2014

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Source Identification and In Situ Quantification of Oil-Refrigerant Mist Generation by Discharge Valve Opening Process

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ABSTRACT

Oil in circulation in refrigeration systems generally degrades their thermodynamic and reliability performance. The vast majority of compressors used in the residential, automotive and light commercial air conditioning and refrigeration use pressure actuated reeds as the discharge valves. These valves are the gateway for the oil to leave the compressor to the rest of the system. In this work, a residential AC scroll compressor was equipped with sight windows on the discharge plenum and visualization studies were carried out using high speed imaging and processing techniques to identify the moment of oil mist generation, and also provide quantification of the droplet size and velocity distributions inside the discharge plenums. The compressor was run in a full system setup with measuring devices for mass flow rate, pressure, temperature and OCR (by sampling according to ASHRAE Standard 41.4). Oil viscosity was varied from 32cSt to 120cSt along with compressor volumetric flow rate (through operating frequency), all while using R134a as the refrigerant. It was found that a very fine mist (drops with diameters below 114 micrometers) is generated right at the start of the opening process of the valve followed by interaction between the vapor flow and liquid (oil-refrigerant mixture) flow with the internal geometric features of the discharge plenum to generate larger droplets. It was observed that at higher volumetric flow rates, smaller droplets are produced and that the more viscous the oil, the larger the droplets generated, however this effect was not significant. In the discharge plenum, smaller droplets were identified and quantified.

1. INTRODUCTION

Oil in circulation in an air conditioning system is known to cause a reduction in heat transfer coefficient and increase in pressure drop in heat exchangers and connecting lines (DeAngelis and Hrnjak, 2005; Kim et al., 2010; Pehlivanoglu et al., 2010), as well as reducing the oil level inside the compressor crankcase. It is reported in the literature (Toyama et al., 2006) that OCR reduction plays a pivotal role in scroll compressors design applied in residential air conditioning. It is not uncommon to see OCR values in the 2-4% range, even though this work only achieved a maximum of 1.2%.

In order to reduce the OCR of such systems by keeping the oil inside the compressor, separation strategies need to be ideally integrated into the discharge plenum of the compressor. Obtaining a good liquid separation requires knowledge of the liquid flow characteristics.

One way of obtaining the two-phase flow characteristics is to investigate the developing flow at the discharge tube after it leaves the compressor (Wujek, 2011). Previous studies show that the predominant flow regime is of the mist-annular type due to low liquid loading and high vapor velocities. Separation in a horizontal tube by letting the droplets deposit into the film has shown an asymptotic behavior when it comes to the reduction of the liquid flow in the form of droplets as the flow progresses down the tube. This happens due to the eventual balancing of the entrainment and deposition rates for the fully developed flow (Wujek, 2011).

External oil separators have been used for very long time in the refrigeration and air conditioning industry with quite success. However, in order to effectively separate the liquid from the vapor one should consider the following aspects: (i)volume required; (ii)allowable pressure drop; (iii)amount of refrigerant dissolved in the oil;

The first aspect is related to the most simple separation mechanism one can think of: gravity. If gravitational settling is to be used as a separation mechanism, one should look into the terminal velocity of the droplets to determine which maximum vapor velocity is allowed so that the droplets do not get carried away with the vapor. Such velocity is directly proportional to the droplet diameter and therefore the smaller the droplet the lower the velocity and the higher the volume. The volume that a gravitational separator can take is often times prohibitive.

The second aspect refers to compact separators that might use obstacles or centrifugal forces to drive the droplets towards a wall and/or metal mesh, so they can be collected at a certain location and returned to the compressor. Such devices can partially solve the volume problem but they introduce pressure drop at the discharge line and that can, sometimes, be detrimental to the performance of the system. Pressure drop required is also a function of the droplet size, since smaller droplets present smaller Stokes number and have a tendency to follow the gaseous flow, they might not have enough inertia to be driven to the wall.

The last aspect has to be taken into consideration whenever an oil-refrigerant mixture is miscible at the compressor discharge conditions. For all practical purposes, the refrigerant mass fraction that is dissolved into the oil is the lowest right after it flows through the discharge orifice, since it is at its highest apparent superheat. As the mixture flows away from the compressor, it is cooled and more refrigerant is allowed to be absorbed into the oil, resulting in a loss in cooling capacity when that oil is directed back to the compressor crankcase, in this case a low pressure sump.

