into each section of the system. The Remove and Weigh Technique is then applied to measure the refrigerant mass. The retained oil mass in the sections, except for the compressor, is determined by the Mix and Sample Technique. Five experiments are conducted to cover a full heating-up of five hours.

The experimental data shows that the most of the refrigerant charge is in the condenser and the evaporator retains much less refrigerant during the heating-up (Figure 4). It is logical because of the greater internal volume of the condenser and lower overall void fraction, mostly due to presence of subcooled region. The inventory of refrigerant generally decreases in the evaporator during the heating-up due to an increased inlet vapor quality; increased liquid fraction and vapor density mainly contribute to the increased inventory of refrigerant in the condenser (Figure 4 and Figure 5).

Most of the oil stays in the compressor during the heating-up (Table 2). The escaped oil mainly distributes in the condenser and the evaporator - close to being equal (Figure 7). In the heat exchangers, the oil is most likely accumulated in the subcooled and superheated region. Increased oil retention in the evaporator mainly attributes to an increased superheated region; even though both superheated region and subcooled region in the condenser are increasing with the time, the smaller solubility of the refrigerant in the oil makes the oil retention first decrease and then increase in the condenser.

NOMENCLATURE

A	Area	m^2
g	Gravitational acceleration	$m \cdot s^{-2}$
G	Mass flux	$kg\ m^{-2}\ s^{-1}$
L	Length	m
$\dot{m}$	Mass flow rate	$kg\ s^{-1}$
M	Mass	kg
P	Pressure	kPa
t	Time	s or h
T	Temperature	$^o C$
v	Velocity	$m\ s^{-1}$
V	Volume	m^3
x	Vapor quality	-

Greek Symbols

α	Void fraction	-
ρ	Density	$kg\ m^{-3}$
σ	Surface tension	$N\ m^{-1}$

Subscript

avg	Average
liq	Liquid
mix	Mixture
ref	Refrigerant
sat	Saturated
vap	Vapor

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