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Effects of Orientation and Valve Opening Speed on Oil Circulation Rate Measurements Using an Evacuated Type Sampling Cylinder

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ABSTRACT

The lubricating oil used in vapor compression systems helps to reduce the wear and tear between the moving parts of the compressor and in the long run extends the useful life of the compressor. But at the same time, the oil can leave the compressor and be in circulation or get held up in certain locations. The percentage by mass of oil present in the oil-refrigerant mixture which moves through the system is known as the oil circulation rate (OCR). The OCR can affect the system performance, so accurate knowledge of OCR and OCR measurement is crucial. The ASHRAE standard 41.4 describes the method of OCR measurement through sampling using an evacuated type sampling cylinder, but this method can often be open to interpretation. Factors such as sampling cylinder orientation, shape and size, valve opening speed, etc. can influence the OCR measurements, but the standard provides little to no information regarding these.

The present study investigates OCR sampling results for different evacuated sampling cylinder orientations, namely, horizontal, vertically downward, and vertically upward flow to a dead end. The flow patterns inside the sampling cylinders were visualized by using transparent sampling cylinders and high-speed camera. The study also compares the OCR results obtained with the sampling cylinder valves opened at different speeds for the different orientations.

1. INTRODUCTION

Oil is used in vapor compression systems primarily as a lubricant to reduce the frictional wear and tear between the moving parts, and to increases the longevity of the compressor. Alongside its function as a lubricant, the oil also helps to reduce noise and vibrations, aids heat dissipation and acts as a sealant to maintain good volumetric efficiency. The oil is usually required to stay within the compressor only, however, the oil, mixed with refrigerant, can leave the compressor and either be in circulation or get retained in components such as heat exchangers, receivers, and accumulators. The presence of oil in the system affects flow regimes and may negatively impact refrigerant distribution. The properties of pure refrigerant within the system are altered when it is mixed with oil. From the works of Radermacher *et al.* (2006), Youbi-Idrissi and Bonjour (2008) and many others, it was found that with high OCR, the amount of oil hold up in the evaporator increases, decreasing the heat transfer area and reducing the heat transfer coefficient. Shen and Groll (2005) showed that according to most studies, oil presence increases pressure drop during evaporation and condensation. The works of Liu and Hrnjak (2016) show that with the increase of OCR, both system capacity and COP are seen to decrease.

Too much oil in the system can have detrimental effects on the performance at both the system and component levels. And because of this, nowadays, there is an industry trend towards low-OCR compressors, and with the OCR values getting increasingly smaller, it has become even more important to be able to measure OCR accurately. There are a variety of in-situ or online methods of OCR measurement, and they usually depend on different physical fluid properties such as density, speed of sound, refractive index, etc., while other methods include flow visualization such as in the works of Xu and Hrnjak (2017).

However, all methods of OCR measurement require calibration, and this is contingent upon the specifics of the test, and the oil-refrigerant combinations used. The calibration is done against the OCR sampling technique described by the ASHRAE standard 41.4 (2015) which employs an evacuated type sampling cylinder with a dead end, performed at the liquid line. This method, however, might be prone to some limitations, e.g., lack of specificity of sampling cylinder orientation, shape and size, immiscible combinations of oil and refrigerant, valve opening speed, vacuum time, etc. Wujek and Hrnjak (2006) showed that for different orientations of the sampling cylinder, for a system running on R744 and PAG 46 oil, the measured OCR values showed quite a lot of variation. But since R744 is not completely miscible in PAG 46 oil in all conditions, it was not clear whether the discrepancies were due to the immiscibility or due to the sampling technique employed.

The present work takes a closer look at the oil sampling technique described by the ASHRAE standard 41.4 (2015). An evacuated type sampling cylinder was employed, and different orientations and sampling cylinder valve opening speeds (fast = 0.5 second, slow = 3 seconds) were tested to see their effects on OCR measurement for an electric variable speed scroll compressor. The sampling cylinders were made of transparent polyvinyl chloride (PVC) tubing, and this allowed visualization of the flow patterns inside using a high-speed camera. The images of flow into the evacuated sampling cylinder provided interesting information about the OCR data obtained using this method, and some of the factors which may affect the data.