2. FACILITY FOR EXPERIMENTS

In this work, a typical scroll compressor for residential air conditioning applications, having 3 discharge valves, volumetric displacement of 57.36 cc/rev, and a low pressure shell arrangement. The compressor was designed for operation at 50Hz, however in this work a variable frequency drive was used to set the compressor operating frequency to the desired level.

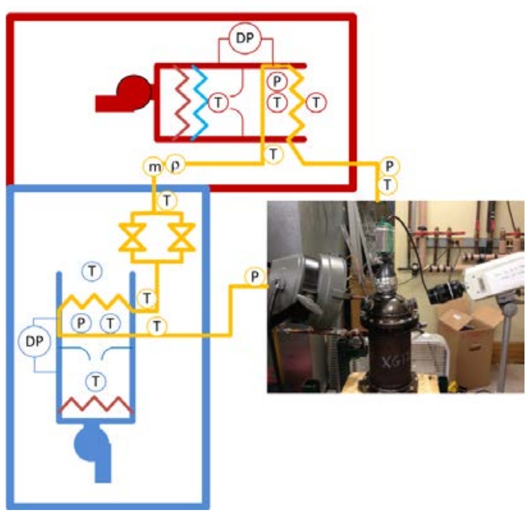


Figure 1: Facility for experiments

A complete air conditioning system (see Fig. 1) is used to maintain desired pressure and temperature conditions at the suction and discharge of the compressor, as well as the necessary subcooling degree at the liquid line to allow for refrigerant and oil mixture sampling and determination of OCR according to ASHRAE Standard 41.4. A coriolis type mass flow meter is used to measure mass flow rate and density. A manual and an electronic expansion valve are used to control flow rate and evaporator superheat.

3. DROPLET SOURCE IDENTIFICATION

Since the predominant flow regime at the discharge is in the mist-annular region for a tube and it is well documented that inside a high pressure shell or a discharge plenum the oil will be found usually in the form of a fine mist. Since in the case studied in this work the compressor is of a low pressure type, we decided to focus on the discharge plenum. The compressor was initially equipped with sight glasses that provided good visual access to the discharge volume, as can be seen on Figure 2. The droplet generation identification is considered in two operating conditions: startup and steady state.

Figure 2: Compressor equipped with sight glasses and visualization set up

A high speed CMOS type of camera was used to perform the visualizations. The camera has a 512x512 sensor and is capable of capturing video at 2,200 frames per second at full resolutions and 90,000 frames per second at minimal resolution. During the experiments, several settings of the camera were used to best suit flow speed, type and intensity of lighting and spatial resolution.

2.1 Startup conditions

Startup is usually the condition when the compressor will experience its highest mass flow rate(under equalized pressures) and consequently the highest lift on the valve is expected since the pressure difference will be the greatest over the first few operating cycles of the compressor. Zimmermann and Hrnjak (2013) showed that during startup, at the very beginning the liquid mist inside the discharge plenum is originated mostly from liquid film accumulated in between the reed valve and its seat, and after a few opening cycles of the valve the discharge plenum is inundated with liquid coming from the system to the compressor suction due to the sudden pressure change. Their result is valid for R410A. Figure 3 shows the starting process sequence for the compressor at the conditions of this work. The pictures show the evolution in time from the moment the compressor is turned on until there is a first full opening of the valve. At 297ms the valve hits the stop, and a very large amount of liquid is pushed through the discharge orifice. On the intermediary steps, the interaction between the small amount of vapor coming out of the discharge port and any oil that was present in the plenum in the vicinity of the valve is seen, and large droplets (>1mm) are being generated.

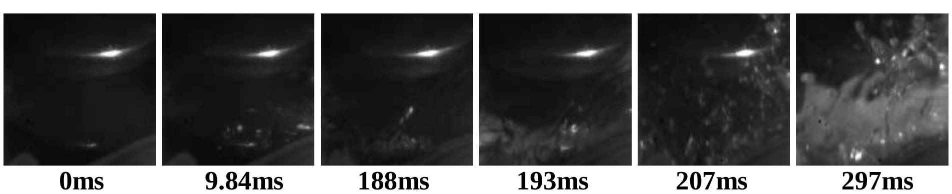
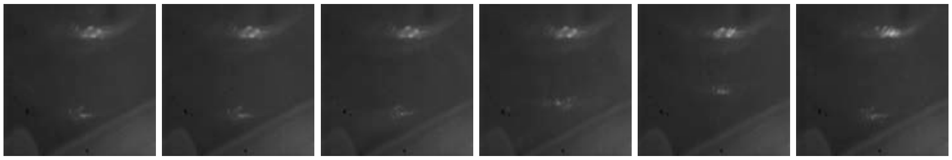


Figure 3: Startup sequence for compressor with PVE32 oil: initially oil droplets are generated by film breakup but afterwards liquid rushes in from the system due to high flow rate.

