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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. This work is focused on the breakup process of the film that is formed between a reed valve and its seat. Emphasis is given on visualization of the breakup pattern and determination of the critical valve lift and velocity at which the film breaks during typical compressor operation. Preliminary experiments were carried out outside of the compressor environment, using a typical valve plate from a reciprocating compressor for household refrigerators. Observations of the breakup pattern show that the liquid film does not remain continuous until breakup into ligaments and droplets. In fact the stretched liquid film is first broken up into equally spaced liquid columns and then by means of the drag force promoted by the vapor flow due to the pressure difference it is blown away from the valve edge and starts the atomization process into a fine mist. Additional experiments were also carried out with two different oil viscosities (32cSt & 120cSt), and four different operating frequencies ranging from 30Hz-60Hz in a scroll type compressor operating under typical residential air conditioning conditions. High speed videos were utilized to quantify the droplet cloud velocities, and also valve critical lift before oil is ejected from the gap between valve and seat. The droplet cloud velocity is compared to a calculation using a compressor thermodynamic model to estimate the vapor velocity at the discharge valve.

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.

Wujek and Hrnjak (2011) have shown that there is a direct correlation between the discharge valve opening frequency and the droplet population periodicity in mist-annular flows at the discharge of a five cylinder dual action swash plate compressor running with R134a and PAG46 oil combination.

Zimmermann and Hrnjak (2013a) showed that it was possible to achieve good visualization of the opening process of the reed valve at the discharge of a scroll compressor, when OCR value was below 1%, and very good images were showed at OCR less than 0.4%. From their visualizations they were able to extract valve lift, velocity and also identify if any oscillatory movement about the longitudinal axis of the valve was present and quantify it as a function of time.

Zimmermann and Hrnjak (2014) indicated that during the most significant source of droplet generation of small diameters in a scroll compressor is the breakup of the film between the valve and the valve seat at the very beginning of the valve's opening motion. Therefore it is important to understand the opening process of the reed valve with the presence of oil for the sake of characterizing the liquid atomization process which can lead to better integrated separator designs.

In this work, two sets of experiments will be explored, one set of preliminary experiments which are more rudimentary, but still very valid for the purpose of a qualitative discussion of the process and provides some insight on how the oil film breaks up when stretched by the valve lifting movement. The second set of results comes from the best attempts at visualizing the valve opening process in a real compressor operating in a full system.

2. PRELIMINARY EXPERIMENTS

The first step into understanding how the opening process of a discharge reed valve would look like was to try to replicate similar conditions in an environment that provided easy access for visualization. Therefore an experiment using a real valve plate from a reciprocating hermetic compressor was developed to provide some insight into the process.

Youshizumi et al.(2011) visualized oil film breakup structures in discharge reed valves. In their experiment, they tried to reproduce the same pressure pulse observed in their compressor and submitted a real valve installed in a glass seat with and orifice the same size as in the compressor for the gas flow. Figure 1 shows an image from their work showing the structure of the liquid oil film just before the film breaks, this is a view from underneath the valve. Notice how there is wide spread collapse and rupture of the liquid film from the tip to the root of the valve.

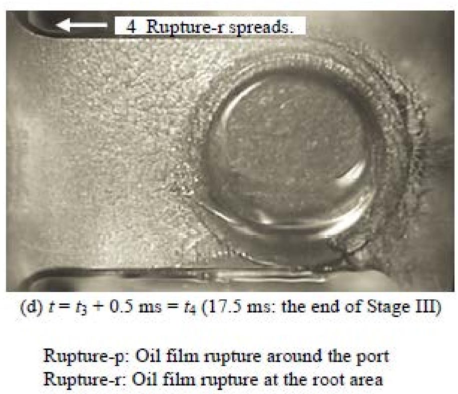

Figure 1: Oil film breakup as visualized by Youshizumi et al. (2011).

2.1 Visualization setup outside compressor

The experiment for the valve opening process visualization consisted of generating a pressure pulse inside the discharge orifice of a real compressor valve plate. The valve seat or the surface underneath the valve was treated with a known quantity of oil before the pressure pulse was generated. The fluid of choice to generate the pressure pulse was nitrogen gas. Care was especially taken to ensure that the gas velocity was compatible to what could be encountered in the compressor and that the pressure pulse had an amplitude that was also the same order of magnitude as expected in the compressor. Figure 2 shows a schematic of the set up for the experiment.