2. EXPERIMENTAL FACILITY

The experimental setup consists of a vapor compression air-conditioning setup with a compressor, an evaporator, and a condenser inside environmental chambers, and an EEV. The temperatures inside the environmental chambers were maintained at the AHRI A_{Full} condition as prescribed in AHRI standard 210/240 (2017), with the outdoor temperature (condenser air-side temperature) at 95°F (35°C) and the indoor temperature (evaporator air-side temperature) at 80°F (26.7°C). Heaters, blowers, and cooling water circuit are available inside the environmental chambers to ensure that the desired conditions are achieved and maintained at steady-state condition. The miscible combination of R134a as the refrigerant, and PAG 46 oil as the lubricant was used for the current study. The pressure, temperature, mass flow, etc. are collected and transferred to a data-logger, which then sends the data to a VEE software that provides the real-time values and graphs. The software has a recording feature with an interval of 5 seconds. At steady-state condition, the recorded data are time averaged. Properties of refrigerants and other fluids are calculated using REFPROP 10.0 (2018). Details about the experimental facility, the different equipment used, and uncertainties are provided in the works of Haider *et al.* (2022). To avoid repetition, they have been omitted from the contents of the present paper.

3. OCR SAMPLING

3.1 Calculation of OCR
OCR sampling is performed by taking a sample of oil-refrigerant mixture from the liquid line of the system. After the sample is taken, the refrigerant trapped inside the sampling cylinder is completely removed, leaving just the oil inside. Knowing the dry mass of the sampling cylinder, M_1, and the mass of the sampling cylinder with oil-refrigerant mixture, M_2, and with only oil, M_3, the mass of the oil-refrigerant mixture and the oil can be calculated. The OCR is the ratio of the mass of oil to the total mass of the oil-refrigerant sample entrapped. For the present study, the focus was on the evacuated type sampling cylinder, where one end of an evacuated cylinder is connected to the liquid line, with the other being a dead end, as prescribed by the ASHRAE standard. The sampling cylinder orientations used are provided in Figures 1 and 2. Based on the oil-refrigerant sample taken, the OCR is calculated using Equation (1).

$$OCR = \frac{m_{oil}}{m_{oil} + m_{refrigerant}} = \frac{M_3 - M_1}{M_2 - M_1} \tag{1}$$

Error propagation showed that the absolute uncertainty in OCR was in the order of ±0.001, but since there can be many other non-quantifiable sources of uncertainty, two digits after the decimal point were taken for all OCR values.

3.2 Sampling Cylinder Orientations
The goal of the present study was to investigate OCR results for different orientations of the evacuated type sampling cylinder. The sampling cylinder orientations investigated were vertically upward flow, horizontal flow, and vertically downward flow, all to a dead end. Figures 1 and 2 show images and schematics of the orientations used.
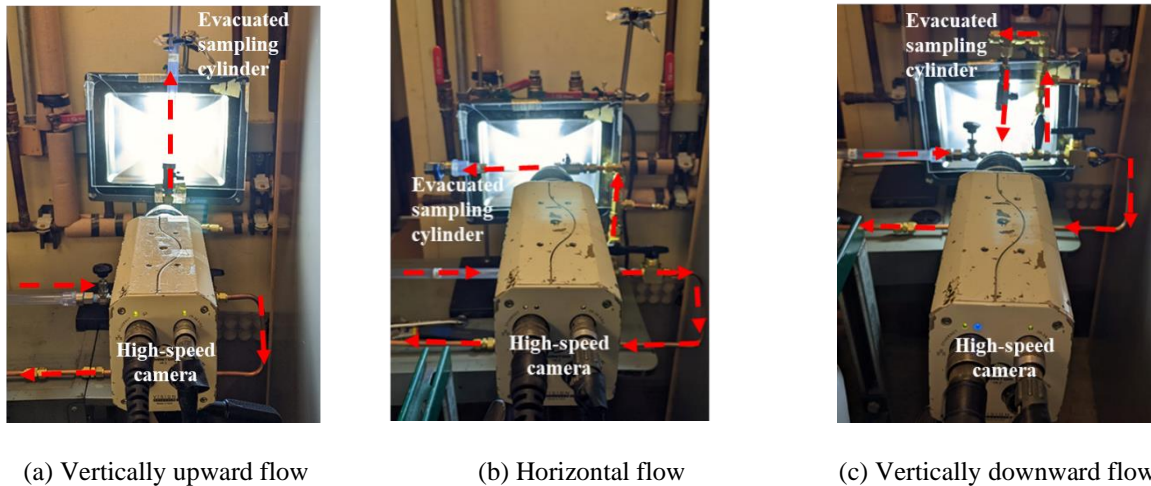
(a) Vertically upward flow   (b) Horizontal flow   (c) Vertically downward flow

