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Xin Wang

Syed Angkan Haider

Pega Hrnjak

Stefan Elbel

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Xin WANG[1], Syed Angkan HAIDER[1], Pega HRNJAK[1,2], Stefan ELBEL[1,2]*

[1]Air Conditioning and Refrigeration Center, Department of Mechanical Science and Engineering, University of Illinois at Urbana-Champaign, 1206 West Green Street, Urbana, IL 61801, USA

[2]Creative Thermal Solutions, Inc., 2209 North Willow Road, Urbana, IL 61802, USA

* Corresponding Author: elbel@illinois.edu

ABSTRACT

This paper focuses on the characterization of the transient behavior of oil at the discharge and the suction of the compressor. The characterization can help to reduce migration and further improve oil separation within the compressor. This study uses high-speed camera to record oil-refrigerant mixture flow at transient startup in variable speed electrical scroll compressor system. Warm and cold startup conditions are recorded and compared. Oil flow during startup is different from the annular mist flow in steady-state conditions. Oil flow is composed of oil droplets traveling with refrigerant vapor flow and oil film attached to the inner wall of discharge tube. During startup, small oil droplets are carried by vapor refrigerant to the discharge where some of droplets are attached to the tube wall and form film flow in low velocity, others coalesce into larger droplets.

1. INTRODUCTION

Oil is essential in vapor compression system to ensure lubrication inside the compressor. Oil inside the compressor can reduce friction and minimize wear, provide sealing to achieve high volumetric efficiency. Ensuring enough oil in compressor is beneficial to enhance heat transfer and lower startup pressure by absorbing some of the refrigerant. However, oil migrated to other components of the system has negative impact on system performance and capacity. Ossorio and Navarro-Peris (2021) studied oil circulation ratio in variable speed scroll compressor and concluded that the existence of oil being heated in compression process can decrease compressor efficiency by up to 5%. Large oil circulation ratio can reduce COP and imply extra pressure drop (DeAngelis and Hrnjak, 2005).

Many oil measurement and management approaches have been studied to reduce oil circulation ratio and increase system performance. ASHRAE Standard 41.4 (2015) presented oil circulation ratio (OCR) sampling measurement method using evacuated cylinder at liquid line. Xu and Hrnjak (2017) illustrated a novel method to quantify oil retention and oil circulation in compressor discharge based on visualization technique using high-speed camera and video analysis. This method largely shortened sampling time and complexity, and the results show good agreement with sampling method.

Most of the OCR measurement methods are taken at system steady state to acquire repeatable and reliable results. While the effect of transient migration of oil especially at compressor startup on the compressor performance and longevity was not studied extensively. Zimmermann and Hrnjak (2014, 2015) showed oil mist formation inside the compressor at discharge valve opening by visualization. The oil droplet size and velocity are affected by compressor speed and refrigerant-oil miscibility. At startup, abrupt refrigerant flow enters compressor and carries oil out of compressor. Two-phase refrigerant flow in saturation condition foams the oil in crankcase and decreases lubrication ability for the friction surfaces. Sudden pressure and temperature change influence solubility of refrigerant in oil, which can affect refrigerant-oil mixture equilibrium and properties. To keep high quality oil inside compressor and decrease potential harm to compressor due to sudden flow change, transient migration of oil at compressor discharge and suction is explored during startup. Oil and refrigerant transient migration need attention to better understand startup mechanism and improve oil separation.

2. EXPERIMENT DESCRIPTION

The experimental setup is composed of compressor, condenser, EEV and evaporator. The schematic of experimental facility is shown in Figure 1. An electrical scroll compressor for automotive application is mainly used in this study. The speed of the compressor varies from 1100 min^{-1} to 2650 min^{-1}. R134a and PAG46 are used as refrigerant and lubricant for the experiment. An oil concentration sensor based on speed of sound installed at liquid line shows real-time OCR data. Oil circulation ratio sampling method is also employed for validation.

Two environment chambers are used to reach required conditions. The evaporating and condensing ambient temperatures are maintained at 24°C/39 °C. The superheat at evaporator outlet and subcooling at condenser outlet are kept at 15 °C/5 °C. The mass flow rate of the system is measured by a Coriolis-effect mass flow meter. The Oil Circulation Ratio (OCR) varies with compressor speed from 0.5% to 3%. The gauge pressure transducers and T-type thermocouples are installed at compressor inlet and outlet to measure pressure and temperature change during startup. The uncertainties of measurement for sampling method and visualization method are shown in Table 1.

