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T. Yoshimura
Matsushita Refrigeration Company

H. Akashi
Matsushita Refrigeration Company

A. Yagi
Matsushita Refrigeration Company

T. Nagao
Matsushita Refrigeration Company

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BEARING CHARACTERISTICS AT THE SMALL END OF A CONNECTING ROD IN RECIPROCATING COMPRESSORS FOR HFC-134a

Takao Yoshimura[1], Hironari Akashi[1], Akio Yagi[1], Takahide Nagao[2]
1 Compressor Research Office, Refrigeration Research Laboratory,
Matsushita Refrigeration Company, Japan
2 Engineering Department, Compressor Division,
Matsushita Refrigeration Company, Japan

ABSTRACT

This paper intends to clarify the experimental and theoretical characteristics of a swing journal bearing at the small end of the connecting rod in reciprocating compressors and further to clarify the difference in lubricating characteristics between a combination of HFC-134a/ester oil and that of CFC-12/mineral oil. In order to observe the metallic contact states at the bearing under both stable and transient operating conditions, electrodes were mounted on the sliding surface at the bearing and variations of the contact resistance were measured. Then these experimental results were compared with the theoretical results calculated using the lubricating theory based on the Reynolds equation.

As a result, we found that the bearing at the small end was in a severe lubricating condition, which partial metallic contact occurred. And there existed a correlation between the metallic contact ratio and the bearing modulus. These experimental results of metallic contact variations agreed qualitatively with the theoretical results of oil film changes. We also noticed that there was no significant difference in lubricating characteristics between a combination of HFC-134a/ester oil and that of CFC-12/mineral oil, and the lubricating condition under the transient operating condition of the refrigerator continued to be severer than that under stable conditions for a long period of time.

INTRODUCTION

In reciprocating compressors for refrigerators, that are commonly used in the worldwide, the bearing at the small end of the connecting rod is considered to be in a severer lubricating condition than any other sliding parts because of a peculiar swing motion. In the past studies, there have been no reports on the lubricating condition of the small end bearing in the field of refrigerant compressors. On the other hand, there are some reports that evaluated the lubricating condition of the bearing at the small end in reciprocating engines which has a similar sliding motion. However, they are mainly focused on theoretical analysis and less deal with experimental evaluation (1) (2).

In order to clarify the lubricating condition of the small end bearing, this study first experimentally compared various states of metallic contact by measuring the contact resistance. The experiment was conducted by varying operating conditions and combinations of refrigerants and lubricating oils when a compressor was actually operating stably.

We then theoretically analyzed the behavior of the bearing in the swing motion based on the Reynolds lubricating theory and compared the analysis results with the experimental results to make a detailed study of lubricating conditions. We also experimentally investigated changes in metallic contact state under the transient condition that is often encountered in actual use of refrigerators and compared them with those under stable conditions.

CONFIGURATION OF COMPRESSOR

The cross section of the reciprocating compressor for refrigerator used in this study is shown in Figure 1. The motor is located in the upper portion of the casing and the mechanical parts, such as the piston and cylinder, is in the lower. They are connected via a crank shaft, connecting rod and piston pin. The connecting rod consists of a small end on the piston side and a large end on the shaft side. This small end and the piston pin secured to the piston constitutes a true round bearing and the small end of the connecting rod and the piston pin make a relative swing motion. The bearing at the small end used for this study had no oil grooves on either the shaft or bearing. Lubricating oil accumulated in the bottom of the casing is pumped up by centrifugal force from the oil supply pipe at the bottom of the shaft. Part of it lubricates the bearing at the large end of the connecting rod, then is fed to the bearing at the small end through the oiling port in the connecting rod. The rest of oil is supplied to the main bearing.

