Observation of Oil Film Condition in a Cylinder of Rotary Compressor

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OBSERVATION OF OIL FILM CONDITION IN A CYLINDER OF ROTARY COMPRESSOR

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ABSTRACT

Refrigeration oil is supplied into a cylinder of rotary compressor in order to reduce internal leakage and to lubricate sliding parts. The oil seals the leakage flow through clearances in the cylinder in the form of either liquid flow or two-phase flow. In order to analyze the leakage flow in the cylinder, it is important to know how the oil is distributed in the cylinder and how the flow pattern of the leakage at the clearance is. In this study, we made a compressor cylinder of acrylic resin for visualization, and the oil film condition in the cylinder during operation of the compressor was observed by using air as a working fluid. In order to visualize the oil behavior clearly, we used two types of oil containing different dyes as a lubricant. One was red dyes and the other was fluorescent dyes. It was found that radial clearance between the cylinder and a roller was sealed by the oil normally, and gas leakage around a vane was remarkable when the oil was not supplied to a back chamber of the vane. We also observed a comb-shaped oil film on the cylinder wall. Although separation of refrigerant from the oil occurred when the oil mixed with the refrigerant entered the cylinder, formation of bubbles was not observed. The fluorescence method was useful to observe the oil film distribution, and hereafter it will be possible to evaluate thickness of the oil film based on the intensity of fluorescence.

INTRODUCTION

Refrigeration oil is supplied into a cylinder of rotary compressor in order to reduce internal leakage and to lubricate sliding parts. The oil seals the leakage flow through clearances in the cylinder in the form of either liquid flow or two-phase flow. In order to analyze the leakage flow in the cylinder, it is important to know how the oil is distributed in the cylinder and how the flow pattern of leakage at the clearance is. In this study, we made a compressor cylinder of acrylic resin for visualization, and the oil film condition in the cylinder during operation of the compressor was observed by using air as a working fluid. In order to visualize the oil behavior clearly, we used two types of oil containing different dyes as a lubricant. One was red dyes and the other was fluorescent dyes. In addition, we supplied the oil mixed with refrigerant in order to investigate an influence of separation of the refrigerant from the oil film.

EXPERIMENT

Figure 1 shows a photograph of experimental rotary compressor whose cylinder and upper end plate were made of acrylic resin for visualization in the cylinder. Figure 2 shows a schematic view of an experimental apparatus. The compressor was driven by an external motor under the atmospheric pressure by using air as a working fluid. Lubricating oil in an oil tank was pushed out by pressure and supplied to a suction line and to an inside of roller. Flow rates of the oil were controlled by control valves, and measured by positive-displacement type flow meters. Mixture of oil and air discharged from the compressor entered an oil separator and only the air was discharged to the atmosphere. The oil in the separator was supplied to a back chamber of vane by discharge pressure. The discharge pressure was regulated by a control valve installed on a discharge line. We observed oil film distribution and leakage flow at each part in the cylinder by using a stroboscope which was synchronized with rotation of a driving shaft, and recorded them by a digital camera. In order to visualize the oil behavior clearly,
the oil was colored by a red dyes. Moreover, we adopted a fluorescent method done by H. INAGAKI et al. /1/. In the fluorescent method, lubricating oil containing fluorescent dyes (coumarin 6) was supplied to the compressor. Light of the stroboscope was thrown through a blue filter into the cylinder and the fluorescence from the oil was observed and recorded by the camera through a yellow filter. Figure 3 shows characteristics of absorption and emission spectra of fluorescent dyes to wavelength (dotted line) and transmittance characteristics of the color filters (solid line). The blue filter is transparent to the light having the absorption wavelength of fluorescent dyes and the yellow filter is transparent to the light having the emission wavelength of that. Since the yellow filter is opaque to the most of the light through the blue filter, reflection of the light incident upon the surface of the acrylic plate is not recorded on the camera mounting the yellow filter.