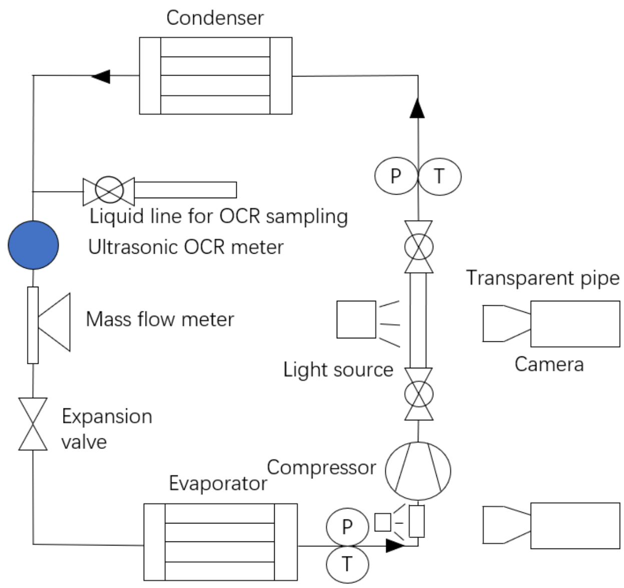


Figure 1: Schematic of the test facility

Figure 2 shows the facilities for flow visualization at discharge. A transparent perfluoroalkoxy alkane (PFA) tube is used to observe the flow change at the discharge of the compressor. The inner diameter of the tube is 6 mm (1/4 inch), the outlet diameter is 9 mm (3/8 inch), wall thickness is 1.5 mm (1/16 inch). Light sources from the LED panel behind the tube. A Phantom v4.2 high-speed camera with Nikon lens is used to capture the transient flow. The location of flow visualization is 0.8 m downstream the compressor. Facilities of visualization at suction of the compressor is composed of LED light, PFA tube and high-speed camera as well. The tube is 0.5 m upstream of the compressor.

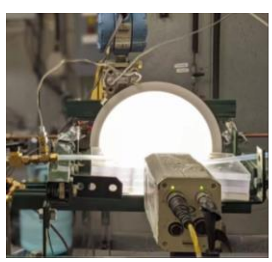


Figure 2: Flow visualization of discharge

Table 1: The uncertainty of measurement properties

Measurement	**Temperature (°C)**	**Pressure (kPa)**	**Mass flow rate (g/s)**	**Tube geometry (mm)**	**Weight by electronic balance (g)**
Uncertainty	±0.2	±3.5	±0.2%	±0.01	0.001

3. FLOW CHANGE AT SUCTION DURING STARTUP

3.1 Pressure and Temperature Change at Suction

Compressor starts after long-time off (more than 2 hours) in ambient temperature (25°C) is defined as cold startup. In contrast, compressor starts after short time (10 mins) off with discharge temperature (40°C) higher than ambient temperature (25°C) is defined as warm startup. The discharge temperature is measured at discharge tube inlet. During long-time off, refrigerant condenses to two-phase condition. While in warm startup case, a few minutes after shutdown, the refrigerant in suction can still maintain as vapor, which results in different refrigerant and oil flow behavior at startup.

The temperature and pressure change at suction during warm and cold startup are shown in Figure 2. Before the startup, warm restart had lower pressure (686 kPa) and temperature (24 °C) compared to cold startup pressure (690 kPa) and temperature (25 °C). This is because the compressor and suction hadn't been cooled down to ambient temperature. After startup, both warm and cold startup experienced large pressure and temperature decrease. While compared to warm startup, compressor dragged larger sudden pressure and temperature drop during cold startup. The minimum pressure after cold startup (298 kPa) was much lower than warm startup (372 kPa). During cold startup, the suction temperature dropped to 17 °C, while suction temperature decreased gradually after warm startup and the first extreme value experienced was 23 °C. The possible reason behind the difference between cold and warm startup can be refrigerant flow rate difference as observed by Wu *et al*. (2017). During long-time off, large amount of refrigerant at low pressure side transferred to high pressure side due to temperature increased in low pressure side and saturation at high pressure side. However, the temperature change and saturation effects were relatively small for warm startup. So, large amount refrigerant can enter compressor after warm startup and helps with balance.