Figure 1: Different orientations of the evacuated type sampling cylinder

(a) Vertically upward flow   (b) Horizontal flow   (c) Vertically downward flow
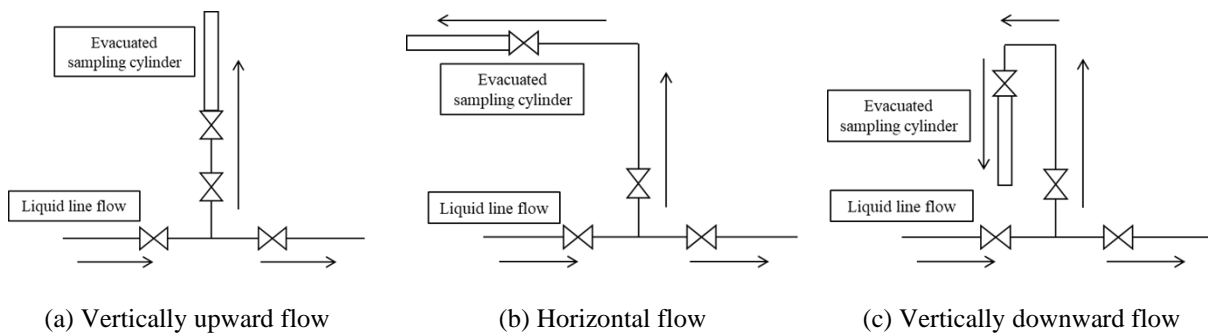
Figure 2: Schematic diagrams of the different sampling setups

4. RESULTS

4.1 Vertically Upward Flow

The study performed by Haider *et al.* (2022) discussed how for the vertically upward flow into an evacuated sampling cylinder, at the slow valve opening speed, the OCR was lower. Flow visualizations done at the evacuated sampling cylinder entrance revealed that there was a circulation zone of viscous fluid. It was suspected that for slow valve opening, the viscous liquid thought to be oil-rich mixture produced due to refrigerant flashing was leaving the sampling cylinder, resulting in lower oil content, and hence lower OCR. To investigate the effect further, and to see if a lower OCR was obtained consistently for the slow valve opening case, the OCR measurements were performed at speeds ranging from 1500 min^{-1} to 2500 min^{-1}. The results are shown in Figure 3.

Figure 3 shows how the OCR values are consistently lower for the slow valve opening case as compared to the fast valve opening case at all five speeds. This observation supports the claim that for the vertically upward flow into a dead end, slower valve opening speeds could lead to lower OCRs. A possible explanation could be churning flow at the sampling cylinder entrance which can occur with flows going against gravity, meaning the viscous oil-rich region could leave the sampling cylinder and so the total oil content and the OCR decrease.

To confirm that the lower OCR at slow valve opening was indeed due to a churning flow, other flow orientations such as horizontal and vertically downward flow into an evacuated sampling cylinder were also investigated as part of the study. For these orientations, the flows wouldn't be against gravity, and could be expected to result in similar OCR for both slow and fast opening cases.
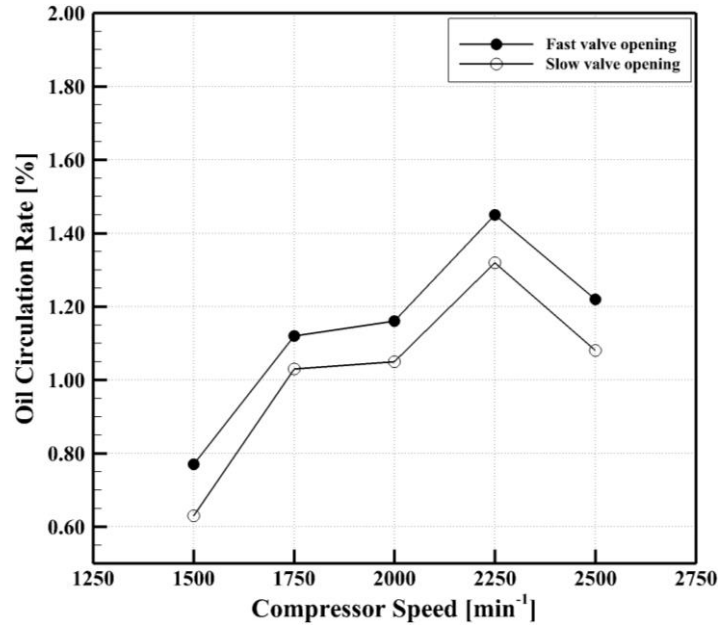
Figure 3: OCR at different compressor speeds and valve opening speeds (vertically upward flow)