In the experiment, rotational speed of the compressor was 900 rpm or 1500 rpm and the discharge gauge pressure was changed from 0 to 300 kPa. We used spindle oil whose kinematic viscosity is about 7 mm²/s at room temperature and the flow rate was adjusted so that the amount of the oil which existed in the cylinder became roughly the same with that in the cylinder of a practical refrigerant compressor operated with 3500 rpm. We also used refrigeration oil (19 mm²/s at 40 °C) mixed with refrigerant in order to investigate an influence of refrigerant separation from the oil on the formation of the oil film. Specifications of the compressor are listed on Table 1.

RESULTS AND DISCUSSION

Figure 4 shows a photograph of the transparent cylinder when rotational angle of the roller is 1.6π rad (290 deg.) under the condition that the discharge pressure was 300 kPa, rotational speed was 900 rpm and the total oil flow rate was about 90 cm³/min which corresponds to oil rate of 25 % in the practical compressor. Rotational direction was from right to left of the figure, and the oil trapped at a radial clearance between the cylinder inner surface and the roller outer surface moved with movement of the clearance. The radial clearance was sealed by the oil except for the case that little oil was supplied to the compressor and the discharge pressure was high. Since an intensity of fluorescence increases with increasing thickness of the oil film, it will be possible to evaluate the oil film thickness based on the intensity of fluorescence.

Figure 5 shows a comb-shaped oil film which was formed on the cylinder wall after the roller pass by on the surface. It was caused by a cavitation /2/ in a divergent clearance space at trailing of the radial clearance. It grew larger with increasing discharge pressure because the leakage oil flow through the radial clearance increased with the discharge pressure. By the way in the practical compressor, certain amount of refrigerant dissolves into the oil. The refrigerant separates from the oil by pressure reduction and disturbance of flow. It, therefore, suggests that in the practical compressor the disruption of oil film at the radial clearance due to the cavitation promotes the separation of refrigerant from the oil.

Figure 6 shows droplets entering from a suction port into the suction chamber. The oil flowed along the wall of suction line and hit against the wall of roller with relatively big droplet.

Figure 7 shows a leakage flow from a compression chamber (upper part of the figure) into the roller face clearance when the discharge pressure is larger than that of the oil supplied to the inside of the roller. It is shown that small bubbles reach the inside of the roller and they flow toward a suction chamber (bottom right of the figure).

Figure 8 shows a re-expansion of the working fluid, which is mixture of oil and compressed gas, from a discharge port (clearance volume on a discharge valve) set on the lower end plate of the experimental compressor. When the roller passes the discharge port, the gas-oil mixture in the discharge port expands to the following chamber and the oil hits against the upper end plate.

We made an extra experiment in which the oil was supplied only into the inside of the roller and the discharge
gauge pressure was 0 so that the oil from the back chamber of the vane did not enter to the cylinder. Figure 9 (a)-(c) show photos of the oil film formation at the radial clearance when the rotational angle is 0.4\pi, 0.9\pi and 1.6\pi rad (75, 165, 290 deg.) respectively. The rotational speed was 900 rpm and the oil flow rate through a roller face clearance was 28 cm³/min. As the rotational angle increases the oil leaking through the roller faces in the cylinder is trapped at the radial clearance and the oil amount leading the clearance becomes large. Since an upper clearance of the roller face was larger than a lower one, the leakage flow rate through the upper clearance is more than that through the lower clearance as a result region of the oil trapped is inclined to the upward.

When the oil was not supplied to the back chamber of the vane and the discharge pressure was increased, suction air flow rate decreased remarkably. This is because gas leakages through clearances around the vane occurred. Figure 10 shows the gas leakage from the compression chamber (left part of the figure) to the suction chamber (right part of the figure) through the clearance on the vane end. Performance of the practical compressor will decrease due to the vane leakage if the back chamber of the vane is filled with gas or foam for some reasons although the back chamber of the vane in the practical compressor is usually filled with the oil.

