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Oil Flow Measurement at the Compressor Discharge

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ABSTRACT

Oil circulating in the vapor compression system has a significant impact on the system performance. This paper presents a method to calculate the oil retention and oil circulation ratio (OCR) based on oil flow parameters, including oil film thickness and velocity, oil droplet size and velocity, and system mass flow rate. Oil flow parameters are determined by visualization using high-speed camera and video processing program. The estimated oil retention and oil circulation ratio results are compared with the experimental sampling results under different compressor speed. The agreement between video results and sampling results verifies the accuracy of the optical method, which can be applied in other annular-mist flow analysis. It also shows that most of the oil exists in film by mass while oil droplets contributes more to the oil mass flow rate because oil droplets travel in a much higher speed.

1. INTRODUCTION

Oil presence in the vapor compression system ensures the lubrication of the compressor moving parts, evacuation of the heat generated by frictions and sealing between the compression. Oil also affects the performance of the system besides the compressor. Despite few researchers indicating small amount of lubricant has positive effect in some cases on heat transfer (Nidegger et al., 1997)(Zürcher et al., 1998)(Kim and Hrnjak, 2012)(Hrnjak and Kim 2013), refrigerant distribution or capacity (Li and Hrnjak, 2014) (Li and Hrnjak, 2015), adverse effects of oil on system performance has been identified by many other researchers (McMullan et al.,1992)(DeAngelis and Hrnjak, 2005a)(DeAngelis and Hrnjak, 2005b).

The origin of oil circulating in the system is the compressor so research on oil flow starts with the compressor discharge. Toyama et al. (2006) concluded that oil flow inside scroll compressor is mainly mist flow. The mean diameter of the oil droplets decreases as the flow speed of the refrigerant gas increases. Zimmerman and Hrnjak (2014) showed with visualization that the form of the flow in the compressor plenum is misty. Oil enters the discharge chamber during the opening and closing process of the discharge valve. Therefore, discharge valve is the gateway for the oil to leave the compressor. Wujek and Hrnjak (2011) showed the form of the oil-refrigerant flow is developing mist-annular flow in the compressor discharge tube. The oil mist generated by the periodic movement of the discharge valve flows to the discharge tube. Oil droplets may collide, coalesce or splash during the process and then part of oil is entrained by the high gas flow rates. Therefore, annular mist flow in a horizontal tube consists of two forms of oil: oil film spread around the inner wall and oil droplets in the vapor core.

With the importance of oil flow in the refrigeration systems, it raises the interest to develop different techniques to quantify the oil flow parameters. Wada et al. (1992) used a novel approach to measure the in-line OCR based on the ultra-violet light absorption behavior of the oil. Fukuta et al. (2004) used reflective index of oil-refrigerant mixture to measure the oil concentration of the mixture. Peuker and Hrnjak (2010) presented three different techniques to determine the oil distribution in the major components of a R134a automotive system. Xu and Hrnjak (2016) measured the OCR in a non-invasive way based on the real-time images and videos of the refrigerant-oil mixture in the compressor discharge tube of an automotive AC system. The main purpose of this
research is quantifying the oil flow with developed visualization techniques and verifies the method by experimental results for both swashplate compressor and scroll compressor. Furthermore, in order to ensure the reliability of compressor and reduce the negative effect of oil on the system performance, it is important to separate the oil from the refrigerant vapor and drain it back to the compressor. A better understanding of flow parameter of oil at the compressor discharge can provide guidelines for oil separator design.

2. FACILITIES
Both scroll compressor (for residential systems) and swashplate compressor (for automotive systems) driven by variable frequency drive motor are used as research objectives. PVE 32 oil is used for the scroll compressor while PAG 46 is used for the swashplate compressor. The refrigerant used for both systems is R134a. As shown in Figure 1, two environmental chambers maintain the desired pressure and temperature conditions at condenser and evaporator. In order to achieve different system mass flow rate as well as vapor velocity at compressor discharge, the motor speed is varied from 1200~4000 rpm. The compressor pressure ratio is maintained the same (around 3) through the experimental by varying the working condition at condenser and evaporator. The mass flow rate of the system is measured by a Coriolis-effect flow meter.

![Facilities for oil flow measurement in the compressor discharge tube](image)

A section of perfluoroalkoxy alkane (PFA) tube is used as the transparent observation window at the discharge of the compressor. The inner diameter of the PFA tube is 6 mm (1/4 inch) while the wall thickness is 1.5 mm (1/16 inch), which is the same as the copper tube size used for the compressors. For video capture, a Phantom high speed camera is used to catch the flow image at the compressor discharge. An optical platform offers the precise adjustment of horizontal and vertical position of the camera. The resolution of the position adjustment is 0.02 mm. Halogen lamps are used for back-light of the video, which can offer enough brightness while prevent adding extra heat to the flow.