EXPERIMENTAL AND ANALYTICAL METHODS

(1) Experimental method

As illustrated in Figure 2, in order to observe the condition of metallic contact at the bearing, electrodes C1 to C6 were mounted on the sliding surface at the bearing. The electrodes, made of polyester coated copper wires, were connected to steel wires coated with teflon tubes, then pulled out of the casing. Then each steel wire and ground wire were connected to the electric circuit having two resistors R_1, R_2 and a DC power supply(V_0) shown in Figure 3. In this measuring circuit, the electric resistance becomes zero when the electrodes in the small end bearing and the piston pin come into a complete contact and becomes infinite when they are completely separated. Further, when the electrodes and the piston pin are in intermediate contact state, an intermediate resistance value is indicated. By measuring the voltage V at the electrodes that varies according to resistance, it is possible to evaluate a qualitative contact state.

The evaluation of lubricating conditions while the compressor was operating was made in two conditions; stable and transient. First the metallic contact state under stable operating condition was evaluated by using a calory meter test equipment with both combinations of HFC-134a/ester oil and CFC-12/mineral oil listed in Table 1. At this time, in order to evaluate the influence of load, viscosity and rotating speed on the formation of oil films, the metallic contact states were estimated by varying the operating conditions.

As for the evaluation of lubricating condition under transient condition, we installed a test compressor on 300 liter refrigerator and operated it intermittently at 30℃ ambient temperature. Then we measured changes in conditions of metallic contact under the normal intermittent operation and the first intermittent operation after defrosting in a period between the start and stop of the compressor. This intermittent operation experiment was conducted with a combination of CFC-12/mineral oil.

(2) Theoretical analysis method

The theoretical analysis of the characteristics of the bearing at the small end of the connecting rod was conducted using the Reynolds fundamental equation under the conditions of dynamic load and swing motion. For this analysis, the bearing was assumed to be an infinitely small bearing and the boundary condition used was the Gümbel condition.

$$\frac{\partial}{\partial \theta}\left(\zeta^3 \frac{\partial p}{\partial \theta}\right) + r^2 \frac{\partial}{\partial y}\left(\zeta^3 \frac{\partial p}{\partial y}\right) = 6\mu\left(\frac{r}{\Delta r}\right)^2 \left(-\varepsilon\,\omega_0 \sin\theta + 2\frac{d\varepsilon}{dt}\cos\theta\right) \qquad (1)$$

$$\zeta = 1 + \varepsilon\cos\theta\ , \qquad \omega_0 = \omega_{pp} - 2\,\omega_f - 2\frac{d\phi}{dt}$$

Where, p is oil film pressure, r is small end bearing radius, Δr is radius clearance, θ is angle from maximum oil film thickness location, ε is eccentricity ratio, ϕ is attitude angle, y is axial direction co-ordinates, t is time, μ is oil viscosity, ω_{pp} is piston pin relative angular velocity, ω_f is angular velocity of dynamic load direction. In the calculation, we obtained the eccentricity and eccentric angle using the Runge-Kutta method by dividing one revolution of the shaft of the compressor and repeated the calculation until the eccentricity ratio and attitude angle would match at a shaft angle of 0 and 2 π rad.

RESULTS

(1) Characteristics under stable condition

Figure 4 shows the measurement results of voltages of the electrode C2 when the compressor was operated under the standard operating conditions using a combination of HFC-134a and ester oil. In Figure 4, it is known that the electrode voltage drops at the shaft angle of around π and 2 π rad. Therefore it is considered that the small end of the connecting rod is in a severe lubricating condition which partial metallic contact occurs even under the standard condition. Further, the results obtained with suction pressure and discharge pressure varied are shown in Figure 5, and the results with the operating frequency varied in Figure 6 and the results with the lubricating oil temperature varied in Figure 7. From these results, it can be known that the electrode voltage drops more as the discharge pressure is higher, the suction pressure is lower, the operating frequency is lower and the lubricating oil temperature is higher.