4.2 Horizontal Flow

For tests performed with liquid line flow of oil-refrigerant mixture into a horizontal evacuated sampling cylinder, the compressor speed of 2250 min^{-1} was chosen since the highest OCR was obtained at this speed for the vertically upward flow case. Sampling was performed once system steady state conditions were achieved. For sampling with both slow and fast valve opening speeds, the high-speed camera was used to visualize the flow. The high-speed camera images for the fast and slow valve opening speeds are provided in Figures 4 and 5 respectively (flow is from right to left).
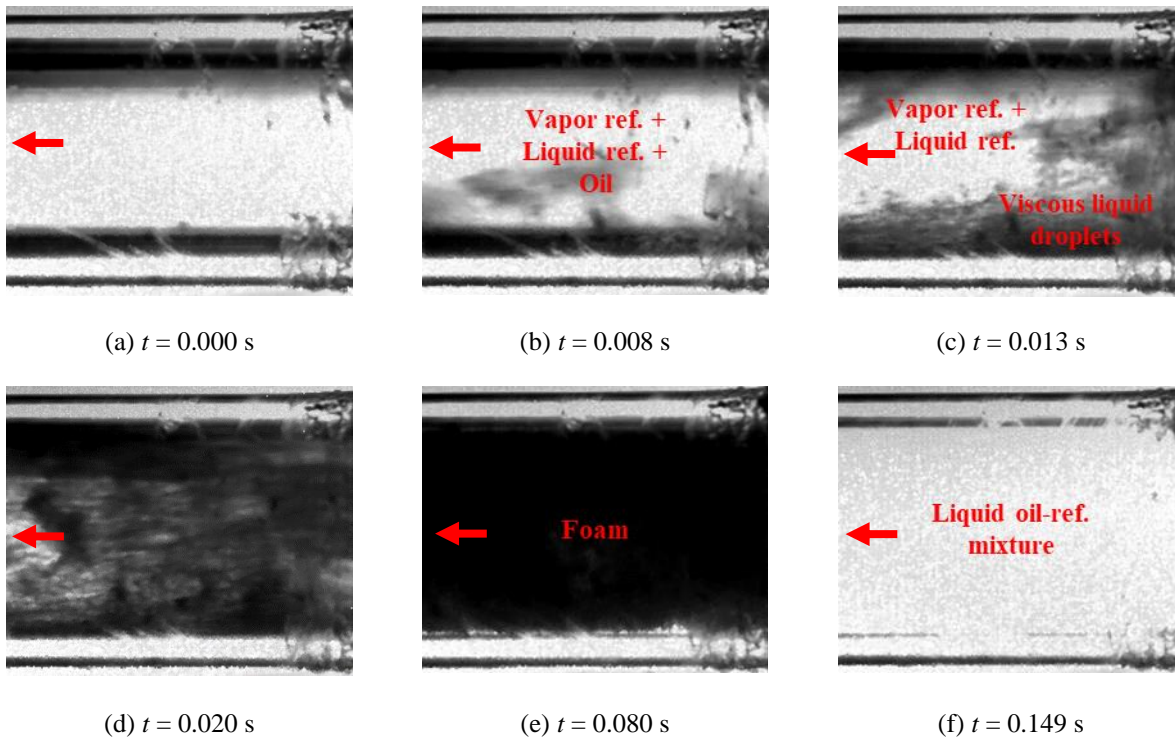

(a) $t = 0.000$ s   (b) $t = 0.008$ s   (c) $t = 0.013$ s

(d) $t = 0.020$ s   (e) $t = 0.080$ s   (f) $t = 0.149$ s

Figure 4: Fast valve opening case for horizontal flow entering evacuated cylinder

From Figure 4, in (a) and (b), it can be seen that as the valve opens, the refrigerant flashes into the evacuated sampling cylinder, and the vapor is seen as grey smudges. In (c), droplets of viscous liquid form on the wall of the cylinder, and this liquid is thought to be oil-rich mixture. As the valve opens more, more liquid enters in (d), and the mixture starts to fill up the cylinder. The image in (e) indicates a foamy region of mixture, which transitions to clear liquid in (f). The flow is seen to only go towards the left, and no circulation zones were seen for the fast valve opening case.

For the slow valve opening case in Figure 5, (a) and (b) show the refrigerant flashing into the tube as the valve is first opened. As the valve opens more, again the viscous oil-rich mixture created due to flashing is seen to enter the cylinder in (c), and more of this liquid collects on the top and bottom walls of the tube in (d) and (e). As the valve opening increases, more of this viscous layer/film and oil-refrigerant mixture from the liquid line are sucked into the sampling cylinder, quickly filling it up in (f) and (g). As the cylinder fills up completely, transparent liquid is seen in (i).