The oil used in the experiments was POE ISO 10 which was the original oil for the compressor. Ambient temperature and pressure were maintained while doing the visualizations. The camera used for the recording of the movies is a Phantom V671, with a 512x512 CMOS sensor with capability of recording at 2200 frames per second at the highest resolutions. Higher framing rates can be achieved by using a smaller portion of the sensor.

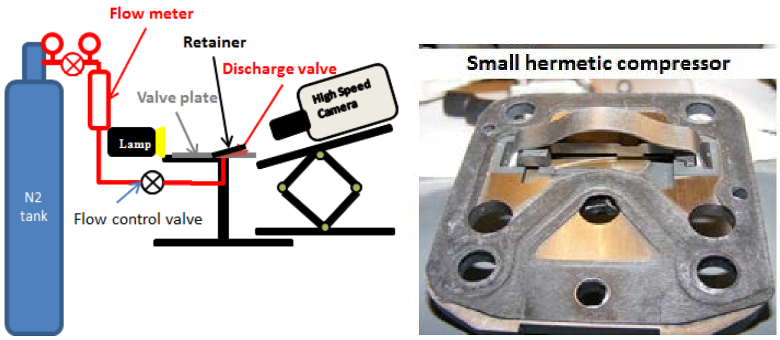

Figure 2: Set up for preliminary experiment and sample valve plate used

2.2 Film breakup patterns

The gas flow rate was adjusted to yield the same average velocity at the discharge orifice of 9m/s, this resulted in a pressure difference pulse amplitude of 324kPa. The amounts of oil used were 10µl and 20µl. Figure 3 shows the snapshots of the film breakup pattern at the time just before oil burst from the valve.

It is interesting to note the appearance of light and dark regions in a well-defined pattern in the gap between valve and valve seat. This might be an indication that cavitation cells are forming inside the oil film the causing discontinuities in the film, leading to some areas protrude outwards before other areas thus causing some areas to reflect light before others. This behavior for film breakup correlates well with what was seen by Yoshizumi et al. (2011). What was not provided in that work was the spacing between cavitation sites. Here by visually inspecting the image and manually estimating the size of these gaps, it is possible to say that these distances are in the range of 400-500µm, depending on the condition.

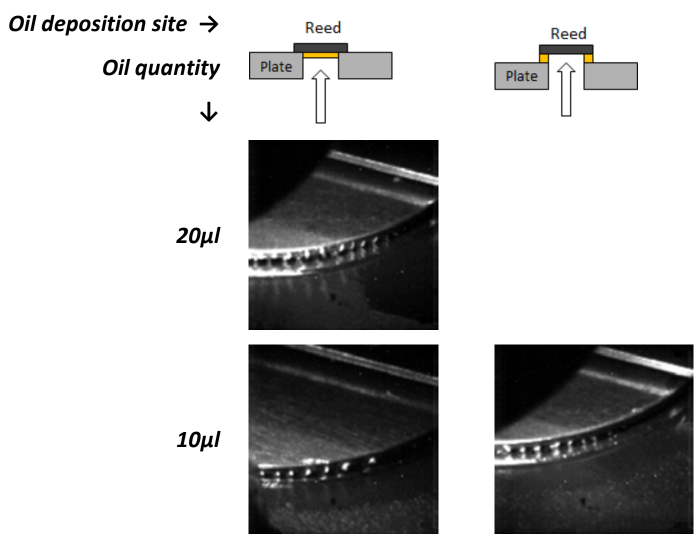

Figure 3: Oil film breakup as visualized in this work.

This evidence, together with the results of Yoshizumi et al. (2011) and Zimmermann and Hrnjak (2013a) also shows that the generally accepted assumption of a continuous liquid film for stiction forces calculation in valve dynamics might not be completely accurate, since both previous works show discontinuities on the film structure.