As mentioned before, the refrigerant dissolves into the oil in the practical compressor. The refrigerant separates from the oil when the oil enter the suction chamber and its pressure decreases. It is well-known that the separation of refrigerant from the oil causes a foaming phenomenon of the oil. We therefore investigated the influences of the separation of refrigerant and the foaming of oil on the formation of the oil film by supplying the oil mixed with refrigerant to the experimental compressor. Concentration of the refrigerant was about 20 wt%. Figure 11 shows a photo when the oil mixed with refrigerant was supplied to the inside of the roller under the condition that the compressor was not operated and the roller was in a state of rest. The foaming can be seen at the circumference of the roller due to the separation of refrigerant as shown in Fig. 11.

On the other hand, Fig. 12 is a photograph under the operating condition with the rotational speed of 900 rpm and the discharge pressure of 300 kPa. It shows that although the foaming occurs slightly at the vane tip due to the leakage from the compression chamber, no foaming occurs at the circumference of the roller. This is because the bubble formed by the separation of the refrigerant is broken by movement of the roller. Similarly, there is no bubble in the oil trapped at the radial clearance as shown in Fig. 13.

CONCLUSIONS

In order to observe the oil behavior and the leakage through the clearances in the cylinder under the operating condition of the rotary compressor we made the compressor cylinder of acrylic resin. The two types of oil, one was colored by the red dyes and the other contained the fluorescent dyes, were used for visualization. The radial clearance between the roller outer surface and the cylinder inner surface was usually sealed by the oil. We observed the comb-shaped oil film on the cylinder wall, which suggested that the separation of refrigerant from the oil is promoted in the practical compressor. Occurrence of the gas leakage around the vane was remarkable when the oil was not supplied to the back chamber of the vane. When the oil film was not formed well at the vane, the suction flow rate decreased. Although the separation of the refrigerant from the oil occurred when the oil mixed with the refrigerant entered the cylinder, the formation of bubbles was not observed at the circumference of the roller and in the oil trapped at the radial clearance. The fluorescent method was useful to observe the oil film distribution, and hereafter it will be possible to evaluate thickness of the oil film based on the intensity of fluorescence.

REFERENCES

Table 1  Specifications of compressor

<table>
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<th>Value</th>
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<tr>
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<td>Cylinder height</td>
<td>23.8 mm</td>
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<td>Roller radius</td>
<td>23.4 mm</td>
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<td>20 μm</td>
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<tr>
<td>Clearance on roller face</td>
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Fig. 6 Droplets entering from suction port into cylinder

Fig. 7 Leakage from compression chamber into roller face clearance

Fig. 8 Re-expansion from discharge port

(a) Rotational angle = 0.4\pi (75 deg.)

(b) Rotational angle = 0.9\pi (165 deg.)

(c) Rotational angle = 1.6\pi (290 deg.)

Fig. 9 Oil film formation at radial clearance
Fig. 10 Leakage through clearance on vane end

Fig. 11 Forming due to separation of refrigerant from oil

Fig. 12 Oil at circumference of roller with supplying oil mixed with refrigerant under operating condition

Fig. 13 Oil film at radial clearance with supplying oil mixed with refrigerant under operating condition
A Study on Lubricity of Polyolester for Alternative Refrigerant HFC-134a

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² Human Environment Research Laboratory, Matsushita Electric Industrial Co., Ltd.

ABSTRACT

This paper presents the experimental research into the evaluation of lubricity for polyolester (POE) lubricant with HFC-134a refrigerant in rotary and reciprocating compressors for household refrigerators. In order to evaluate the lubricity for POE lubricant with HFC-134a refrigerant, we conducted 4-balls wear tests in the mixing environment of POE lubricant and HFC-134a refrigerant. In the present study, the effects of the weight fraction of the refrigerant on the lubricity for POE lubricant with HFC-134a refrigerant were clarified. In addition, wear configuration changes from adhesive wear to corrosive (chemical) wear, as the fraction of refrigerant increases, which is caused by metal fluoride and carboxylic acid salt generated by decomposition of HFC-134a refrigerant and POE lubricant. Also, for the factor by which corrosive (chemical) wear occurred in the high weight fraction of HFC-134a refrigerant, it was found that the metal fluoride was more dominant than the carboxylic acid salt.