Unlike the vertically upward flow, the horizontal orientation does not show any circulation zones for both the fast and slow valve opening cases. The OCR values obtained for both cases (average of 3 samples) were 1.32% and 1.29% respectively; Haider *et al.* (2022) found that for vertically upward case, the OCR values were 1.45% and 1.32% for the fast and slow valve opening speeds respectively. From the flow visualization and the sampling results it can be said that for the horizontal orientation, the flow into the sampling cylinder is somewhat similar for the fast and slow valve opening cases in that it does not have a viscous circulation region, and hence it results in similar OCR values.
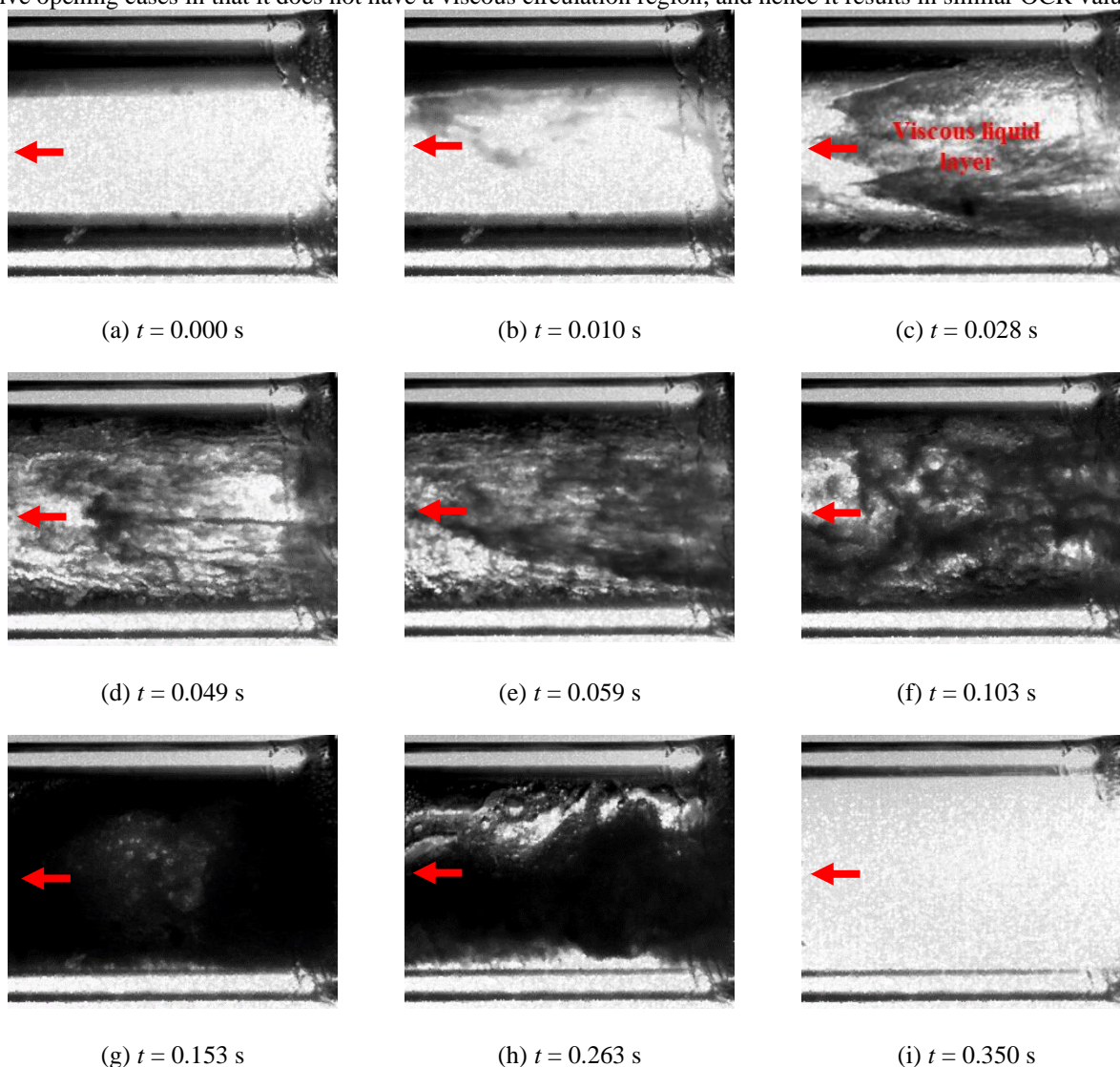

(a) $t = 0.000$ s (b) $t = 0.010$ s (c) $t = 0.028$ s

(d) $t = 0.049$ s (e) $t = 0.059$ s (f) $t = 0.103$ s

(g) $t = 0.153$ s (h) $t = 0.263$ s (i) $t = 0.350$ s

Figure 5: Slow valve opening case for horizontal flow entering evacuated cylinder

4.3 Vertically Downward Flow

With a compressor speed of 2250 min^{-1} and in steady state conditions, the OCR measurements and flow visualizations were repeated for the vertically downward flow. Figure 6 shows the high-speed camera images for the fast valve opening case. In (a), the valve just begins to open and refrigerant flashes into the tube. With increase of valve opening, droplets of viscous liquid (oil-rich mixture) start to form on the sides of the tube as seen in (b), and these droplets coalesce into a viscous layer in (c) and (d). As more oil-refrigerant mixture starts to enter the sampling cylinder, the viscous layer is forced to the dead end, and a foamy region forms in (e). Finally, a transparent liquid is seen in the tube, indicating that its completely filled with liquid mixture.