3. VALVE OPENING IN REAL COMPRESSOR

3.1 Hypothesis for the source of oil in circulation

One of the unanswered questions that this work can try to address is that of the origin of the droplets that end up at the compressor discharge. One simple hypothesis is that some oil comes entrained in the gas from the compression chamber, some is scraped from the clearances and some might be coming from the volume that accumulates in the gap between valve and seat. The other possibility is that the majority of the oil being dispersed in the discharge plenum is actually coming from the film breakup between valve and seat and then, when valve closes the gap gets replenished with some oil that comes from the gas and some that come from the seals.

To help answer this question, the compressor was operated in a full size residential air conditioning systems placed in environmentally controlled chambers so the suction pressure and temperature and the discharge pressure were held fairly constant to the compressor. The compressor is of scroll type designed for residential air conditioning applications, having 3 discharge valves, volumetric displacement of 57.36cc/rev, and a low pressure shell arrangement. It 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.

In order to evaluate the influence of compressor speed/mass flow rate and also the effect of viscosity, a test matrix listed on Table 1 was used. OCR was determined according to ASHRAE 41.4 Standard and the scale used had accuracy of ±0.1g and the sample size averaged about 90g. As a result the maximum absolute error found in OCR was 0.2%. Even though the points at 30Hz are listed in the test matrix, there was no useful result that could be derived from it since OCR was too low to be measured accurately.

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

By calculating the amount of oil that is pumped out at every compression cycle, it is possible to estimate the volume and then also, for the case of this compressor calculate the volume present in the gap between valve and seat. Figure 5 shows schematically how the main valve of the compressor in study is assembled and table 2 shows the calculated oil volume in the gap and the actual oil volume being discharged in each cycle. It is clear that the gap can hold an order of magnitude more oil that is discharge at every cycle so for this particular compressor design the second hypothesis that the majorty of the oil comes from this location during the valve opening process is very strong.

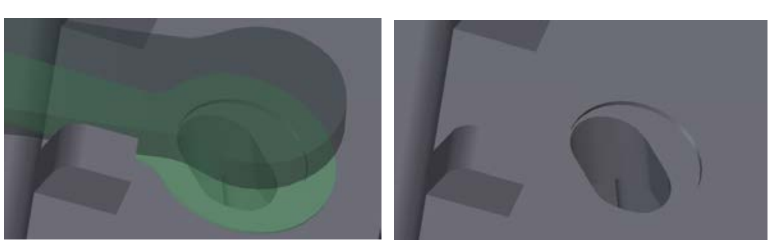

Figure 5: Detail of the main discharge valve assembly showing a gap volume between valve and the discharge orifice.

Table 1: Test conditions for oil mist characterization

Oil	Frequency [Hz]	Volume of gap [cm^3]	Volume of oil discharged/cycle [cm^3]
PVE32	40	2.05e-2	3.36E-03
	50		4.64E-03
	60		4.95E-03
POE120	40		2.88E-03
	50		4.69E-03
	60		4.46E-03

In order to explore it more, a visualization study was carried in parallel to the experiments to determine OCR.

3.1 Visualization set up and test conditions

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 4 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 4: Visualization setup: transparent flange and glass barrier to enhance optical access to the valve and sample image for the valve vicinity.

3.3 Video analysis

In order to extract information from the video, the Camera software Phantom V675 was used. It allows for certain filters to be applied and also allows for measurements of distances and velocities in the frames and in between frames of the video.

The filter chosen in the case of processing these videos was a sharpen filter which enhances the edges and sharpens transitions so it becomes easier to pinpoint features such as the edge of the valve or the edge of a droplet cloud in movement.

With such tools it is possible to extract information about the valve lift, valve velocity and cycle periodicityas shown by Zimmermann and Hrnjak (2013b).

Figure 5 shows a sample sequence of images showing one cycle of opening and closing of the discharge valve with the compressor operating at 40Hz with PVE oil and viscosity 32cSt.