We compared the lubricating conditions between a combination of HFC-134a/ester oil and that of CFC-12/mineral oil. For this comparison, we introduced a concept of contact ratio in order to quantify the severity of lubricating condition. The contact ratio is, as shown in Figure 8, a ratio of the shaded area to the whole area (A × B) of the electrode voltage waveform. The comparison was conducted using a dimensionless bearing modulus μ N/P (μ : oil viscosity on the sliding surface, N: average rotational frequency of the small end, P: average bearing pressure of the small end) that indicates the degree of sever operating conditions as a parameter. The results are shown in Figures 9 and 10. From these results, it is known that the contact ratio is highly related to the bearing modulus and as the bearing modulus decreases, the contact ratio tends to increase. By comparing a combination of HFC-134a/ester oil and that of CFC-12/mineral oil, we noticed that the overall tendency of the contact ratio is almost equal and there is no significant difference in lubricating characteristics.

In order to make a detailed study of lubricating conditions, the above experimental results were compared with the theoretical analysis results of bearing characteristics. The theoretical characteristics of the eccentricity ratio and attitude angle under the standard operating condition using a combination of HFC-134a/ester oil are shown in Figure 11. The eccentricity ratio changes little during one revolution of the shaft and is constant at $\varepsilon = 0.991$. The attitude angle changes like a sine waveform and its amplitude is about half of the swing angle (27.8°).

Based on the above calculation results, the oil film thickness between the small end bearing and the piston pin at the center line position of the connecting rod were calculated, where the contact signal of C2 was measured in the experiment. The results are shown in Figure 12. The calculation results indicate that the oil film thickness on the center line of the connecting rod tends to become the thinnest at the shaft angle of 5 π /4 and 7 π /4 rad because the attitude angle becomes zero. The shaft angle position where the oil film thickness is the thinnest well agrees with the shaft angle position where the electrode voltage drops as shown in Figure 4. Under other conditions, the theoretical results of the oil film thickness changes agreed qualitatively with experimental results of the metallic contact variations measured by electrodes too. As mentioned above, it has experimentally and theoretically been confirmed that the swing journal bearing at the small end of the connecting rod is under a severe lubricating condition.

(2) Characteristics of transient condition of the compressor installed on a refrigerator

The variations of the contact ratio after the start of the compressor are shown in Figure 13 regarding the normal intermittent operation and the first intermittent operation after defrosting. From this figure, in both operating conditions, it is known that the contact ratio at the initial stage of start is higher than that before the stop of the compressor and decreases as time passes. Figure 14 shows the contact ratio characteristics under transient condition using the bearing modulus. In Figure 14, the solid line indicates the regression line under the stable operation in Fig.10 and the broken line indicates $\pm 3\sigma$ (σ : standard deviation) of the regression line. When variations in measurement are taken into consideration, it can be considered that when the contact ratio is within this $\pm 3\sigma$ region, the conditions are stable. From this point of view, it can be known that the contact ratio is substantially out of the stable operating condition up to about 30 seconds after the start despite the bearing modulus is large enough. And the severe lubricating condition exists that can not be observed in the standard stable condition. Also, up to about 10 minutes, though the condition approaches the 3σ line, the lubricating condition that is slightly severer than under the stable operating condition still continues. When about 10 minutes have passed after the start of the compressor, the lubricating condition becomes the same as that under stable operating condition.

Thus, the fact that the lubricating condition is severest in a period of 30 seconds immediately after the start is considered to be attributable to a delay in supplying lubricating oil to the sliding surface at small end bearing. The continuation of lubricating condition that is slightly severer than that under the stable operating condition seems to be caused by less lubricating oil quantity to the sliding surface than that under the stable operating condition. It is due to a slow drop of the viscosity of the lubricating oil in the bottom. As mentioned above, it has been clarified that compared with lubricating condition in the stable operating condition, the lubricating condition of the small end bearing under the transient condition is severer and its condition continues for a relatively long period of time.