2.2 Steady state operation

From the startup images it becomes clear that there are two main modes of liquid atomization in the compressor, the first one is the burst of the liquid film that is between the valve and its seat and then there is the interplay between vapor shear and the geometric features of the discharge plenum design. In steady state operation however, there is much less liquid coming in from the system and inundation does not occur. As an example one can look at the image sequence in the vicinity of the valve during compressor operation at 40Hz, with PVE32 oil (see Fig. 4).



0ms **0.49ms** **0.86ms** **1.85ms** **5.17ms** **25.83ms**

Figure 4: Opening sequence for discharge valve: note the cloud of small droplets that flows from the valve edge as the valve breaks open, very short period of time that cloud is noticeable.

At 0ms is the initial moment right before the valve starts to open, the next image shows the position of the valve at so called critical valve lift, or right before a droplet cloud or mist is seen being expelled from the gap between the valve and the seat, at 0.86ms the cloud is completely developed and approximately 1ms later the cloud had already been dissipated. After this moment no new cloud of droplets or significant number of drops is seen coming off of the discharge port. This indicates that the majority of droplets that leave the compressor are generated at this location. The next two images show the valve at its maximum lift and at the moment of closing. As an interesting point at this particular operating frequency, the valve closes for just a fraction of a millisecond, remaining open most of the time. Although the authors recognize the difficulty in distinguishing one picture from the other as still images, when played as a movie it becomes much clearer how the process described happens. These and other characteristics are explored on paper 1569.

Since during the opening process it becomes clear that this initial cloud of droplets that is expelled from between the valve and its seat is the major contributor to the mass flow of oil coming from the compression chamber, more focus is directed on trying to characterize it.

3. MIST CHARACTERIZATION

3.1 Visualization set up

The sight glass installation on the compressor discharge cover was enough for qualitative studies of flow morphology but showed to be very limited when it comes time to perform quantification of sizes and velocities inside the discharge plenum, especially close to the discharge valve, which is the main place of interest. In order to provide optical access to the discharge valve, and more importantly access of light, a transparent flange was specially manufactured to fit between the discharge cover and the compressor body. Inside the discharge plenum, a glass barrier was placed in order to remove interference of fine mist that was present between the transparent flange wall and the valve which is located in the center of the compressor. This glass barrier allowed for a cleaner medium between a plane about 5mm from the tip of the valve. Figure 5 shows pictures of the transparent part and the final assembly of the compressor with the transparent discharge. As can be seen also, the compressor has three discharge valves, being one main and two auxiliary valves that help avoid over compression. In this work, the two auxiliary valves where intentionally forced to be closed so focus of the visualization could be on the main valve.

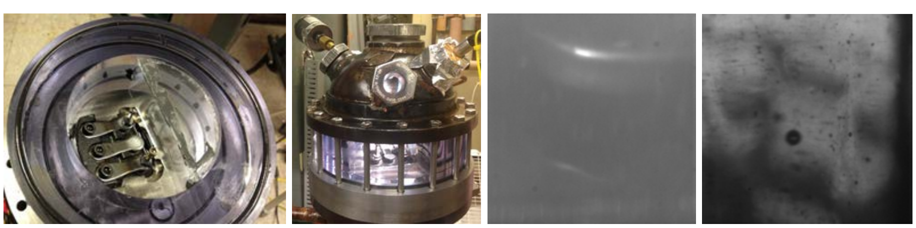


Figure 5: Visualization setup: transparent flange and glass barrier to enhance optical access to the valve and sample images for the valve vicinity and the discharge plenum.

While recording the videos two types of lighting strategies where used. When recording videos of the discharge plenum, backlighting was used since it is the preferred mode for achieving good contrast and crisp images of the droplets. On the case of the valve, backlighting was not possible so front lighting was used. When using front lighting, instead of concentrating and absorbing the light, the droplets actually appear as a reflection, which poses some challenge to the image processing procedure.

3.2 Image processing

For the videos that used backlighting the image processing procedure used was the same as Wujek, 2011, which was in turn based on Hay et al., 1998. The procedure consists of first eliminating any noise by averaging the pixel values at each location on the image over the whole period of time of the video and subtracting it from each frame. After that first step is completed the processing code searches for peaks and valleys between frames and applies a cross-correlation to determine where the peaks and valleys coincide, this is used to remove the waviness of any liquid film that might be present on the walls. Once this clean image is present, then a thresholding process is applied to the in which the same is transformed into a binary matrix with a cut-off level determined by Otsu's method of thresholding. Figure 6 shows both the raw image and a thresholded image after the manipulation and the droplets identified are represented by red circles.