To measure the oil retention by sampling, two valves are used to cut off the flow at a steady working condition. The compressor was shut down at the same time as the two valves are closed. The section of transparent tube is then taken out of the system and weighed by an analytical balance with a readability of 0.1 mg. Another refrigerant and
oil mixture sample is taken in the liquid line (between condenser outlet and throttling valve) to measure the OCR. Both oil retention and OCR sampling results are compared to the video results under the same working condition.

3. METHODS

3.1 Analysis of oil retention and OCR
Refrigerant-oil mixture flow in the compressor discharge tube is mist-annular flow (Wujek and Hrnjak, 2011). In order to quantify the oil retention and OCR, oil droplets and oil film need to be considered separately. Oil retention is a measurement of mass staying in a certain section while OCR is a measurement of mass flow rate circulating in the system. The relation between these two parameters and different physical quantities are shown in Figure 2.

![Figure 2: Annular-mist flow in compressor discharge tube and break-down of the contributions of film in annulus and droplets in mist on oil retention and OCR](image)

Oil retention in the form of the film can be calculated as

$$M_{film} = \rho_{oil} V_{film} = \rho_{oil} \pi(D - \delta)\delta L$$  

(1)

Similarly, OCR contributed by the oil film can be calculated as

$$OCR_{film} = \frac{\dot{m}_{oil}}{\dot{m}_{oil} + \dot{m}_{ref}} \frac{\rho_{oil} \dot{\Phi} D \delta u_{film}}{\dot{m}_{oil} + \dot{m}_{ref}}$$

(2)

where $\rho_{oil}$ is the density of the oil, $D$ is the inner diameter of the tube, $\delta$ is the average thickness of the oil film, $L$ is the length of the tube, $u_{film}$ is the average velocity of the oil film, $\dot{m}_{oil}$ and $\dot{m}_{ref}$ are the mass flow rate of oil and mass flow rate of refrigerant, respectively.

In the same way we can derive the equations for oil retention and OCR in the form of droplets. Since the video only represents a small part of the tube, the ratio of tube volume over video volume needs to be multiplied to the droplet totally volume acquired by the video. For the video control volume, the projection area is easy to estimate but the depth of focus $D_f$ is determined by the method which will be discussed in 3.4. In short, the total volume of droplets in the tube is the sum of the volume of each droplet; the total mass flow rate contributed by oil droplets is the sum of the mass flow rate of each droplet.

$$M_{drop} = \rho_{oil} V_{drop,video} \frac{V_{tube}}{V_{video}} = \frac{\pi^2 \rho_{oil} D^3 L \sum d^3}{24 A_{video} D_f}$$

(3)
\[ OCR_{\text{drop}} = \frac{\dot{m}_{\text{drop}}}{\dot{m}_{\text{oil}} + \dot{m}_{\text{ref}}} = \frac{\rho_{\text{oil}} \nu_{\text{drop,video}}}{\Delta \nu_{\text{drop}} \nu_{\text{video}}} = \frac{\pi^2 \rho_{\text{oil}} D_f^3 \sum (d' u_{\text{drop}})}{24(\dot{m}_{\text{oil}} + \dot{m}_{\text{ref}}) \Delta A_{\text{video}} D_f^2} \]  

where \( d \) is the equivalent diameter of the droplets recognized by the video processing, \( u_{\text{drop}} \) is the velocity of oil droplets, \( D_f \) is the depth of focus (will be discussed in 3.4), \( \Delta A_{\text{video}} \) is the video projection area.

From equation (1)-(4), it can be concluded that we need determine the oil film thickness and velocity, oil droplet diameter and velocity in order to calculate the oil retention and OCR from the video. The details of these measurements will be discussed in the following sections.

### 3.2 Oil film thickness

Shedd and Newell (1998) used an optical method to determine the liquid film thickness of annular flow in a horizontal tube. Xiao and Hrnjak (2015) used the same method to estimate the liquid film thickness for refrigerant condensation in a horizontal tube. The method utilized the light reflected from the surface of a liquid film flowing over a transparent wall to generate an image. The image can be processed to determine the position of reflected light rays and calculate the film thickness without intruding into the tube.

As shown in Figure 3, a laser beam shoots to the transparent tube wall to generate an ellipse pattern. The ellipse pattern is formed by the reflection and deflection of the laser on curved surfaces and oil-tube, oil-refrigerant interfaces. A webcam provides the image of ellipse pattern. Numerical model shows that with oil film thickness inside the tube getting larger, the size of the ellipse will grow almost linearly. The angle between the laser beam and the camera can never be zero but the error caused by a small camera view angle can be neglected.