1. INTRODUCTION

Because of the ozone layer depletion issue, alternative refrigerants HFCs have been used as the refrigerants for household refrigerators. It is known that HFCs refrigerants with no chlorine have poor lubricity in compared with CFCs and HCFCs refrigerant¹). In order to maintain the oil’s compatibility with HFCs refrigerant, the refrigeration oils have been also changed from mineral oils to synthetic lubricants such as Polyolester (POE) lubricant. Therefore, the improvement of wear resistance is required for the POE lubricant with HFCs refrigerant.

As for the lubricity of POE lubricant with HFCs refrigerant, the results is reported that the wear amount increases as the weight fraction of the refrigerant increases²) and that the wear amount increases and the worn surface roughness becomes very smooth if the load is increased³). However, the effects of the fraction of the refrigerant on the lubricity for POE lubricant with HFC-134a refrigerant and its wear mechanism have not been well studied.

In this present study, the effects of the fraction of the refrigerant on the lubricity of POE lubricant, such as wear amount, worn surface roughness and friction coefficient, were clarified by conducting the 4-balls wear test under the pressurized mixing environment of POE lubricant and HFC-134a refrigerant. Subsequently, by conducting the analysis of the deposit around the worn surface after wear tests, the mechanism of the atmosphere effect of HFC-134a refrigerant on POE lubricant was also discussed.
2. FRICITION TEST MACHINE AND PROCEDURE

Fig. 1 shows the schematic of 4-balls wear test machine. The 4-balls wear test section consists of piled four ball of a size. In the lubricant oil, one ball is loaded against three balls which are fixed, and rotates. The three contact points make circular wear scars.

Kinematic viscosity of POE lubricant is 31.2 mm²/s (40°C) and 5.13 mm²/s (100°C), without an extreme pressure agent. HFC-134a refrigerant is used in this wear tests. The material of tested ball is high carbon chromium bearing steel, and the size of each ball is 1/2 inch. The balls were rinsed in acetone by the ultrasonic-washer for 10 minutes and mounted in the test machine after dried. Table 1 shows the test condition. In order to evaluate wear amount, we measured wear scar diameter (maximum) of fixed balls after wear tests.

3. EXPERIMENTAL RESULTS

Fig. 2 shows the effects of the weight fraction of the refrigerant on the lubricity for POE lubricant, such as wear amount, worn surface roughness, and friction coefficient. Oil temperature is 40°C. Decreasing and increasing of the wear amount occur, as the fraction of the refrigerant increases gradually. That is to say, there is the optimum fraction of the refrigerant that the wear amount is minimized. It also shows that wear amount is almost constant at 50 to 96.5 wt% of the fraction of the refrigerant. Then as the fraction of the refrigerant increases gradually, the worn surface roughness and friction coefficient decrease, thus approaching to a constant value. Fig. 3 shows the photomicrograph of the wear scar. As seen in Fig. 3(a), the wear scar in case of 1 wt% of the fraction of the refrigerant is rough extremely, which shows that adhesive wear occurs. On the other hand, as seen in Fig. 3(b) (c), the wear scar in 40, 96.5 wt% is very smooth and the wear amount is large, and we can estimate that corrosive (chemical) wear occurs.

Fig. 4 shows the effects of the fraction of the refrigerant on the lubricity for POE lubricant, such as wear amount, worn surface roughness, and friction coefficient. Oil temperature is 80°C. Decreasing and increasing of the wear amount occur, as the fraction of the refrigerant increases gradually, which shows same tendency as the results of 40°C. Also friction coefficient decreases as the fraction of the refrigerant increases gradually. In addition, decreasing and increasing of the worn surface roughness occur as the fraction of the refrigerant increases gradually to 32 wt%. Therefore the worn surface roughness in case of 40 wt% of the fraction of the refrigerant decreases remarkably in comparison with one in 32 wt%. Fig. 5 shows the photomicrograph of the wear scar. As seen in Fig. 5(a), the wear scar in case of 1 wt% of the fraction of the refrigerant is rough extremely, which shows that adhesive wear occurs. On the other hand, as seen in Fig. 5(b), the wear scar in 40 wt% is very smooth and the wear amount is large, and we can estimate that corrosive (chemical) wear occurs.