The cold startup temperature and pressure change could also be related to EEV opening. During standstill, the EEV was closed to block refrigerant migration between low- and high- pressure side. After startup, the EEV opening ratio increased from 0 to certain value in several seconds in auto mode. The refrigerant flow rate at low-pressure side increased as EEV opens gradually. The two-phased flow in evaporator and suction absorbed heat which explained the sudden temperature drop at cold startup.

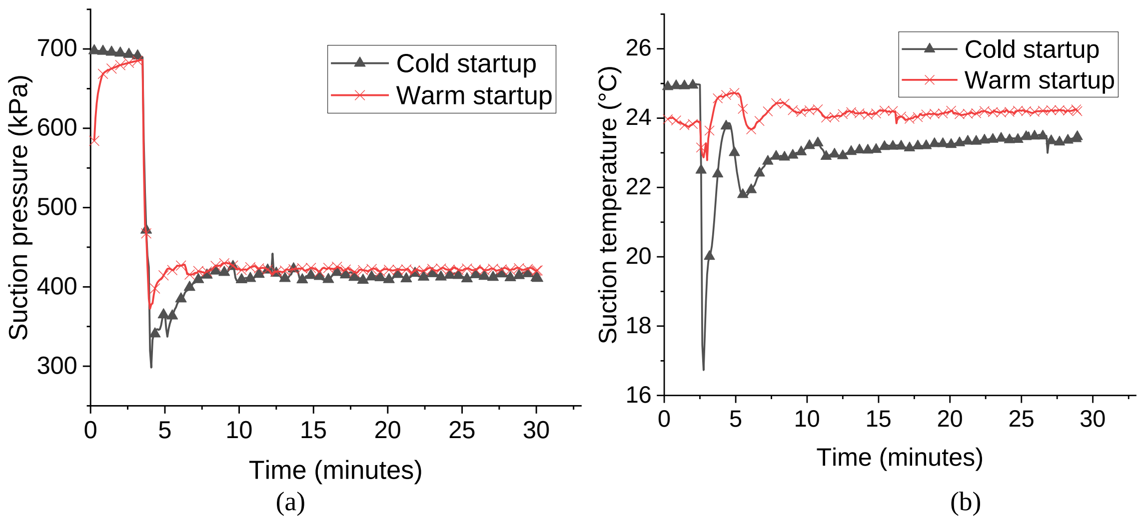


Figure 2: Suction pressure and temperature change at startup (a) pressure (b) temperature

3.2 Flow Visualization at Suction during Cold Startup

The refrigerant flow captured at transient cold and warm startup are shown in Figures 3 and 4. Wongwises *et al*. (2002) visualized described the two-phase flow with different oil concentration and defined flow in different pattens. After cold startup, the liquid flow with small gas bubbles first appears at 0.3 s as Figure 3 (b) shows, then flow rate increases in 1.2 s and transfers to froth flow with much larger vapor quality as shown in Figure 3 (c). The transition flow exists more than 5 s and gradually develops to wavy two-phase flow in 5.5 s after startup in Figure 3 (d). The two-phase flow transformation is observed several times during startup and becomes stable in 33 s in Figure 3 (e). Finally vapor refrigerant flow with oil annular mist flow attached on the tube inner wall stabilized in 2 minutes in Figure 3 (f). The whole process shows refrigerant phase transaction at startup with solubility variation.

The whole process validated cold startup temperature and pressure change discussed above. The series of cold startup images show that refrigerant flow experienced phase transition with temperature and pressure change. In the first two minutes, liquid refrigerant enters compressor, which can be harmful to compressor crankcase and oil lubrication. The liquid refrigerant mixes with lubricant oil inside the compressor and causes large viscosity decreases (Wang *et al*. 2022). As a result, the friction surface does not have sufficient lubrication at startup. In addition, liquid refrigerant boils at compressor oil sump causing oil pressure and temperature change as well as severe foaming (Wu *et al*. 2015). Wear and corrosion may be caused in multiple cold startups without protection.