Calibration is necessary in order to get the correlation between the oil film thickness and the ellipse major axis. A half tube is used to hold the oil whose film thickness is measured by a point tip micrometer. The difference between a half tube and a full tube is negligible because the reflection and deflection from the upper part has a minor impact on the image pattern. Therefore, the calibration result of a half tube is considered as the same with that of a full tube. Multiple data points at different liquid level can fit into a linear curve. It is important to mention that the relative error of oil film thickness measurement may be considerable when the thickness is very close to zero.
Oil film circumferential distribution inside horizontal tube is considered to be uneven because of the effect of gravity and surface tension. Hurlburt and Newell (2000) developed a model to predict the circumferential film thickness distribution in horizontal annular gas-liquid flow. The model fits well with experimental results in our case. The ratio between oil film thickness at different circumferential location and oil film thickness at bottom of the tube is shown in Figure 4. Higher superficial gas velocity will lead to a more uniform film distribution. With a relatively high superficial gas velocity in our case, it is reasonable to use the average of oil film thickness measured at θ=0°, 60°, 120°, 180° to estimate the volume of oil film in the tube.

![Figure 4: The circumferential distribution of oil film in the horizontal tube](image)

### 3.3 Oil film velocity

From the video taken at the transparent tube, it is clearly shown that oil film with wavy pattern spread on the tube inner wall and the discrete droplets in the vapor core.

In order to calculate the mass flow rate contributed by the oil film, the oil film average velocity needs to be determined. Since the oil is viscous, the axial film velocity is not the same along the radical direction of the tube. Hurlburt and Newell (2000) developed a model for horizontal annular flow to estimate the average velocity of the liquid film by mass and momentum conservation. In this research, as shown in Figure 5, average axial velocity in the film is a function of gas superficial velocity and oil film thickness. Therefore, the oil mass flow rate contributed by the oil film can be calculated using equation (2).

![Figure 5: Average oil film velocity given by annular mist flow model in the horizontal tube](image)
3.4 Oil droplets size measurement

From the same video taken at the discharge tube, the size and velocity of oil droplets in the vapor core can be calculated from video processing. Wujek and Hrnjak (2011) developed a video processing program which can eliminate the droplet image based on the steepest grayscale gradient method.

The basic idea of the steepest grayscale gradient method is to determine the boundary of droplets by the sharp grayscale transition. 8-bit grayscale allows 256 different color intensities which defines pure black as 0 while pure white as 255. Therefore, one frame of the video can be converted to a matrix where each element represents the pixel grayscale.

The grayscale gradient in a 2D picture is defined as

$$ V_G = \sqrt{\left(\frac{\partial G}{\partial x}\right)^2 + \left(\frac{\partial G}{\partial y}\right)^2} \tag{5} $$

For an image matrix shown in Figure 6, the value of grayscale is shown in each grid element. The boundary detected by the video processing is where steepest grayscale gradient takes place (red line in Figure 7).

One of the limitations of grayscale gradient is that the video processing cannot tell if the droplet is in-focus or not. As shown in Figure 6, if we adjust the distance between the camera and a known size particle, the image captured by the camera will be blurry when it is too close to or too far away from the particle.

![Figure 6: Droplet image matrix for boundary detection and droplet images under different camera-droplet distances](image)

![Figure 7: In-focus criteria defined by critical grayscale indicator $GI^*$](image)

Koh et al. (2001) used the grayscale gradient indicator ($GI$) to determine the in-focus criteria for a processed image of a specific particle. Grayscale gradient indicator is defined as the local grayscale gradient divided by the difference between maximum grayscale and minimum grayscale in the image.

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\[ GI = \frac{\nabla G}{(G_{\text{max}} - G_{\text{min}})/2\Delta x} \]  

Therefore, the steepest grayscale gradient of droplets in focus on the boundary will be higher than that of droplets out of focus. In order to tell in-focus image from out-of-focus, \( GI^* \) is defined as in-focus criteria. All the droplets with boundary \( GI \) less than \( GI^* \) are excluded out of the visualization control volume. In Figure 7, the blue and green lines show the \( GI \) less than \( GI^* \) which is considered as out-of-focus while the red line has a steeper gradient represents in-focus. A practical \( GI^* \) value is given by Koh et al. (2001) as

\[ GI^* = GI_{\text{max}} - 0.22 \]  

The value of \( GI^* \) could be adjusted according to the image quality. A higher \( GI^* \) will include less in-focus droplets with sharper boundaries.

With the in-focus criteria, we can estimate the depth of focus for different particles and build a correlation between the particle size and depth of focus. The correlation is calibrated by four known size particles and compared with the results in other literatures, as shown in Figure 8.