From the above results, decreasing and increasing of the wear amount occur and wear configuration changes from adhesive wear to corrosive (chemical) wear, as the fraction of the refrigerant increases. We can consider that they are caused by refrigerant solved in POE lubricant because corrosive (chemical) wear occurs at the higher fraction of the refrigerant. Furthermore, calboxylic acid salt generated by decomposition of POE lubricant due to the friction, is a factor of corrosive (chemical) wear.

Then, we conducted 4-balls wear tests by increasing the concentration of 2-Ethylhexanoic acid which
is the raw material of POE lubricant. Fig.6 shows the effects of the concentration of the acid on lubricity for POE lubricant, such as wear amount, worn surface roughness, and friction coefficient. Fig.7 shows the photomicrograph of wear scar. If the acid is solved in POE lubricant, wear amount increases, and worn surface roughness and friction coefficient decreases. Consequently, corrosive (chemical) wear occurs, if the concentration of the acid increases. From these results, it was found that HFC-134a refrigerant and acid solved in POE lubricant affect the lubricity of POE lubricant with HFC-134a refrigerant.

4. ANALYSIS

After wear tests, we extracted the deposit around the wear scar, and analyzed from view points of organic/inorganic chemistry. Fig.8 shows the results of FTIR analysis for the deposit in 40wt% of the weight fraction of the refrigerant. The carboxylic acid salt is detected obviously, due to absorption in 1610~1550cm⁻¹ and 1450~1400cm⁻¹ wave number. Similarly, the carboxylic acid salt is detected obviously at 1 to 40wt% of the fraction of the refrigerant. As POE lubricant is synthesized from acid and alcohol, it is considered that detected carboxylic acid salt is generated by decomposition of POE lubricant due to the friction.

Fig.9 shows the results of XMA analysis (wave length dispersive method) for the deposit in case of 1, 20, 40wt% of the fraction of the refrigerant. It follows that fluorine increases remarkably as the fraction of the refrigerant increases. It is considered that detected fluorine is generated by decomposition of the refrigerant due to the friction⁴. In addition, we obtained the results formerly that fluorine was combined with metal (iron) by analyzing the worn surface. Therefore, it was clarified that the generated amount of metal fluoride increases as the fraction of the refrigerant increases gradually.

5. DISCUSSION

Decreasing and increasing of the wear amount occur and wear configuration changes from adhesive wear to corrosive (chemical) wear, as the weight fraction of the refrigerant increases. Their wear characteristics are caused by metal fluoride and carboxylic acid salt generated by decomposition of HFC-134a refrigerant and POE lubricant due to the friction.

Furthermore, as the fraction of the refrigerant increases gradually, the wear amount increases and the worn surface roughness decrease obviously. So, it is considered that the condition of the lubrication becomes mild. And in the mixture liquid (POE lubricant and HFC-134a refrigerant), the fraction of POE lubricant decreases, as the fraction of the refrigerant increases. Therefore, it is considered the generated amount of the carboxylic acid salt caused by decomposition of POE lubricant doesn't increase remarkably, as the fraction of the refrigerant increases. On the other hand, it is cleared that the generated amount of the metal fluoride increases, as the fraction of the refrigerant increases, considering the above mentioned results at XMA analysis. Consequently, for the factor by which corrosive (chemical) wear occurred in the high weight fraction of HFC-134a refrigerant, it was found that the metal fluoride was more dominant than the carboxylic acid salt.

At the decreasing region of wear amount (adhesive wear occurs), as the weight fraction of the refrigerant increases, the wear amount and the worn surface roughness decreases because metal fluoride and carboxylic acid salt generated on the worn surface have an extreme pressure effect on the lubricity of
POE lubricant with HFC-134a refrigerant. But as generated amount of metal fluoride and carboxylic acid salt isn’t enough, it follows that adhesive wear occurs.