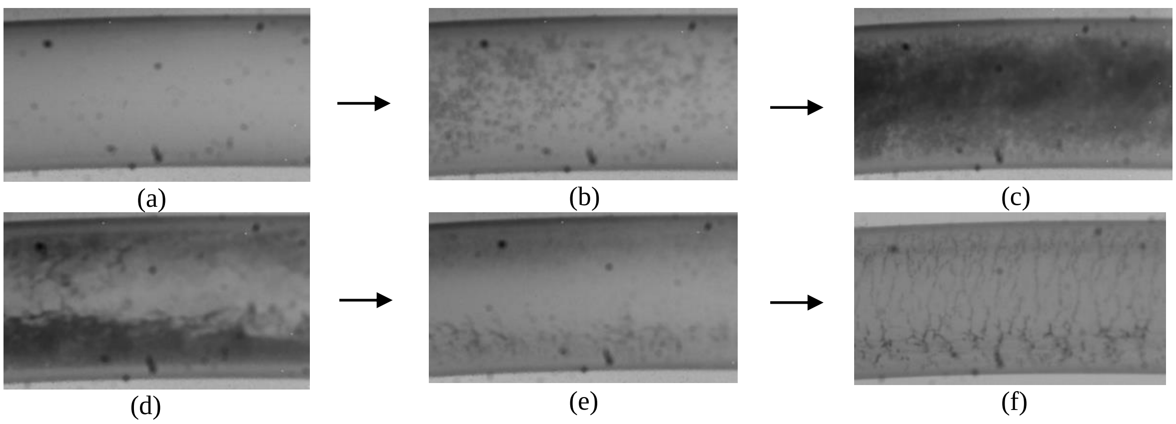
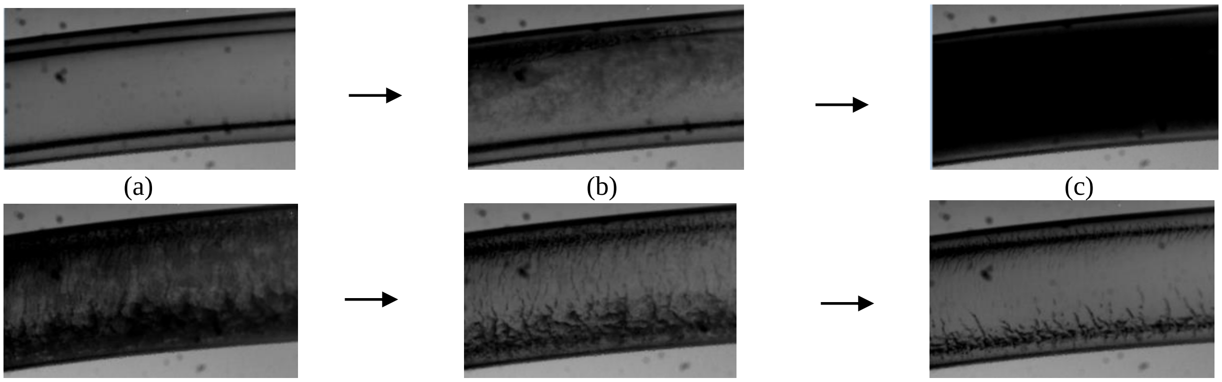


Figure 3: Flow development at suction during cold startup (a) before startup (b) after 0.3 s (c) after 1.5 s (d) after 5.5 s (e) after 33 s (f) after 2 mins

3.3 Flow Visualization at Suction during Warm Startup

Figure 4 shows the flow variation during warm startup. Two-phase flow appeared in 1.3 s after the startup and reached peak in 1.5 s as shown in Figure 4 (b) and (c). After 2.4 s, as shown in Figure 4 (d) and (e) flow transitioned to vapor flow and finished in 2.7 s. Steady refrigerant vapor flow and annular oil flow were achieved in 4.6 s after warm startup.

Compared to the cold startup, refrigerant only experienced transition once during warm startup and finished in seconds. The steady condition took much less time to reach as well. Although liquid refrigerant still entered compressor, the amount of liquid was much less than cold startup. Oil lubrication is less influenced by liquid refrigerant as very mild foam happens (Wu *et al*. 2017).