Once the images are thresholded, then MATLAB has a set of built in functions that once called can identify, label and determine properties of white areas in the image such as centroid coordinates, perimeter, area, equivalent diameter, minor axis, major axis. The code then applies a maximum derivative approach to identify the droplets in the raw image, by going back to the original clean image and looking at the slope of the sharpest change in pixel values along the horizontal and vertical axis of the identified droplet. A minimum slope criterion is then applied to discard droplets that might not be in focus. Other criteria such as aspect ratio of the major and minor axis, the region being darker than the average surrounding pixels are also applied to discard possible false droplet or droplets which dimensions cannot be identified with desired accuracy.

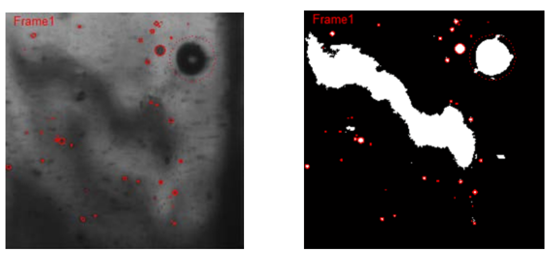


Figure 6: Raw and thresholded frame of a visualization movie: the red circles represent identified droplets, some are clearly not identified since they are out of the focal plane.

For the videos with front lighting one of the first tasks to be done is to invert the pixel values with respect to the midpoint between black and white and then what was once dark becomes and light and vice versa. This makes it easier for the processing algorithm. In this case also, since there is a moving part on the video, it does not make sense to have an average frame since it would make it lose information wherever the valve passes by.

The uncertainty associated with these methods can be found well documented in Hay et al., 1998 and the limiting factor was cited to be the pixel width of the camera sensor for these types of flows. In their work Hay et al., 1998, estimated the uncertainty in their method to be ± ½ a pixel width. The pixel width is a function of the magnification and the size of the pixel array of the camera. In this work the sensor array consists of 512 x 512 pixels and the resulting pixel widths were 51.5μm for the valve videos and 21.47μm for the plenum videos, resulting in ±25.75 μm and ±10.73μm. Considering that the minimum drop size identifiable was set to two pixels in width we can determine that the maximum uncertainty for the histograms is ±25% for the smallest droplet. The relative uncertainty gets lower than 10% at about a droplet size of two and a half times the minimum identifiable droplet which is what Hay et al, 1998 had taken as an acceptable inaccuracy.

3.3 Test conditions

The testing conditions were determined to provide the most realistic operation under air conditioning conditions, while assuring the safety of the experiment and operators by keeping the discharge pressure and temperature levels low enough o avoid failure of the transparent part. Two levels of oil viscosity grade were used, 32cSt and 120cSt.

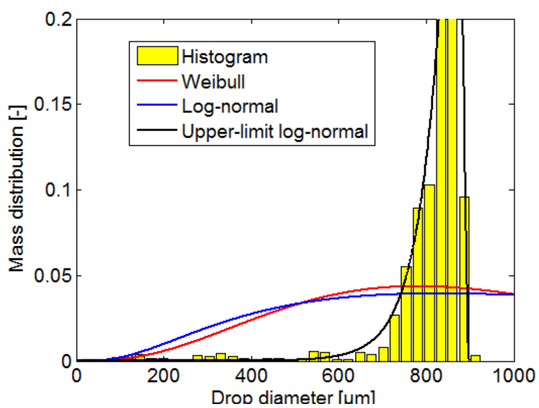
Since not much difference was observed in the results a third level in between was not considered. The compressor operating frequency was varied from 30Hz to 60 Hz while ti pressure ratio and pressure levels were kept relatively close so the only change would be the refrigerant mass flow rate and the OCR as a result of more or less oil pumping in the crankcase. OCR was determined using sampling according to ASHRAE 41.4 Standard and gravimetric methods that lead to the maximum absolute uncertainty to be ±0.2%. Table 1 shows the testing conditions and the measured values for the pertinent variables. Temperature measurements carry an uncertainty of ±0.25°C, and pressure measurements are accurate to ±0.25%, mass flow rate carry uncertainty of ±0.5%FS. All experiments were performed using R134a as the refrigerant.