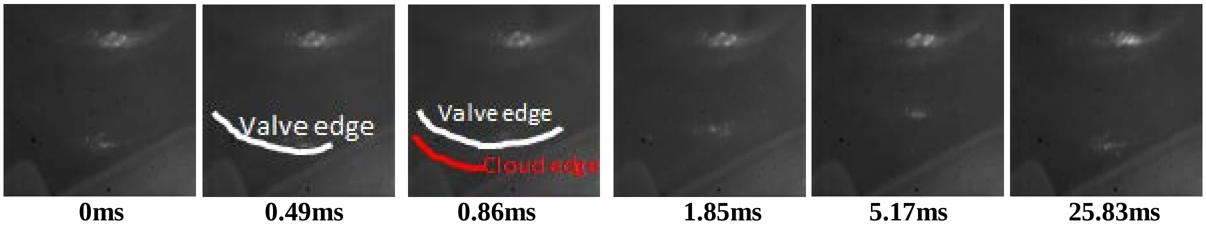

Figure 5: Opening sequence for discharge valve: note the cloud of small droplets that flows from the valve edge as the valve breaks open, very short period of time that cloud is noticeable.

By identifying the valve edge it is possible to watch the video frame by frame and determine when a droplet cloud starts to flow from underneath the valve, at that moment, by measuring the displacement of the valve edge it is possible to infer the order of magnitude of the valve lift so that the liquid film breaks and starts being atomized. The results will be further explored.

Another result that can be extracted is the expansion velocity of the droplet cloud, and the time period for which the cloud can be noticed in the video, and that can be compared to the total cycle time and the time for which the discharge valve remains open.

3.4 Critical valve lift for film breakup

One of the interesting observations from the videos was that usually there was a delay between the start of valve movement and the appearance of a cloud of most likely droplets being expelled through the gap between valve and seat, by the flowing compressed vapor from the compressing chamber. Not in all videos it was possible to determine this valve lift necessary for the droplet cloud to start showing on the image. In some cases the image was too cloudy already due to higher OCR or even due to positioning of the camera in relation to the valve in a way that the initial position of the valve was not properly determined. Figure 6 shows the results when it was possible to obtain it.

At first these results might indicate that as the frequency goes up the film is able to stretch more before it starts to breakup. However one should note that the error in this inference is very large and it can be as high as 15% since we are talking about 100μm in the 600μm to 900μm measurement range. This result indicates then that there is not much influence of the compressor speed on the critical valve lift for film breakup. Unfortunately the images for the POE oils with viscosity 120 cSt did not give much confidence in determining the same type of results.

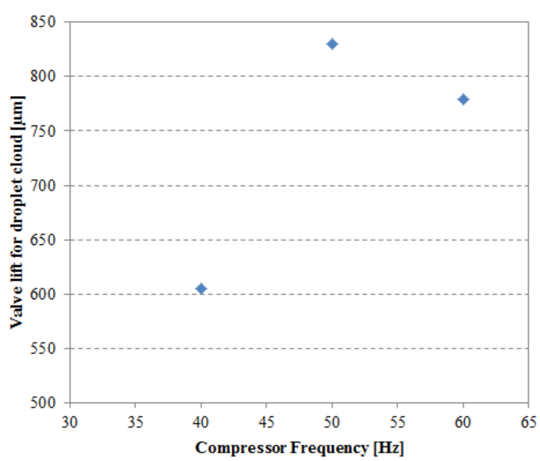

Figure 6: Critical valve lift before droplet cloud appears on video.

3.5 Droplet cloud velocity

A second piece of information can be extracted from the videos as mentioned before, the velocity at which the droplet cloud is expanding. This velocity has direct relationship with the initial droplet velocity into the discharge plenum and also with the vapor velocity flowing through the gap between valve and seat.

Figure 7 shows the average over 5 cycles for the drop cloud velocity using PVE 32 oil as a function of compressor frequency. As can be seen, very little difference on the values of the peak velocities is noticeable. However the shape of the profiles differs quite a bit between the three curves. This can be attributed to some measurement uncertainty in identifying the droplet cloud and differences in lighting from condition to condition. It is known that for higher frequency it also translates into higher OCR, and therefore the videos become cloudier.

