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Visual Techniques to Quantify Behavior of Oil Droplets in a Scroll Compressor

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ABSTRACT

In the shell of a compressor, oil used for the lubrication of sliding parts and for oil film sealing of the compression chamber is atomized by the refrigerant gas flow. In order to reduce the oil concentration ratio (OCR), it is necessary to develop a method to quantify the size, number and speed of these oil droplets.

This report describes methods to quantify oil droplet behavior using high-speed photography of the flow in the shell via sight glasses in the scroll compressor, as well as Particle Image Velocimetry (PIV) and Particle Tracking Velocimetry (PTV) to process the images.

The results show that the size of the oil droplets is not uniform: they are distributed in accordance with the χ² distribution law. It was also discovered that the mean diameter of them decreases as the flow speed of the refrigerant gas increases. Further, the oil droplets in the motor stator core cut passage move against the upward flow of the refrigerant gas, and their falling velocity is extremely low.

1. INTRODUCTION

As shown in Figure 1, OCR in the compressor is directly connected not only to the efficiency and reliability of the compressor; it also has a great effect on the efficiency of the air conditioner system. Therefore, reduction of OCR is one of the highest priority issues for development of a compressor.

Taniguchi¹¹ states that, in a visualization test in the shell of the compressor, oil in the mist state was suspended in the refrigerant gas flow during operation. The size and number of mist-state oil droplets must have a great effect on OCR. Forces specified by the diameter of droplets effect their behavior in the refrigerant gas flow: for example, the drag is the square of the oil droplet diameter, and the gravity and buoyancy are the cube of the same. The diameter thus has an effect on the behavior in the oil droplets. The number has the effect on the gross flow of the oil component, and interaction between the dispersed phase (oil droplets) and the continuous phase (refrigerant gas) cannot be ignored as the number increases. It is thought that the larger the particle diameter of the oil droplet, the greater the effect of gravity to return the oil to a liquid state in the oil sump. On the other hand, the smaller the particle diameter of the oil droplet, the easier it can flow out of the compressor together with the refrigerant gas, which may contribute to an increase in OCR. The size and number of the oil droplets therefore have a great impact on the OCR. However, no studies have mentioned the size or the number of oil droplets in the compressor.

The purpose of this report is to quantify oil droplet behavior in the shell of a scroll compressor. More specifically, it describes methods to quantify oil droplet behavior in the flow in the shell via sight glasses in the compressor using high-speed photography, as well as PIV and PTV to process the images. It also discusses the relationship between oil droplet behavior and OCR.
2. STRUCTURE OF SCROLL COMPRESSOR AND VISUAL OBSERVATION TEST APPARATUS

2.1 Structure of Scroll Compressor

Figure 2 is a schematic diagram of the structure of the scroll compressor and the test apparatus.

The interior of the compressor is an improved high-pressure shell structure consisting of a main bearing as a border, a compression mechanism part to create a low-pressure atmosphere, and a motor chamber to create a high-pressure atmosphere. In this structure, the compression mechanism part serves as a low-temperature atmosphere by taking refrigerant gas from the suction pipe and the motor is cooled by discharge gas. As a result, suction superheat loss is reduced and volumetric efficiency is improved [2].

2-2. Flow of Refrigerant

After the suctioned refrigerant is compressed, it is discharged to the discharge chamber from the discharge port, and then introduced to the high-pressure shell via the gas passage in the fixed scroll and main bearing frame. The discharge gas is distributed to the circumferential direction in the upper part of the motor and to the axial direction in the lower part of the motor by the gas guide shown in Figure 3.

Figure 1: Effect of OCR on Reliability, Compressor COP and System COP

Figure 2: Schematic View of Test Apparatus

Photo 1: Compressor for Visual Observation

In Totality

28 Sight Glasses
This gas guide performs both oil separation and motor cooling. The oil is effectively separated by centrifugal separation from the discharge gas distributed in the circumferential direction. On the other hand, the discharge gas distributed in the axial direction is introduced to the lower part of the motor, and cools the motor while returning to the upper part via the stator core cut and air gap. It then joins the gas distributed in the circumferential direction and is discharged from the discharge pipe.