Table 1: Test conditions for oil mist characterization

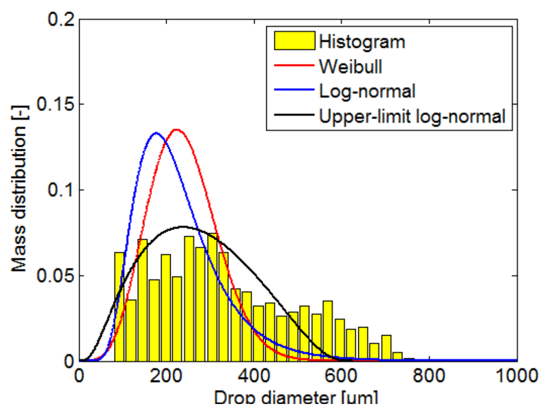
Oil	Viscosity [cSt]	Frequency [Hz]	Mass flow rate [g/s]	P_{suc} [kPa]	P_{disch} [kPa]	r [-]	ΔT_{sh} [K]	Tdisch [°C]	OCR [%]
PVE	32	30	16.70	337.92	906.76	2.68	21.3	77.96	<0.2
		40	20.74	309.72	954.45	3.08	22.95	77.12	0.6
		50	21.88	312.74	960.95	3.07	24.32	81.06	0.98
		60	23.50	315.30	987.20	3.13	24.59	88.69	1.17
POE	120	30	17.25	339.48	832.56	2.45	23.37	72.72	<0.2
		40	19.88	311.79	887.57	2.84	26.52	74.70	0.55
		50	23.72	309.93	906.68	2.92	26.51	82.23	0.94
		60	24.94	309.24	935.94	3.02	26.09	88.21	1.02

3.3 Drop size distribution at valve vicinity

Figures 9 and 10 show the droplet size distribution histograms for two oil viscosity grades as a function of compressor operating frequency. All charts show a trend that as frequency increases so does the contribution of the drops with smaller diameters to the total mass in the drop form. This is expected since as frequency increases, so does the mass flow rate and velocity at the discharge orifice, which is responsible for the breakup or atomization of the liquid film between reed valve and seat.



30Hz



40Hz

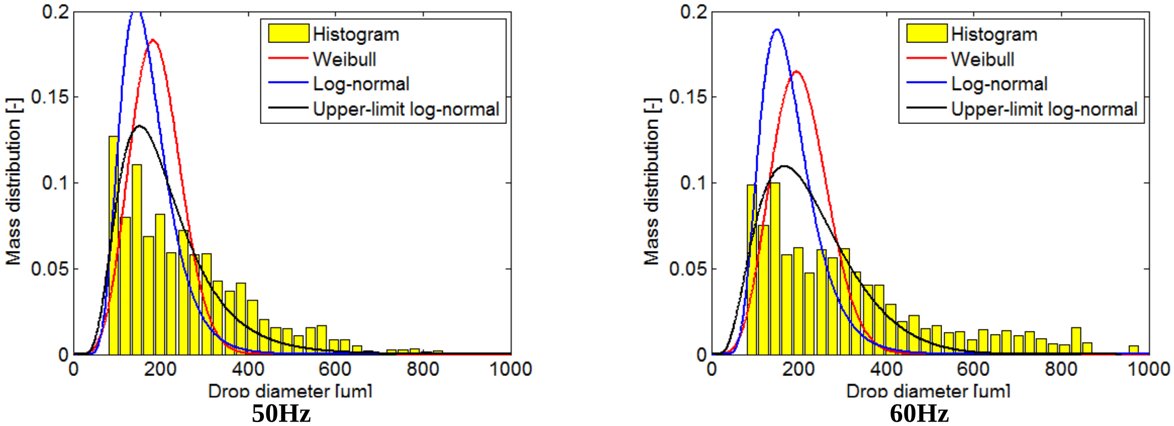


Figure 9: Droplet size distribution functions for PVE32 oil: smaller droplets as compressor frequency increases.

Another way of characterizing a misty flow is by computing several different mean diameters that can characterize a certain histogram. Commonly used means can be the number mean, which only takes into account how many drops are grouped at a certain diameter, or also more meaningful means such as the volume mean which directly correlates to where the mass of the distribution can be found. There are other types of mean such as the Sauter mean diameter which is obtained by means of a ratio between surface forces (i.e. drag) and volumetric forces (i.e. gravity) which in this case have an importance on the separation mechanisms that could be used. Figure 11 shows a comparison of both means for the two viscosities as a function of operating frequency.