CONCLUSIONS

- The small end bearing of the connecting rod is in a severe lubricating condition which partial metallic contact occurs. Also, there exists a correlation between the metallic contact ratio and the bearing modulus as the metallic contact ratio increases with decreasing the bearing modulus.
- There is no significant difference in lubricating characteristics between a combination of the alternative refrigerant HFC−134a and ester oil and that the conventional refrigerant CFC−12 and mineral oil. Accordingly, it has been verified that the reason that the bearing wears more with HFC−134a than with CFC−12 is not due to a difference between lubricating conditions but due to a difference in chemical wear characteristics of the refrigerants themselves.
- In the transient operating condition of the refrigerator, the lubricating condition of the small end bearing is the severest during a period of 30 seconds after the start. It then gradually approaches the lubricating condition under the stable operating condition, but it takes 10 minutes after the start that it becomes the perfect stable condition.

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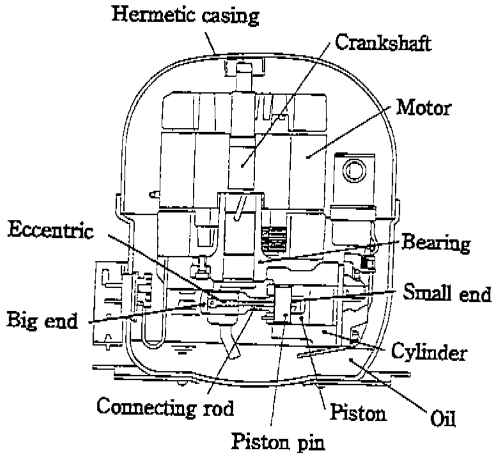

Fig.1 Schematic view of reciprocating compressor

Table.1 Combination of refrigerant and oil

Refrigerant	Oil	
	Type	Kinematic viscosity mm^2/s at 40℃
HFC−134a	Ester oil	22
CFC−12	Mineral oil	30

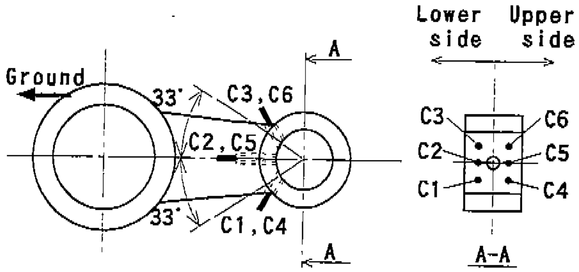

Fig.2 Electrode arrangement for contact resistance measurement

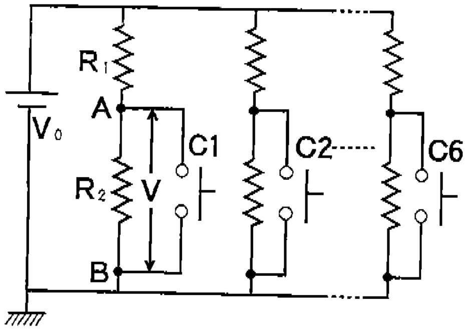

Fig.3 Electric circuit for contact resistance measurement

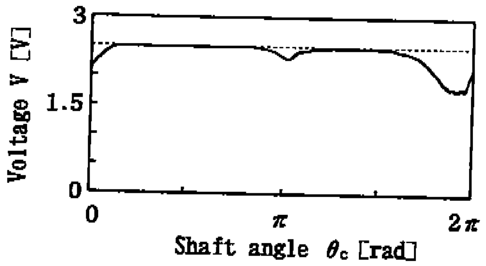

Fig.4 Voltage characteristics (HFC−134a, 60Hz, Pe=85kPa, Pc=1015kPa, oil 80℃)

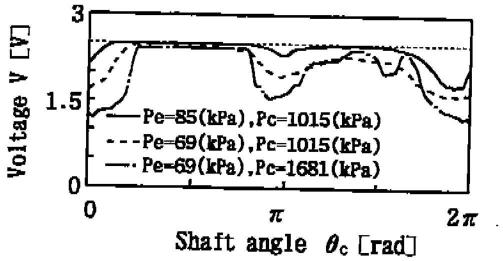

Fig.5 Voltage characteristics under different pressures (HFC−134a, 60Hz, oil 80℃)