(a) (b) (c)

(d) (e) (f)

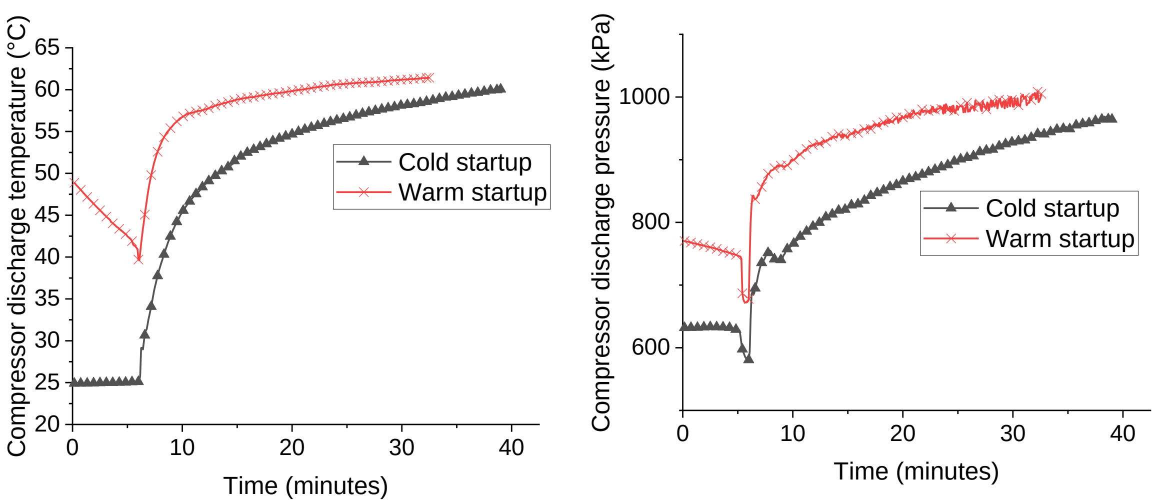
Figure 4: Flow development at suction during warm startup (a) before startup (b) after 1.3 s (c) after 1.5 s (d) after 2.4 s (e) after 2.7 s (f) after 4.6 s

Oil film accumulated in tube bottom during shutdown. After startup, film broke into oil droplets with refrigerant flow. Liquid refrigerant-oil mixture entered compressor at several seconds after startup, then vapor refrigerant carried oil droplets at high speed. Most of the oil formed annular mist flow and spread on tube inner wall moving at much lower speed.

4. FLOW CHANGE AT DISCHARGE DURING STARTUP

4.1 Pressure and Temperature Change at Discharge

Discharge pressure and temperature both increase during cold and warm startup. Due to short standstill time before warm restart, discharge temperature and pressure before warm startup are higher than cold startup and is takes less time to reach pressure stabilization.



(a) (b)

Figure 5: Discharge pressure and temperature change at startup (a) temperature (b) pressure

4.2 Flow visualization at Discharge during Cold Startup

Figure 6 shows flow visualization at discharge during transient cold startup. Oil and liquid refrigerant accumulate at discharge tube bottom during compressor off period. As temperature and pressure decrease, vapor refrigerant dissolves into oil. 0.45 s after startup, as shown in Figure 6 (b) the oil and liquid refrigerant mixture level decreased 1.12 mm because of chiller and blower working caused temperature change in condensing chamber. After 0.54 s, the initial mixture flow left the compressor from discharge as shown in Figure 6 (c), which contains large vapor refrigerant bubble as plug flow. The froth flow appeared in 1.26 s as shown in Figure 6 (d) and reached peak in 1.36 s after startup, and it showed black in Figure 6 (e) because large amounts of bubbles blocked the back light for discharge. The flow continued for more than 10 s then decreased. The flow phase changed from vapor to liquid three times before finally reaching the annular-mist flow. After three minutes, the flow became steady and formed annular-mist flow like in steady state.