On the other hand, at the increasing region of the wear amount (chemical wear occurs), as the weight fraction of the refrigerant increases, the generated amount of the metal fluoride on the worn surface increases. As the results, corrosive (chemical) wear occurs easily because generated metal fluoride is weaker than the material of balls (iron). Therefore, wear amount increases, and friction coefficient and worn surface roughness decrease.

6. CONCLUSION

We evaluated the lubricity for POE lubricant with HFC-134a refrigerant by 4-balls wear tests under the pressurized mixing environment of POE lubricant with HFC-134a refrigerant. In addition, by analyzing the deposit around the worn surface, the mechanism of the atmosphere effect of HFC-134a refrigerant on POE lubricant was also discussed. The following conclusion were obtained.

1) Decreasing and increasing of the wear amount occur, as the weight fraction of HFC-134a refrigerant increases gradually, and there is the weight fraction of HFC-134a refrigerant that the wear amount is minimized.
2) Adhesive wear occurs on the worn surface at the decreasing region of wear amount, corrosive (chemical) wear occurs at the increasing region of wear amount.
3) At the high weight fraction of HFC-134a refrigerant, corrosive(chemical) wear occurs mainly caused by the metal fluoride.

REFERENCE

Fig. 1 Schematic Diagram of Test Machine

Table 1 Test Condition

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<tr>
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<td>Oil Temperature (°C)</td>
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Fig. 2 Effect of Weight Fraction of Refrigerant on Lubricity for POE / HFC-134a

Fig. 3 Photomicrograph of wear scar
(Effect of Weight Fraction of Refrigerant, 40°C)
Tribological Evaluation of Rotary Compressor with HFC Refrigerants

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ABSTRACT

Because of the development of Hydro FluoroCarbon (HFC), it is speculated that there will be some difficulties in lubrication at the sliding parts in compressors, especially at the vanes tip in rotary compressors and that a precise lubrication analysis and an exploit of materials for the sliding parts of compressors will be needed.

In this paper, evaluations of lubricating effects at the vane tip and ratio of metal contact area, an examination of an optimum design of a vane, and an exploitation of materials for a vane were discussed respectively.

First, a friction experiment under dry condition was operated to investigate a lubricating effects from the refrigerants. By this experiment, it was discovered that HFC owned somewhat of lubricating effect from fluoride, although it was smaller than that of Chloro Fluoro Carbon (CFC) and Hydro Chloro Fluoro Carbon (HCFC) from chloride. Therefore, one could say that a lubricating effect would be certainly reduced by using HFC as an alternative refrigerant.

The next experiment conducted was to evaluate the ratio of metal contact area at the vane tip by measuring the electric contact resistance between the vane and the roller, and an optimum design for a vane was attempted to be made. As a result of the experiment, it was discovered that a reduction of the ratio of metal contact area was possible, however, it was awfully difficult to gain complete hydrodynamic lubrication.

Therefore, an exploitation of materials for vanes was progressed by using adhesive energy on the materials, and improvements of scuffing and wear resistances were attempted by using composites of hard particles and ceramic coatings.

INTRODUCTION

The usage of Chloro Fluoro Carbon (CFC) and Hydro Chloro Fluoro Carbon (HCFC) for refrigerants are regulated by law in order to prevent the depletion of Ozone Layer, and exploitations of alternative refrigerants and machinery for those refrigerants are in progress. One of the most important tasks for these exploitations is keeping the reliability of compressors, and Fig. 1 summarizes a problem statement and measures to solve it. This paper discusses lubricating effects at the vane tip using HFC, an evaluation of lubricating condition at the vane tip, and also methods to improve this condition. The compressor used for these experiments is a rotary compressor that requires very severe lubricating conditions.