![Figure 8: Correlation between depth of focus and droplet diameter](image)

Since depth of focus is different for different particle diameters, Equation (3) and (4) can be rewritten as

\[ M_{\text{drop}} = \rho_{\text{oil}} \frac{V_{\text{drop}}}{V_{\text{video}}} V_{\text{tube}} = \frac{\pi^2 D^2 L}{24A_{\text{video}}} \sum \frac{d^3}{D_f} \]  

\[ OCR_{\text{drop}} = \frac{\dot{m}_{\text{drop}}}{\dot{m}_{\text{oil}} + \dot{m}_{\text{ref}}} = \frac{\rho_{\text{oil}} V_{\text{drop,video}}}{(\dot{m}_{\text{oil}} + \dot{m}_{\text{ref}}) \Delta t_{\text{drop}}} \frac{V_{\text{tube}}}{V_{\text{video}}} = \frac{\pi^2 \rho_{\text{oil}} D^2}{24(\dot{m}_{\text{oil}} + \dot{m}_{\text{ref}}) A_{\text{video}}} \sum \frac{d^3 \Delta u_{\text{drop}}}{D_f} \]  

In this way, a more precise estimation of total mass of oil droplets in the discharge tube can be achieved.

3.5 Oil droplets velocity

Wujek and Hrnjak(2011) developed a video processing method similar to the particle image velocimetry(PIV) in order to determine the droplets moving velocity in axial direction. Oil droplets, instead of seeding particles, are used directly to determine the velocity field of the gas core misty flow. Two images of the flow are taken in rapid succession with a high speed camera to make sure the same droplets must appear in consecutive frames. The video processing principle is shown in Figure 9 in the following steps:

1. Wave elimination by subtracting the average pixel value in period of time;
2. Droplet size determination with steepest grayscale gradient;
3. Comparison of two consecutive images in small sections to interrogate potential displacement;
4. Velocity determination with PIV algorithm. Numerous erroneous velocity vectors will be generated throughout this process and the two-dimensional cross-correlation can be used to screen out true velocity vectors.

![Figure 9: Steps of video processing for droplet velocity](image)

### 4. RESULTS

#### 4.1 Oil retention

Figure 10(a) shows that oil film thickness gets thinner when gas velocity goes up because of the higher shear stress. The mass of oil droplets gets higher because of the higher compressor speed. If the oil retention in the form of droplets and that in the form of film are added together, we can compare the oil retention measured by the video to sampling results, as shown in Figure 10(b). Although the uncertainty of oil retention by video is relatively large because of thin film thickness and rough estimation of video control volume, the results can still be compared to oil retention by sampling. It means the optical method is acceptable as a non-invasive way to measure the oil retention.

If we compare the results of the compressor without oil sump and the compressor with oil sump, it can be concluded that from oil retention point of view, oil sump has a minor impact on the amount of oil in the compressor discharge tube.

![Figure 10: (a) Oil retention contributed by oil film or oil droplets in the discharge tube (b) Oil retention in the discharge tube under different vapor superficial velocity (u_v) measured by both video and sample](image)

#### 4.2 Oil in circulation

Both OCR contributed by oil film or oil droplets gets larger, when the gas velocity goes up. This is because higher compressor speed leads to more oil injected by the discharge valves. It is interesting to see that the distribution of OCR in droplets and in film is very different from the distribution of oil retention. OCR is mainly contributed by oil droplets because oil droplets travel in a much higher speed than oil film does. For OCR, both mass and velocity need to be taken into consideration, which means fast-moving oil droplets can contribute more than slow moving oil film even though they are minority by mass. Similarly, Figure 11(b) shows that the OCR measured by video can be comparable with OCR measured by sampling in an acceptable accuracy.
The effect of the oil sump becomes essential when it comes to OCR. Compressor without oil sump cannot hold a lot of oil in the compressor so that higher compressor speed tends to increase the OCR in the system dramatically. The different trends in Figure 10(b) and Figure 11(b) clearly show that compressor without oil sump generates a much higher OCR than compressor with oil sump.

SUMMARY

This paper provides a validated non-invasive method to measure the oil retention and OCR at the compressor discharge tube. The video processing method can give more information, like the oil droplet velocity and size, than the traditional sampling method. Furthermore, the visualization method can be applied to any similar annular-mist multiphase flow in order to quantify the flow parameters.

The distribution of the oil in the annular-mist flow at the compressor discharge is researched at different gas superficial velocity and different compressor types. In the compressor discharge tube, most of the mass is in the form of oil film while most of the mass flow rate is in the form of oil droplets. Velocity difference between the refrigerant vapor core, the oil droplets and the oil film causes the distribution difference of oil retention or OCR. In order to eliminate the oil circulating in the system, it is important to separate oil droplets travelling in the refrigerant-oil mixture annular-mist flow at the compressor discharge.

REFERENCES


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