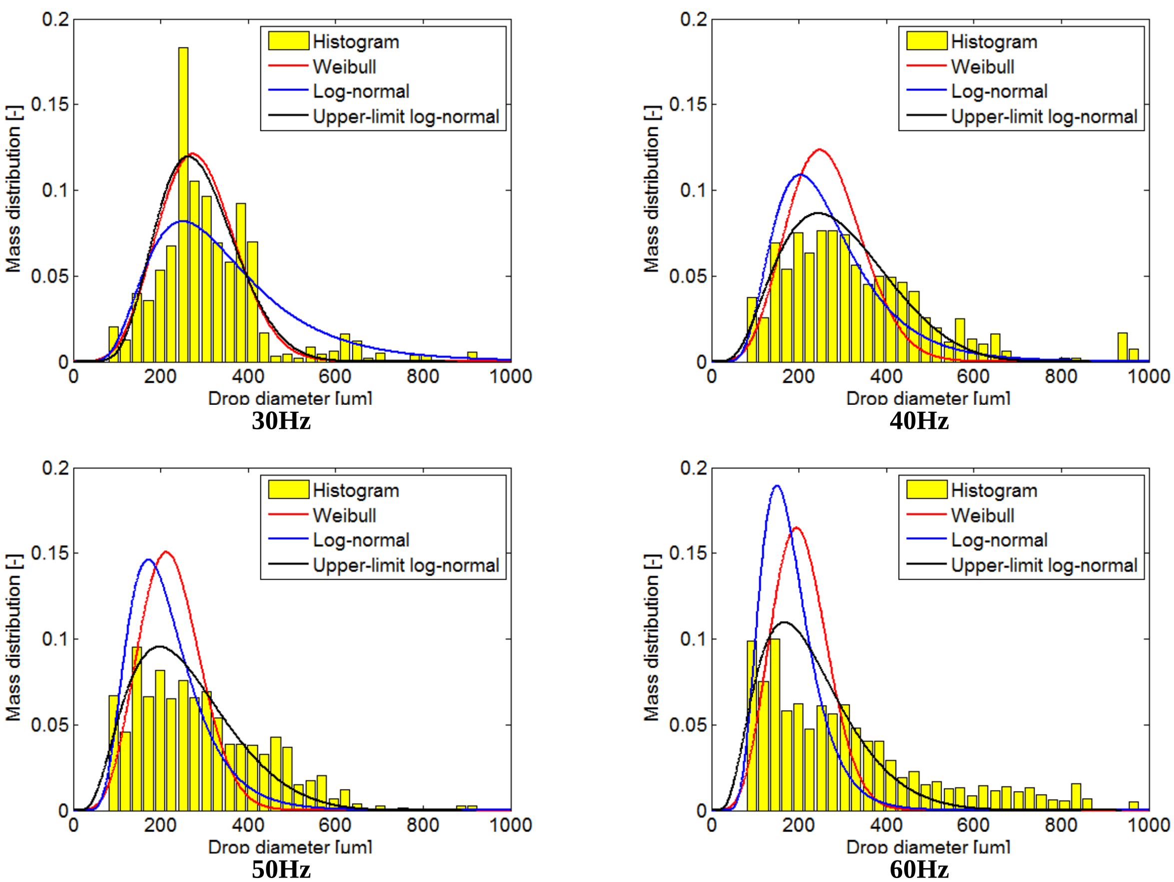


Figure 10: Droplet size distribution functions for POE120 oil

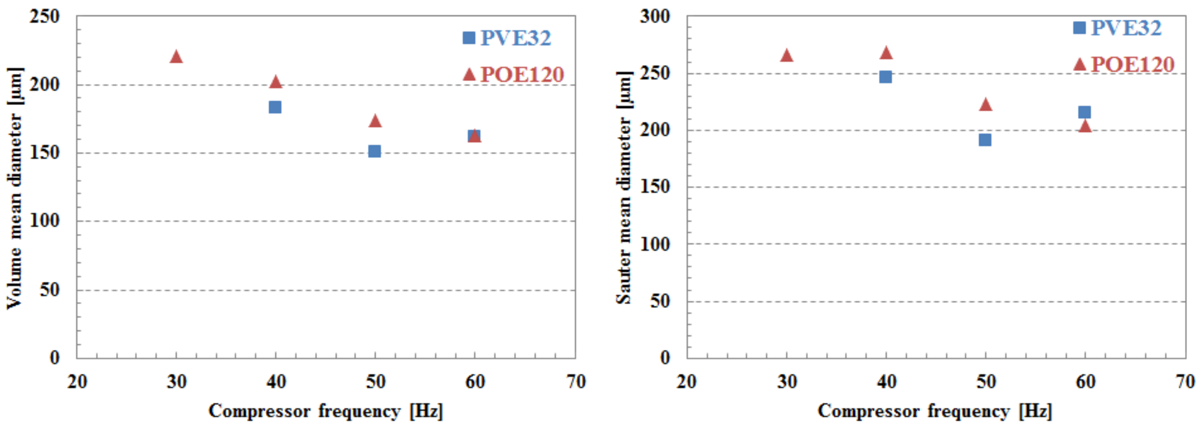


Figure 11: Volume mean diameter and Sauter mean diameter for the valve location

The noteworthy fact in this comparison is that there is not much difference, or our methods were not able to capture, in the mean diameters at different viscosities. Higher viscosity oil tends to generate slightly larger droplets, which is also expected, since viscosity acts as a retardant factor in onset of atomization.

3.4 Drop size inside discharge plenum

Similar drop size distribution functions or histograms can be obtained for the location in the middle of the discharge plenum however, for the sake of saving space, only the final volume based mean and Sauter mean diameters will be reported. It is very easy to note that due to the fact that back lighting is being employed a better special resolution could be obtained by using a microscope type lens. This way it was possible to resolve to droplets as small as 40µm. The trend here observed is that the drop mean diameters actually increase with the operating frequency, which seems counter