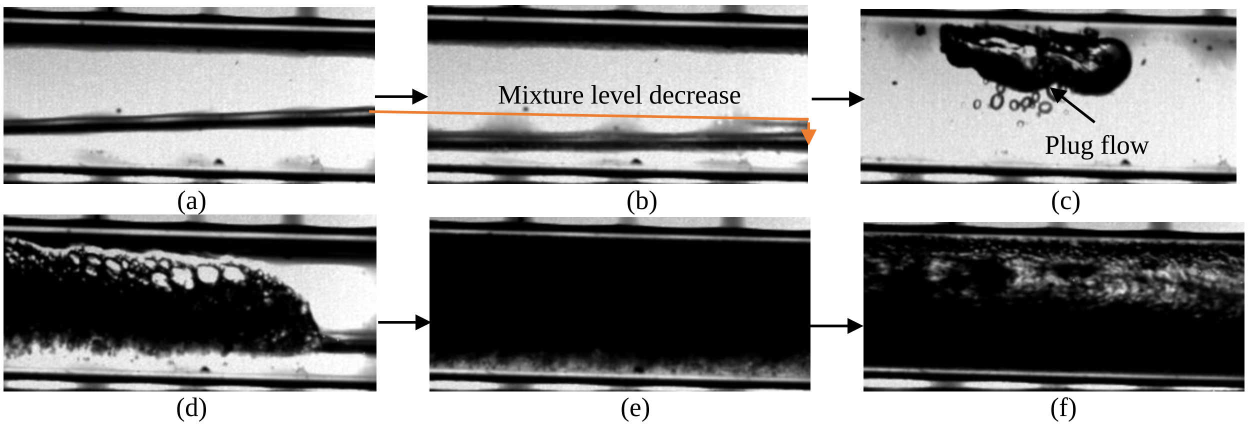


Figure 6: Flow development at discharge during cold startup (a) before startup (b) 0.45 s after startup (c) 0.54 s after startup (d) 1.26 s after startup (e) 1.36 s after startup (f) 11.94 s after startup

The initial refrigerant-oil mixture flow was mostly liquid. The first stream of two-phase flow was then directly discharged with large amount of oil being carried out of the compressor. Foam flow appeared in one second after startup. The foam happens when refrigerant boils from oil, which means large decrease of refrigerant solubility. Castro and Gasche (2006) examined oil-refrigerant mixture foam flow in a small diameter tube, as the flow proceeds to the exit of the tube, solubility of the refrigerant in the oil decreases because of pressure drop, eventually large bubble population forms foam flow and causes sharp decrease of pressure and temperature. So, in our experiment, the foam can potentially come from compressor due to increased oil temperature and decreased pressure in compressor crankcase. On the other hand, discharge temperature also increased after startup, the refrigerant dissolved in oil film during shutdown period can escape and cause foam as well.

After several phase-change waves of flow, vapor refrigerant stably flows through discharge. The oil flow spreads on the inner tube wall and forms annular flow.

4.3 Flow visualization at Discharge during Warm Startup

Flow visualization at discharge during warm startup is shown in Figure 7. Oil droplets attached to the inner wall after shutdown in several minutes as shown in Figure 7 (a). The large droplets started to move after startup in 0.6 s. Small droplets were carried by refrigerant vapor flow and entered discharge. Some of the small droplets stuck to tube inner wall as shown in Figure 7 (c), others migrated into other components of the system with refrigerant. After 4.7 s, oil droplets coalesce into oil stream and converge into oil film in 8.2 s. The film flow is finally formed in 10.5 s after warm startup.

Flow visualization shows relatively large difference between cold startup and warm startup in oil flow formation. First two-phase or foam flow did not appear in warm startup case. The temperature and pressure are still comparatively high a few minutes after shutdown, So the change of solubility is not large enough to cause foam. Additionally, only little vapor refrigerant dissolved in oil due to short off time. Besides, warm startup takes less time (10 s) to form annular mist flow compared to cold startup (2 minutes), which is beneficial to oil balance establishment and OCR measurement. Furthermore, stable vapor refrigerant flow at startup indicates less oil is coerced out of the compressor, which contributes to keeping sufficient oil in compressor and decreasing sudden oil circulation and retention.

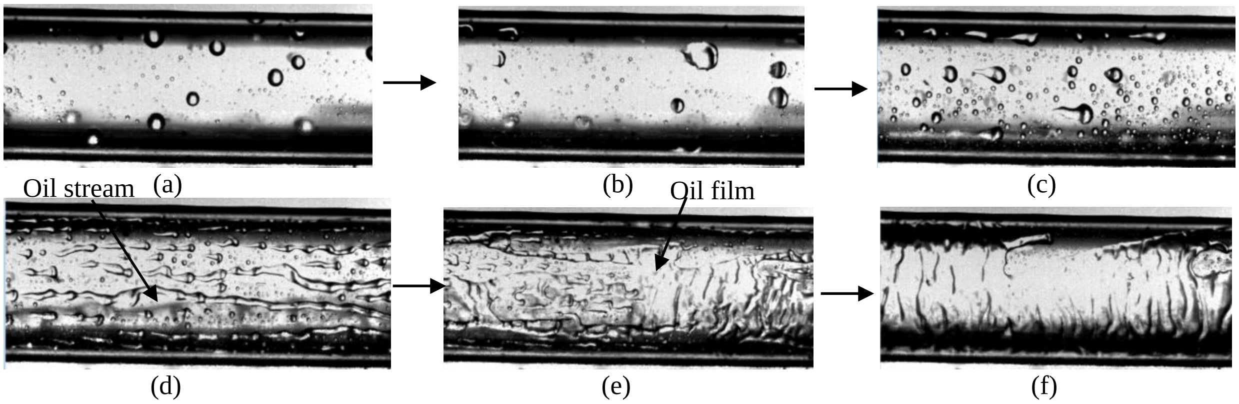


Figure 7: Flow development at discharge during warm startup (a) before startup (b) 0.6 s after startup (c) 1.2 s after startup (d) 4.7 s after startup (e) 8.2 s after startup (f) 10.5 s after startup