2-3. Compressor for Visual Observation

The test compressor has eight core cuts in the stator, with 45º of rotation between each cut; and a body with eight planes made to correspond with these angles. On each of these planes, there are four holes for sight glasses at the height of the upper part of the motor, the core cut, the lower part of the motor and the oil separation plate. With sight glass of pressure-proof glass set in these holes, a range of φ27 can be observed, enabling direct images to be taken of oil droplet behavior using a high-speed camera. To prevent distortion of the images by refraction during shooting, the glass is flat with no curvature. Further, visualization of the interior of the discharge pipe and suction pipe was attempted. As shown in Figure 4, the length of one side of the flow section (square) is the same as the inner diameter of the piping. Evaluation was made at 28 points in total.

The high-speed camera is capable of 2,000 frames/sec at the maximum resolution of 1,024 x 1,024 pixels, and has a maximum speed of 120,000 frames/sec. The photographic data was downloaded immediately to personal computers, and oil droplet behavior was quantified by PIV and PTV processing. A halogen consecutive light was used to illuminate from behind the camera. However, one side of the glass surface was covered in tracing paper to illuminate the suction and discharge pipes, and the photographs were taken from the opposite side.

3. METHOD TO QUANTIFY BEHAVIOR OF OIL DROPLETS

3.1 Size and Number of Oil Droplets

The following is the method used to quantify the size and number of the oil droplets using PTV.

Figure 5 shows the original photographic image of oil droplets and a threshold version at the discharge pipe. As shown in Figure 6, through this conversion process, the centroid, length, and breadth of any oil droplet in the image can be quantified. For simplification, biaxial average \( x \) was used for the diameter.

\[
\text{Definition of Particle Size} \quad x = \frac{1}{2} (l+b)
\]

Figure 7 shows the diameters and number of oil droplets.
In the same manner as the still image in Figure 5, consecutive images were digitalized and the number of oil droplets according to oil droplet diameter is shown in Figure 7. The diameters of the oil droplets were categorized by width in 50 µm increments, and for the number of oil droplets, a simple average of 100 consecutive images was taken. As shown in this figure, the diameter of the oil droplets in the compressor are not uniform but distributed.

3.2 Oil Droplet Flow

A common PIV method is to put tracer particles in the flow to measure its velocity by processing the tracer photograph images. In this test, oil droplets themselves were considered as tracers to evaluate oil droplet flow. As an example of evaluation, Figure 8 shows the appearance of the sight glass in the upper part of the outlet in the circumferential direction of the gas guide shown in Figure 3. The bottom left corresponds to the end of the gas outlet. The image shows the average streamline and the average velocity contour line for two cycles of measurement time. It illustrates clearly that oil droplets flow toward the circumference and at an upward angle of 45º from the outlet, and that their velocity distribution can be quantified.

4. TEST RESULTS

4.1 Frequency Distribution of Oil Droplet Diameters

Figure 9 shows the frequency distribution of oil droplet diameters in the suction and discharge pipes when the operation frequency is changed, and Figure 10 shows the variation in the Sauter mean diameter at this time. Curves in Figure 9 approximate the \( \chi^2 \) distribution expression in formula (1) below by Nukiyama and Tanasawa\(^3\).

\[
\left( \frac{dn}{dx} \right) \frac{1}{n} = Ax^\alpha \exp(-Bx^\beta)
\]  

(1)

Where \( n \) is the number of oil droplets, and \( A, B, \alpha, \beta \) are experimental constants. As apparent from Figure 9, the frequency distribution can be accurately predicted using formula (1), regardless of the measurement point or refrigerant gas flow speed (operation frequency).
In addition, although not shown, the oil droplets at observation points other than the suction and discharge pipes can also be approximated in the same manner.

Formula (1) was derived from a test in which water flow was atomized by high-speed air flow. The present test is a combination of refrigerant and lubricating oil which have density, viscosity and surface tension substantially different from those of air and water, and it is not specifically an atomization process. Despite this, the distribution is apparently predicted by formula (1).

According to Figure 10, the mean diameter of oil droplets in the discharge pipe is much smaller than that in the suction pipe. Although the gas flow velocity is approximately equal in both instances, in terms of the properties of oil droplets, the discharge pipe has lower surface tension and viscosity. As with general atomization, the lower the surface tension and viscosity of the oil, the smaller the oil droplets.

Further, it becomes apparent that, as the operation frequency and gas flow speed increase, the size of the oil droplets in both the suction and discharge pipes decreases.