intuitive. However but diligently looking at the videos it is possible to note that periodically a few very large diameter drops will come into the viewing area. It is suspected that these drops are a result of the detachment of larger volumes of liquid film that are on the ceiling of the discharge plenum cover, therefore even if only a few of these drops are present, the distribution can be skewed towards larger diameters since the volume increases with the third power of the diameter. Figure 13 shows two instances where a large number of small drops are seen together with a few larger drops. The discrepancy is especially more pronounced at larger frequencies and at lower viscosity since it is easier for the liquid to detach from the walls.

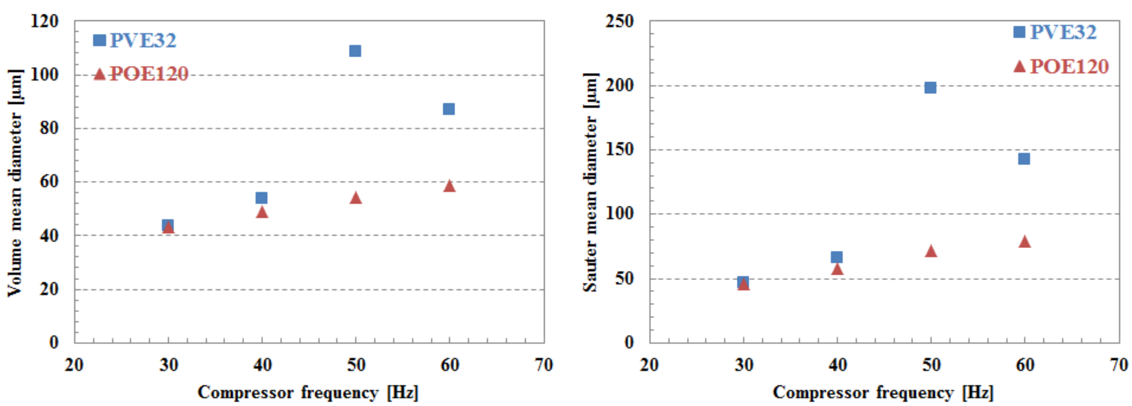


Figure 12: Volume mean diameter and Sauter mean diameter for the discharge plenum

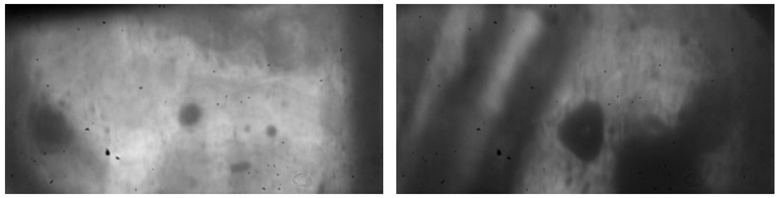


Figure 13: Frame from the videos for the 50Hz and 60Hz operations showing unusually large droplets most likely dripping from the top walls of the discharge cover causing the mean diameters to increase with frequency, picture dimensions are 8.63mm x 4.31mm.