Figure 7 shows the flow into the sampling cylinder when the valve on it was opened slowly. Initially in (a), refrigerant flashes into the cylinder, but soon after, in (b) and (c), the viscous liquid film is seen to form on the walls of the tube. This layer of liquid, thought to be oil-rich mixture, becomes thicker in (d) as the valve opens more. Interestingly, from (e) to (g), a circulation zone of the viscous liquid and oil-refrigerant mixture is seen. This was not expected since the flow was in the same direction as gravity. A foamy region forms in (h) and finally the cylinder is filled, and only clear liquid can be seen.

The OCR values (average of 5 samples) for the fast and slow valve opening speeds for the vertically downward flow were 1.23% and 1.27% respectively. Although the OCR values seem to be close, it is worth comparing the spread of the OCR data between different samples for the vertically downward flow with the horizontal flow. The comparison is provided in Figure 8. In (a), the OCR data spread of each individual sample taken for the horizontal orientation is shown. For both valve opening speeds, the OCR values lie within an average value of 1.31%, with the standard deviation being only 0.03. This proves that the sampling results were precise/repeatable. However, for the vertically downward flow, (b) shows that the sampling results had a much larger spread, with the standard deviation being as high as 0.16, indicating that the sampling results were much less precise, and hence less reliable.
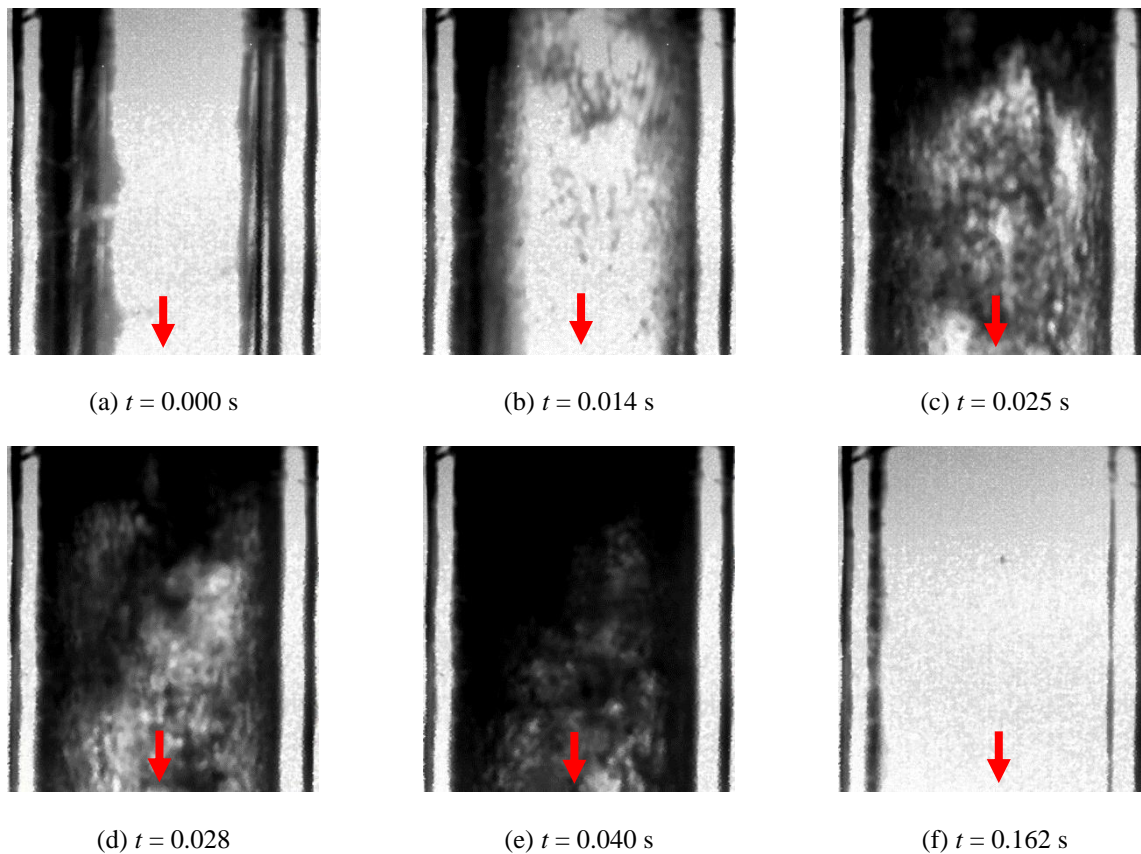