4.3 Flow visualization at Discharge from Startup to Steady State

After annular mist flow forming at startup, the oil flow continues as annular mist flow for the entire steady state as shown in Figure 8 until shutdown if OCR is maintained in relative high range above 5%. Nevertheless, the annular mist cannot exist when OCR decreases below 3%.

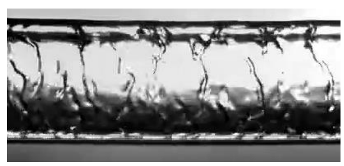


Figure 8: Annular mist flow at high OCR

Flow transition process is shown in Figure 9. Sudden influx of large amount of oil flow results in high OCR in several minutes after startup. Then as required superheat is maintained by EEV, refrierant flow rate is stabilized. As oil flow rate starts to decrease, oil film is no longer continuous as Figure 9 (a). Film starts to break into oil streams as shown in Figure 9 (b) and gradually develops to oil stream and oil droplets attached on the inner the wall. The oil streams break into oil droplets if oil flow rate is even lower as Figure 9 (d) shows. In all the cases studied with different OCR, the oil flow at bottom is always film flow. This is caused by accumulation of oil droplets due to the gravity. Xu and Hrnjak (2017) found the similar effect in annular mist flow where film thickness at the bottom is higher than other parts of the tube. Hurlburt and Newell (2000) developed a model of circumferntial film thickness distribution in horizontal annular gas-liquid flow, which also shows film thickness reaches maxium at the bottom of the tube.

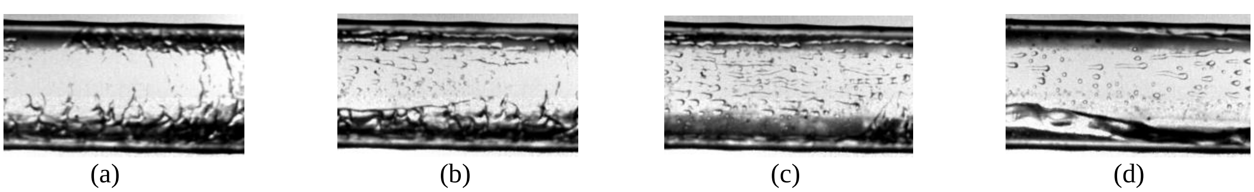


Figure 9: Flow transition after startup in different OCR

The flow transition in discharge indicates OCR variation under same compressor speed from startup to steady state. Figure 10 shows real-time OCR change from OCR meter. A sudden OCR increase happened after both cold and warm startup. The average values of OCR at steady state ranges from 1% to 3%, the maximum OCR value after startup can reach 11% because initial two-phase flow carries large amount of oil out of compressor.

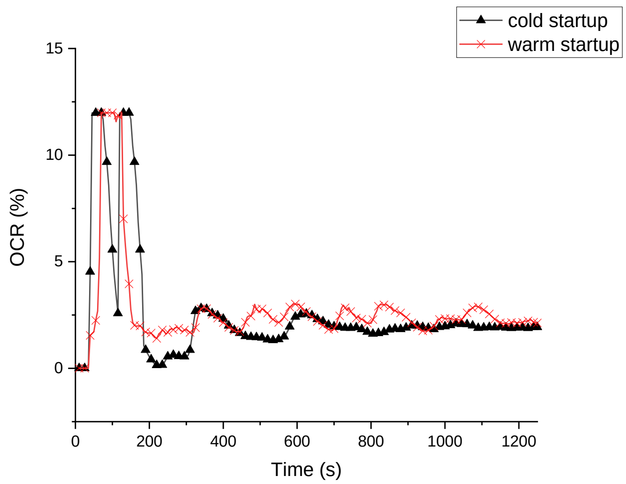


Figure 10: OCR change from startup to steady

The OCR change at startup validated flow visualization at discharge to some degree. Two-phase flow boils in compressor crankcase and coerces oil foam out of the compressor, the oil mass flow rate reaches the maximum in a few seconds after cold startup. The foam flow repeated several times before reaching vapor refrigerant flow and oil annular mist flow. OCR fluctuates rapidly for several times at cold startup as well. While refrigerant flow rate increases rapidly after warm startup once then decreases to average value, OCR also shows the maximum value once then decreases to steady value.