4.2 Oil Droplet Flow

Figure 11 shows streamlines to illustrate oil droplet flow in the high-pressure shell. The streamlines are shown at 45° intervals, with the gas guide position as 0°. The discharge pipe is at 135 degrees, the terminal at 225 degrees, and the oil return pass at 270 degrees. The arrows show the average velocity and direction; these values are relative to the velocity at the gas guide contraction point.

As mentioned above, refrigerant gas diverges, with some gas from the compression chamber going directly to the core cut in the vertically downward direction by the gas guide, and some gas going to the upper part of the motor in the circumferential direction. Oil droplets in the vertical downward direction flow into the core cut and the lower part of the motor with a slight loss of speed so as to collide with the oil separation plate.
Oil droplets flowing in the circumferential direction move to the right at 45° with a velocity of 0.3 (image above). The same flow can be seen if the sight glass mounting angle proceeds, but it gradually slows down. The flow angle in the upward direction also gradually falls to be close to the horizontal flow.

In contrast, the circling flow seen in the upper part of the motor was not observed in any of the sight glasses in the lower part of the motor. In this part, as shown in Figure 12, oil droplets flow through a slot cell of the motor from the compressor axial center, and are blown out in the outer radial direction. The oil droplets flow as if they collide with glass, and move vertically downward.

The flow in the core cut is distinctive. The velocity of the oil droplets falls dramatically except at the gas guide (0 degrees) and the oil return (270 degrees). This is because refrigerant gas flows upward in the core cut passage. Figure 13 shows change over time in the Y-axis velocity at the core cut at the 90° position in Figure 11. In this graph, the upward direction is positive, and two periods are illustrated. On average, oil droplets have negative values, i.e., the velocity falls, but it is clear that positive velocity occurs once in each period. The data also confirms that refrigerant gas flows upward.

<table>
<thead>
<tr>
<th>Normalized OCR</th>
<th>Normalized OCR = 1</th>
<th>Normalized OCR = 3</th>
<th>Normalized OCR = 9</th>
</tr>
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<tbody>
<tr>
<td>Oil Separation Plate</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>60 Hz T/Tc = 0.5</td>
<td>90 Hz T/Tc = 0.5</td>
<td>120 Hz T/Tc = 0.5</td>
<td>180 Hz T/Tc = 0.5</td>
</tr>
</tbody>
</table>

4.3 OCR and Oil Droplet Flow

Figure 14 compares images showing the relationship between OCR and oil droplet flow. According to these three conditions, although the flow rate of refrigerant gas at the discharge side of the compressor is substantially the same, the OCR varies significantly as 1 : 3 : 9.

A high OCR means that there are numerous oil droplets of small diameter flowing in a disturbed manner. In the images, the deep end of the compressor is visible with a low OCR, but oil droplets enter the mist state, and only the glass surface can be recognized. Droplets flow with great disturbance, with generation of vortexes and fluctuation of oil level at oil sump.

The oil separation plate prevents refrigerant gas flowing in the vertical downward direction from the gas guide from colliding with the oil surface at oil sump. The oil surface is therefore calm, and falling oil droplets can be caught by the liquid surface. If there is no oil separation plate, the oil surface is disturbed by refrigerant gas and re-dispersion of oil droplets is facilitated.

The installation of an oil separation plate is an effective means to reduce OCR.
5. CONCLUSION

Using a compressor that enables visual observation of the suction, discharge pipes and high-pressure shell space, images of oil droplet flow were taken with a high-speed camera and analyzed using PTV and PIV. As a result, the following knowledge was obtained.

(1) The size of the oil droplets in the compressor is not uniform and follows the $\chi^2$ distribution law.
(2) The mean diameter of oil droplets is smaller in the discharge pipe than in the suction pipe, and decreases as refrigerant gas flow speed increases.
(3) Oil droplets in the core cut passage resist the upward flow of refrigerant gas, and their downward velocity is extremely low.
(4) The higher the OCR is, the smaller the oil droplet flow. This flow causes great disturbance with generation of vortexes and fluctuation of oil sump level.
(5) Application of an oil separation plate greatly reduces OCR.

This method can quantitatively and visually clarify refrigerant gas flow and oil droplet flow. As a result, OCR reduction can be easily realized and the development period of compressors can be greatly reduced.

REFERENCES