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<td>Depletion of Ozone Layer by Chlorine Element in CFC and HCFC</td>
<td>a deterioration of lubricating abilities of refrigerant</td>
<td>a development of technology in usage of insoluble oils</td>
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<tr>
<td>substituting refrigerants that don't contain chlorine</td>
<td>a deterioration of compressors' reliability</td>
<td>a development of refrigerating machine oil</td>
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<td>a decline in solubility of refrigerant in lubricating oil</td>
<td>an exploitation of materials for the sliding parts of compressors</td>
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<td>redesigning a structure of the sliding parts of compressors</td>
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Fig. 1 A problem statement of compressors caused by substitutions of refrigerants and methods to solve it
LUBRICATION EFFECTS IN HFC REFRIGERANTS

1. EXPERIMENT

A dry friction test was conducted by using Shell Four Ball Test Method. Rolling bearings of steel were used as samples for testing. CFC12, HCFC22, HFC32, HFC134a, HFC125, and nitrogen, that were set at the room temperature, were used as ambient gases.

After the dry friction test, the surface of the samples was analyzed by X-ray Photoelectron Spectroscopy (XPS).¹

2. RESULT and DISCUSSION

The result of the measurement of seizure load was shown on Fig. 2 (a). They were categorized in three groups, and they were CFC HCFC Group that contained Cl in their molecules (CFC12, HCFC22), HFC Group that did not contain Cl in their molecules (HFC134a, HFC32, and HFC125), and Inert Gas Group (nitrogen).

CFC HCFC Group that contained Cl had the heaviest seizure load, and this fact could be representing the effect of Extreme Pressure (EP).

HFC Group that did not contain Cl had the next heaviest seizure load, and remarkable difference was observed between the seizure load in HFC Group and in Inert Gas Group (nitrogen). This result proved that some sort of EP was affected, and then, elements on the friction surface were analyzed. Fig. 3 showed the result of it. From this result, F was apparently detected on the friction surface and it was speculated that a fluoridized tunic was formed on the friction surface. This fluoridized tunic could be assumed as fluoride iron by the chemical shift on XPS peak.

From the result discussed above, one could say that in HFC, the seizure load was heavier than that in inert gases by the effect of EP that could be possibly caused by fluoride, and was less than that in CFC and HCFC that contained Cl. Also, Fig. 2 (b) and (c) showed that the same type of trend as the case of seizure load could be seen in wear and friction coefficient.
AN EVALUATION OF LUBRICATING CONDITION AT THE VANE TIP

1. EXPERIMENT

The vane was designed for the purpose of measuring the ratio of metal contact area. The schematic of the vane was shown on Fig. 4. Tool steel used as an electrode was inserted into the ceramic vane.

This vane was mounted in a compressor. The circuit shown in Fig. 5 was giving very small amount of voltage between the vane and the rolling piston, and the electric potential on a contact area was measured at the same time of measuring the rotation angle of the crank shaft.

In this experiment, the value of the impressed voltage was a very important factor. This value was determined as 0.2 volt as a result of optimizing the circuit. Also, it was assumed that the electric potential on a contact area was 0.04 volt from the fact that it did not record under this value when the compressor is and is not running. 2)

2. RESULT and DISCUSSION

The trend of electric potential on a contact surface was shown on Fig. 6. This data was recorded by varying the pressure difference between inlet and outlet. From this diagram, it was noticed that as the pressure difference increased, the electric potential on a contact area decreased, which meant that the ratio of metal contact area was increasing. One of the reason for this phenomenon was that the load on top of the vane was increased since the pressure difference increased. The other reason was that the viscosity of the oil decreased since outlet pressure increased and the temperature of outlet gas rose up.

By observing the crank's one rotation, the highest ratio of metal contact area was recorded around the rotation angles of 90 deg. and 270 deg.. This was because the sliding velocity between the vane and the roller was the smallest at these two angles.

Next, Fig. 7 showed the trend of the electric potential on a contact area with the operating frequency varied from 40 Hz to 90 Hz. This diagram indicated that the ratio of metal contact area was decreased because the rotational speed increased as the operating frequency increased.