6. CONCLUSIONS

The main motivation of the investigation is to improve the understanding of transient effects in oil migration and contribute knowledge for potential oil management strategies of the vapor compression system. In this paper, flow visualization method was used to study the transient behavior of the R134a-PAG46 refrigerant-oil mixture flow at compressor suction and discharge during transient startup. Pressures and temperatures in the vapor compression system during startup process were measured. Meanwhile, the mixture flow behavior during warm and cold startup are compared and discussed. The suction temperature and pressure dropped sharply at cold startup, while the time from startup to steady state is much longer than warm startup. The two-phase flow went through suction several times before reaching continuous vapor flow during cold startup. Liquid slugging and oil foam might have been caused by insufficient superheat at startup and causes insufficient oil lubrication. Discharge temperature and pressure increase more quickly during warm startup. Foam flow happens at cold startup due to rapid solubility change at initial time of startup. After oil annular mist flow formed, the film starts to break into oil streams and droplets because of reduced oil mass flow rate, which is validated by OCR change. To reduce the potential harm to compressor, vapor-liquid separator at suction should be considered at startup, also heating up compressor can reduce foam and liquid slugging.

NOMENCLATURE

T	temperature	(°C)
P	pressure	(kPa)
t	time	(s)
OCR	oil circulation ratio	(%)

REFERENCES

ASHRAE. Standard 41.4-2015, 2015. *Standard Method for Measurement of Proportion of Lubricant of Liquid Refrigerant. ASHRAE*, Atlanta, GA, USA.

Castro, H. O. S., & Gasche, J. L. (2006). Foam flow of oil-refrigerant R134a mixture in a small diameter tube. In *International Heat Transfer Conference 13*. Begel House Inc.

DeAngelis, J., & Hrnjak, P. (2005). Development of transcritical R744 systems for small commercial applications. In *IIR Vicenza conference* (pp. 167-178).

Hurlburt, E. T., & Newell, T. A. (2000). Prediction of the circumferential film thickness distribution in horizontal annular gas-liquid flow. *J. Fluids Eng.*, *122*(2), 396-402.

Ossorio, R., & Navarro-Peris, E. (2021). Study of oil circulation rate in variable speed scroll compressor working with propane. *International Journal of Refrigeration*, *123*, 63-71.

Wang, X., Haider, S. A., Hrnjak, P., & Elbel, S. (2022). Transient Oil-refrigerant Mixture Migration and Change of Properties at Compressor Shutdown. *Proceedings of the International Refrigeration and Air Conditioning Conference*, Paper 2266, West Lafayette, IN, USA (manuscript submitted)

Wongwises, S., Wongchang, T., Kaewon, J., & Wang, C. C. (2002). A visual study of two-phase flow patterns of HFC-134a and lubricant oil mixtures. *Heat Transfer Engineering*, *23*(4), 13-22.

Wu, J., Lin, J., Zhang, Z., Chen, Z., Xie, J., & Lu, J. (2016). Experimental investigation on cold startup characteristics of a rotary compressor in the R290 air-conditioning system under cooling condition. *International Journal of Refrigeration*, *65*, 209-217.

Wu, J., Lin, J., Zhang, Z., Chen, Z., Xie, J., & Lu, J. (2017). Experimental investigation of dynamic characteristics of a rotary compressor and its air conditioner using R290 during warm startup. *Applied Thermal Engineering*, *125*, 1469-1477.

Xu, J., & Hrnjak, P. (2017). Quantification of flow and retention of oil in compressor discharge pipe. *International journal of refrigeration*, *80*, 252-263.

Zimmermann, A. J. P., & Hrnjak, P. S. (2014). Visualization of the opening process of a discharge reed valve in the presence of oil.

Zimmermann, A. J., & Hrnjak, P. S. (2015). Oil flow at discharge valve in a scroll compressor. *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering*, *229*(2), 104-113.

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