(a) $t = 0.000$ s	(b) $t = 0.014$ s	(c) $t = 0.025$ s
(d) $t = 0.028$	(e) $t = 0.040$ s	(f) $t = 0.162$ s

Figure 6: Fast valve opening case for vertically downward flow entering evacuated cylinder

(a) t = 0.000 s   (b) t = 0.035 s   (c) t = 0.049 s

(d) t = 0.062 s   (e) t = 0.077 s   (f) t = 0.093 s

(g) t = 0.113 s   (h) t = 0.174 s   (i) t = 0.555 s
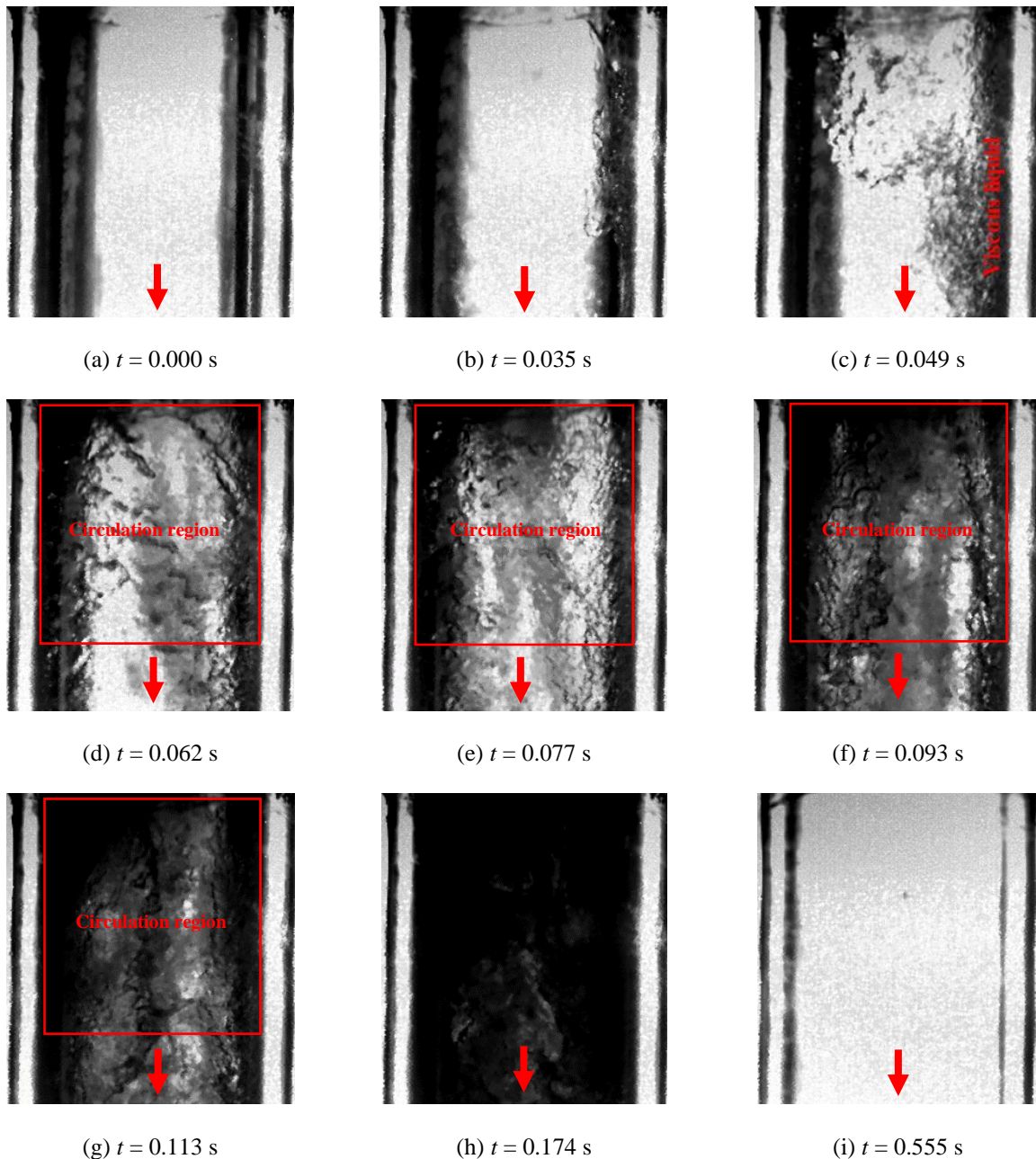
Figure 7: Slow valve opening case for vertically downward flow entering evacuated cylinder

For both the horizontal and vertically downward flow into the sampling cylinder, it was expected that since there was no possibility of churning flow as was for the vertically upward flow case, the OCR results would be similar for both fast and slow valve opening cases. And although the OCR results were indeed similar, the flow visualizations showed some interesting results.