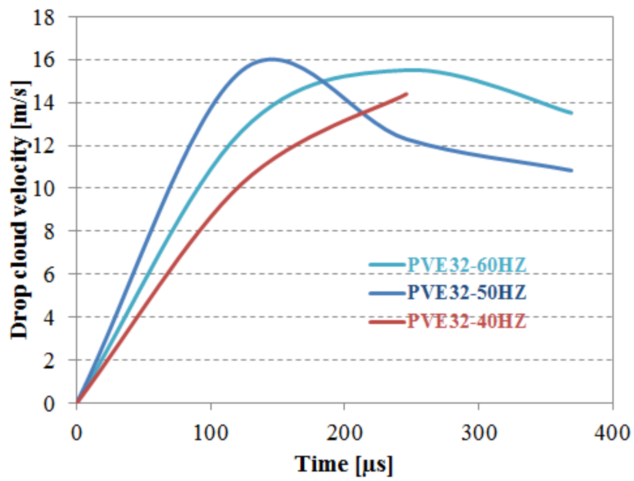

Figure 7: Drop cloud velocity for PVE 32 oil

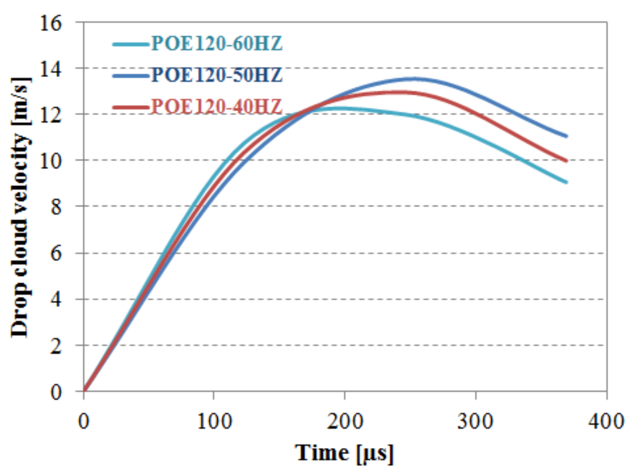

Figure 8: Drop cloud velocity for POE 120 oil

Even though some inaccuracy in the shape of the curves might be present the peak values are very much in line with the expected results given by well-established scroll compressor models. In order to make the comparison, the model proposed by Gomes and Deschamps (2007) was used to first calculate the compression and discharge process and then the valve lift information and mass flow rate from the model were used to estimate the vapor velocity through the gap between the valve and the seat. The model parameters such suction temperature, top clearance and valve stiffness and natural frequency were adjusted to match the experiments for mass flow rate, discharge temperature and valve movement. In order to compare the two results from experiments and modeling, it was chosen to do the comparison with the valve lift at the same value as the experimentally determined valve lift at the peak velocity of the droplet cloud. Table 2 shows the valve lift used for the calculations. Figure 9 shows the comparison between model and experiment. From these results, it is clear that a slip ratio very close to 1 is present in this flow being accelerated out of the valve into the discharge plenum. However it is also clear that in this case the experimental values are consistently higher than the model which could indicate that since the drop cloud velocity measurement uncertainty is ±0.84m/s, and also the built in operator error in analyzing the image, these values actually agree quite well.

Table 2: Experimental valve lift at peak cloud velocity for PVE32 oil and model calculate vapor velocity

Frequency [Hz]	60	50	40
Lift [mm]	0.803	0.855	0.649
Cloud velocity [m/s]	15.5	15.48	14.4
Vapor velocity [m/s]	20.05	13.15	9.75

3.6 Cycle variance and drop cloud lifetime.

Another piece of information that can be extracted from the videos is both the valve cycling times. The overall cycle time showed very good agreement with the period calculated by the frequency set on the variable frequency drive. A few fractions of a ms were observed but that could be due to slip ratio in the motor and is not worth exploring it here.

The most interesting information from timing was the time which the droplet cloud took to disappear from the video. That time is shown on Figure 10 as a function of the operating frequency for both oils used. The uncertainty on the period can be taken as the same as the interval between frames of the video which in this case was ±123μs.It can be seen that the higher the frequency the longer the droplet cloud lingered and that can be related to the fact that for higher frequencies, there is more oil in circulation. Also, since for POE120 the OCR was slightly lower that PVE32, the time that the cloud was seen was also shorter.