3.5 Drop velocities

Due to the predominantly tridimensional nature of the flow at the vicinity of the valve and also in the plenum, and limitations on the number of cameras utilized, only a 2-D flow field can be determined for the locations in which videos were taken. The velocities at the vicinity of the valve will be explored on a different paper in this conference, *Paper 1569*. However an example of the velocity distribution found on the discharge plenum is given on Figure 14. In here it can be seen that the speed distribution has a peak right at 5m/s. It is also worth to say that the bulk direction of the flow is mainly downwards in a mix of motion dominated by settlement of larger droplets and also the bulk movement of the vapor being downwards since the inlet to the discharge tube going to the condenser is at a lower level than where the video was captured.

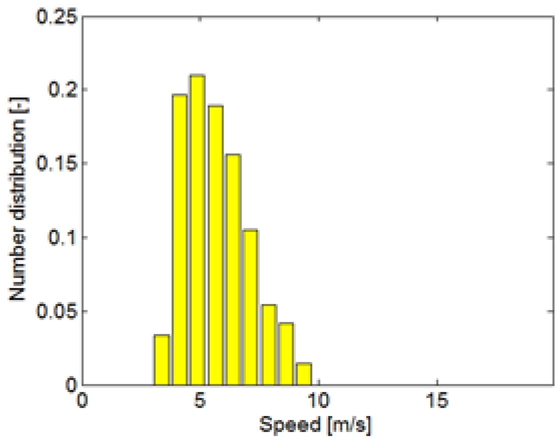


Figure 14: Drop speed distribution in the plenum for PVE32 oil at 50Hz.

4. SUMMARY AND CONCLUSIONS

In summary, in the present work:

- A fully transparent discharge plenum was built and installed successfully in a scroll compressor for residential A/C.
- For the first time it was possible to observe and obtain quantification of the oil flow during the discharge process in a scroll compressor.
- It was found through visualization that the atomization process of the oil film happens very quickly over the opening of the valve and that it most likely is the major source of small droplets inside the compressor.
- In the vicinity of the valve, as the compressor operating frequency rises, the drop size distribution gets skewed towards smaller drops and there is strong indication that those are much smaller than 100µm.
- Droplets much smaller than 100 µm but larger than 40 µm are found in the compressor plenum but the dripping of liquid from the plenum cover generates very large drops that interfere with the expected trend of seeing more smaller droplets as the frequency increases.
- Viscosity plays a role on the volumetric and Sauter mean diameter but it was not dramatic, even with an increase in viscosity grade of 375%.

NOMENCLATURE

OCR	oil in circulation ratio	(%)
P	pressure	(kPa)
r	compression ratio	(-)
ΔT	temperature difference	(K)

Subscript

disch	discharge
sh	superheat
suc	suction

REFERENCES

DeAngelis, J.M., Hrnjak, P.S., *Experimental Study of System Performance Improvements in Transcritical R744 Systems with Applications to Bottle Coolers*, ACRC CR-57, University of Illinois at Urbana-Champaign, 2005.

Hay, K. J., Liu, Z.-C., Hanratty, T. J., *A backlighted imaging technique for particle size measurements in two-phase flows*, Experiments in Fluids, 25(3), 1998.

Kim, S., Pehlivanoglu, N., Hrnjak, P.S., *R744 flow boiling heat transfer with and without oil at low temperatures in 11.2mm horizontal smooth tube* , 13th International Refrigeration and Air Conditioning Conference at Purdue, July 12-15, 2010, West Lafayette, IN, 2010.

Pehlivanoglu, N., Kim, S., Hrnjak, P.S., *Effect of oil on heat transfer and pressure drop of R744 in 6.1mm horizontal smooth tube*, 13th International Refrigeration and Air Conditioning Conference at Purdue, July 12- 15, 2010, West Lafayette, IN, 2010.

Toyama, T., Matsuura, H., Yoshida, Y., *Visual Techniques to Quantify Behavior of Oil Droplets in a Scroll Compressor,* International Compressor Engineering Conference at Purdue, West Lafayette, IN, 2006.

Wujek, S.S., *Mist to annular flow development quantified by novel video analysis*, PhD Dissertation, University of Illinois at Urbana-Champaign, Urbana, IL, 2011.

Zimmermann, A.J.P., Hrnjak, P.S., *Oil flow at discharge valve in a Scroll compressor,* Proceedings of the 8th International Conference on Compressors and their Systems, Paper 176, London, 2013.

ACKNOWLEDGEMENT

The authors would like to acknowledge the support of the member companies of the IAB for the Air Conditioning and Refrigeration Center at the University of Illinois through ACRC project 279 and especially of Danfoss A/S that supplied the compressor used in this study. The authors would also like to thank Dr. Scott Wujek for providing the vast majority of the image processing code used in this work.