For the slow valve opening case for the vertically downward flow, there was a circulation region with the viscous oil-rich liquid. A similar region was observed for the vertically upward flow. The reason behind the circulation zone is still being investigated, but it is clear from both the OCR results and the high-speed camera images that both sampling cylinder orientation and valve opening speeds can influence the flow and the measured OCR. Further investigation is needed to gain a deeper understanding of the circulation region at the entrance to the sampling cylinder for the vertical cases.
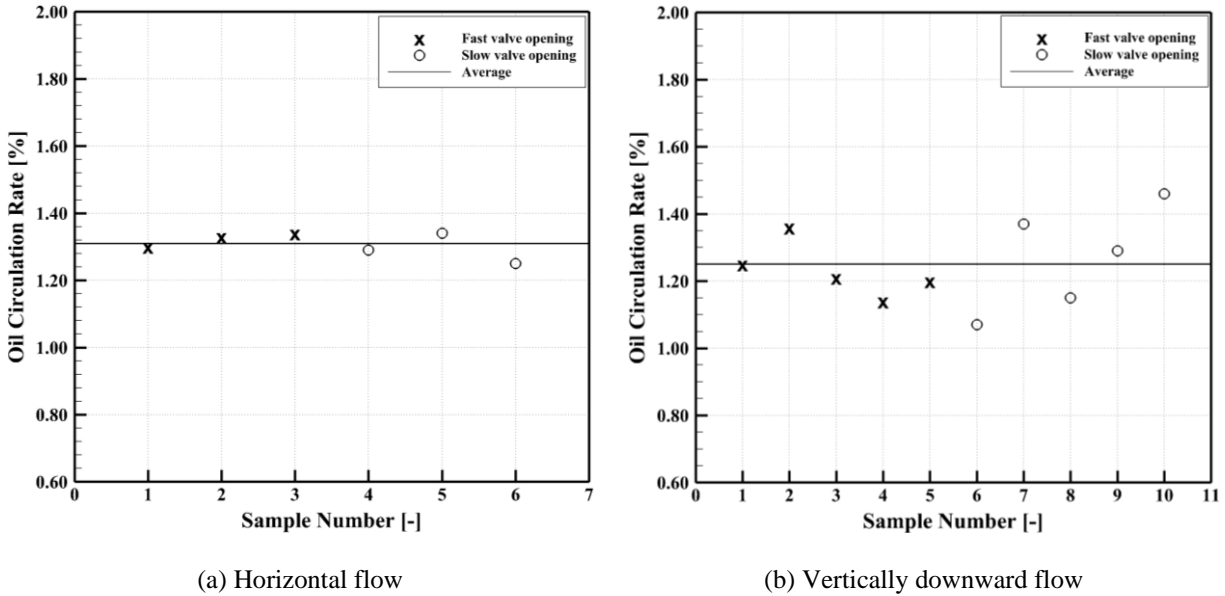
(a) Horizontal flow   (b) Vertically downward flow

Figure 8: Spread of measured OCR data

5. CONCLUSIONS

The method of OCR sampling described by the ASHRAE standard is used to calibrate all other OCR measurement techniques. It involves taking a sample of oil-refrigerant mixture from the liquid line and performing a gravimetric analysis to calculate the OCR as a percentage by mass of oil in the mixture. However, the method does not fully describe the procedure, and it can often be open to interpretation. Since there is no mention of what sampling cylinder orientation or valve opening speed to use while performing OCR sampling, the present study aimed at looking into the effects of these on OCR results. After investigating the results for vertically upward flow, horizontal flow, and vertically downward flow into an evacuated type sampling cylinder, the flow visualizations and OCR measurements indicated that significant variation in OCR data and flow field can result for different orientations and valve opening speeds. For fast valve opening speeds, for all three orientations, the flow was mostly unidirectional, i.e., from the entrance to the dead end. But for slow valve opening speeds, the vertically upward and downward flows revealed a viscous, oil-rich circulation region near the entrance, but the horizontal flow did not show such circulation. While the vertically upward flow had lower OCR for slower valve opening, the data obtained from the vertically downward flow did not show such a clear trend, and the data were scattered, indicating less repeatability. But for the horizontal flow, regardless of whether the valve was opened slowly or fast, the OCR results were the same and the data had low standard deviation indicating better repeatability. The viscous circulation zone observed could be playing a significant role in OCR measurement using the evacuated type sampling cylinder, and it is worth studying in more detail for future research.

NOMENCLATURE

M, m	measured or calculated mass	(g)
t	time	(s)
OCR	oil circulation rate	(%)

Subscript

oil	oil in system
refrigerant	refrigerant in system

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