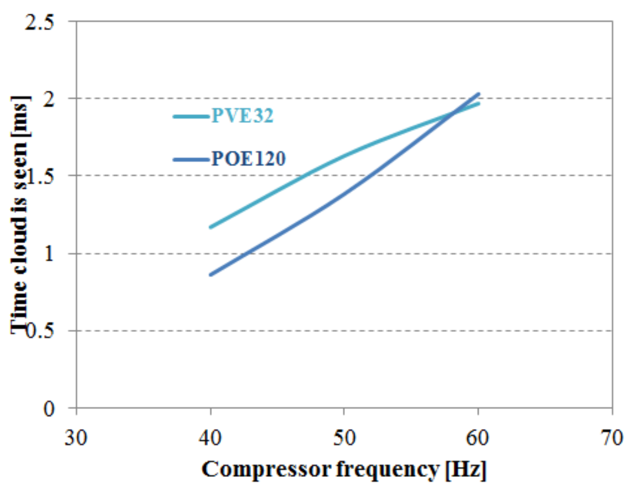

Figure 10: Time that cloud is seen in the video decreases as frequency decreases as result of lower OCR.

Figure 11 also shows percentage of the open time of the valve that the droplet cloud takes to disappear. It can be seen that as the frequency increases the percentage time increases since both the time that it is noticeable increases and also the open period of the valve shortens.

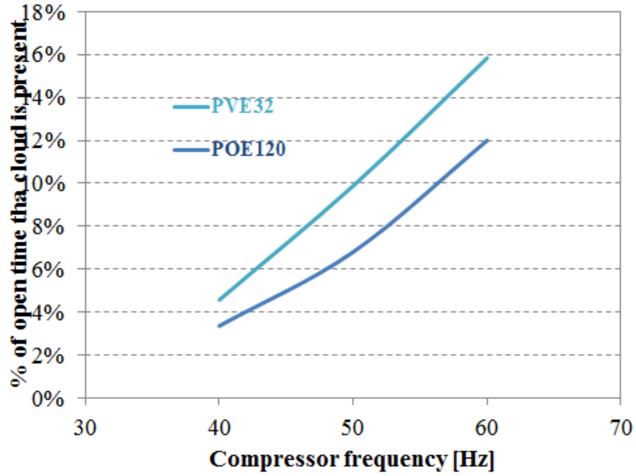

Figure 11: Percentage time that cloud is seen relative to total valve open time. As frequency increases, the % time increases due to both shorter open time and also higher OCR (more oil mass to be expelled).

4. CONCLUSIONS

For this particular compressor the hypothesis that the majority of the oil in circulation comes from the breakup of the oil film between valve and seat, which is later replenished, was tested. The hypothesis was analyzed by comparing the amount of oil discharge during each cycle and the oil amount that can be accumulated between the orifice and the valve. It was show that the holdup capacity of such volume is an order of magnitude greater than the amount of oil being discharged. To support this theory, a visualization study based on high speed video showed that at the very beginning of the opening process, a droplet cloud is expelled at high speed from the valve edge and this cloud lingers for a very short period of time, showing no evidence of continuous oil flow coming from the valve region.

Although the same film breakup patterns as the preliminary experiments were not able to be identified in steady state operation, other important information is extracted from the videos, such as the presence of a fine cloud of droplets at the very beginning of the opening process and information about the velocity at which this cloud is expanding and the time which it remains visible as well as the indication of the critical valve lift at which the cloud is first noticed can be extracted and their behavior as a function of compressor operating frequency and oil viscosity was examined.

It was found that the critical valve lift has no clear trend when it comes to influence of the compressor speed. This was a result of limitations in the special resolution of the image. The influence of oil viscosity was not measurable for this characteristic because of cloudiness in the image.

Droplet cloud velocity reaches a peak at a certain valve lift and then starts to decline. There is limitation for how long the droplet cloud velocity is traceable since after some time there is no more boundary distinction in the image. When compared to a calculated expected vapor velocity based on a thermodynamic model of the compressor, the droplet cloud velocity showed good agreement, however a high expected experimental error might hide a trend on the slip ratio.

The time that the droplet cloud is noticed on the video decreases as compressor frequency decreases, since OCR is also decreasing meaning that less oil mass will be discharge at each cycle.

Future work should include improvement on the droplet cloud edge detection to eliminate operator bias and also better spatial resolution, however the challenge in having better resolution is about the amount of light that can be brought in.

NOMENCLATURE

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

Subscript

disch	discharge
sh	superheat
suc	suction

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