From all the result above, the ratio of metal contact area between the vane and the roller could be evaluated. Also, the trend of the ratio of metal contact area in respect to the pressure difference and the operating frequency could be observed carefully. The lubricating condition between the vane tip and the roller was mixed lubrication that was to happen in any state of metal contact when running a compressor.
Fig. 6  electric potential on a contact area and rotational angle of the crank shaft with different pressure difference

(a) pressure difference: 1.15 MPa  
(b) pressure difference: 1.60 MPa  
(c) pressure difference: 1.97 MPa

Fig. 7  electric potential on a contact area and rotational angle of the crank shaft with different operating frequencies

(a) frequency: 40 Hz  
(b) frequency: 60 Hz  
(c) frequency: 90 Hz
AN IMPROVEMENT OF LUBRICATING CONDITION AT THE VANE TIP

1. OPTIMUM DESIGN OF A VANE

An improvement of lubricating condition was attempted by optimum design of a vane. The mixed lubrication analysis was presented by Tanaka\(^3\), and this analysis was verified by our evaluation of the lubricating condition in this paper. Taking Tanaka's analysis as a guideline, an experiment was conducted to record the ratio of metal contact area with thickness of a vane and radius of curvature at the vane tip varied. These data points were plotted on Fig. 8. It showed that smaller the thickness of a vane was, smaller the ratio of metal contact area became, and that larger the radius of curvature was, smaller the ratio of metal contact area became. From these trends, it was possible to improve the lubricating condition by reducing thickness and by enlarging radius of curvature, however, it was very difficult to gain complete hydrodynamic lubrication.

2. EXPLOITING MATERIALS FOR A VANE

Since it was very difficult to gain complete hydrodynamic lubrication by optimum design, exploiting materials for a vane was essential in order to do so.

To improve scuffing resistence and wear resistence, currently exploiting materials such as steel with surface treatment, composite materials with additive of hard particles, and composite materials with additive of solid lubricant are in progress.

Finding effective parameters was a very significant step of exploiting materials efficiently. It was hypothesized that adhesion energy and plastic index ratio were two of those important parameters. Figure 9 (a) showed a relationship of adhesion energy with seizure load and Fig. 9 (b) showed a relationship of plastic index ratio with the seizure load. Both of adhesion energy and plastic index ratio were correlated with seizure load. It became evident that the seizure load could be maximized by minimizing these parameters.

\[
W_{ab} = \gamma_a + \gamma_b - \gamma_{ab} \hspace{1cm} (1)
\]

\[
\psi = \left( \frac{E'}{H} \right) \cdot \left( \frac{\sigma}{r} \right)^{1/2} \hspace{1cm} (2)
\]

\[
E' = \frac{1}{\frac{(1 - \nu_a^2)}{E_a} + \frac{(1 - \nu_b^2)}{E_b}}
\]

\[
\psi : \text{plastic index} \hspace{0.5cm} \sigma : \text{standard deviation of protuberance height} \hspace{0.5cm} E' : \text{equivalent to Young's modulus}
\]

\[
\nu_a, \nu_b : \text{Poisson's ratio of material(a) and material(b)} \hspace{0.5cm} r : \text{average of radius of curvature at the tip of protuberance}
\]

\[
H : \text{hardness} \hspace{0.5cm} E_a, E_b : \text{Young's modulus of material(a) and material(b)}
\]
CONCLUSION

1. Lubrication effects in HFC refrigerants
   HFC refrigerants forms fluoride on the material surface, and that was capable to improve lubricity. However, the lubrication effect in HFC refrigerants was smaller than that in CFC and HCFC refrigerants.

2. An evaluation of lubrication characteristics at the vane tip
   Metal contact conditon between the vane tip and a rolling piston could be evaluated by measuring the electric contact resistance. A ceramic vane, which a steel electrode was installed on, was used for this measurement. The lubricating condition at the vane tip was mixed lubrication that was to happen in any state of metal contact when running a compressor.

3. Improvement of the lubricating condition at the vane tip
   The ratio of metal contact area could be reduced by varying the thickness and a radius of the curvature at the vane tip. Although, it was very difficult to gain complete hydrodynamic lubrication.
   In order to improve the lubricating condition by means of exploiting materials for vanes, an effective method would be reducing adhesion energy and plastic index.

REFERENCES