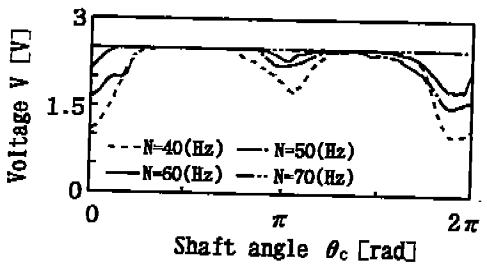

Fig.6 Voltage characteristics under different frequencies (HFC−134a, Pe=85kPa, Pc=1015kPa, oil 80℃)

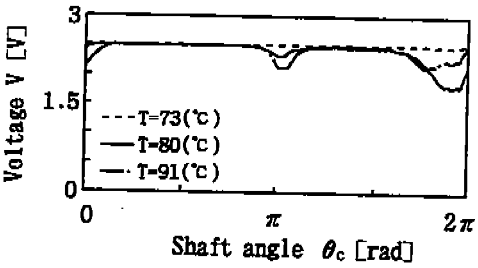

Fig.7 Voltage characteristics under different oil temperatures (HFC−134a, 60Hz, Pe=85kPa, Pc=1015kPa)

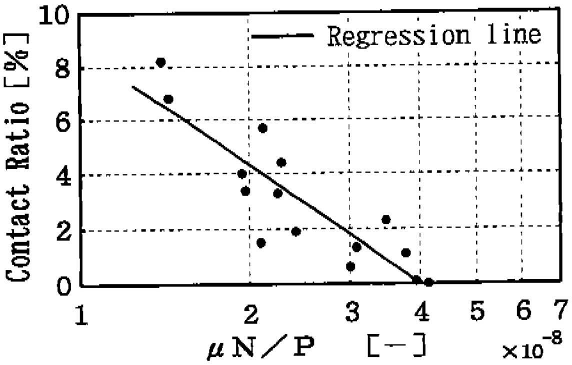

Fig.9 Contact ratio characteristics (HFC-134a)

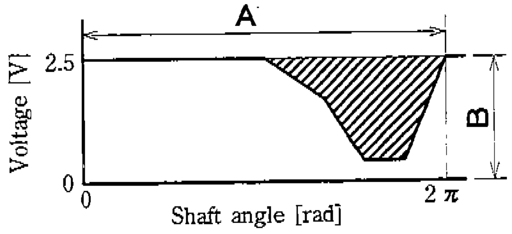

Fig.8 Concept of contact ratio

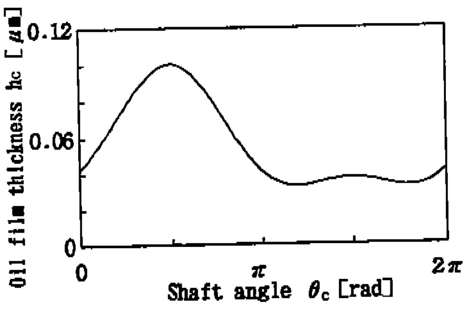

Fig.12 Theoretical results of oil film thickness (HFC-134a, 60Hz, Pe=85kPa, Pc=1015kPa, oil 80℃)

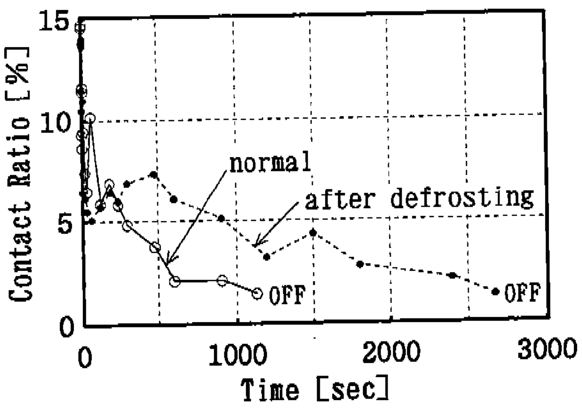

Fig.13 Variation of contact ratio with the time (CFC-12, on refrigerator, 60Hz, ambient temp. 30℃)

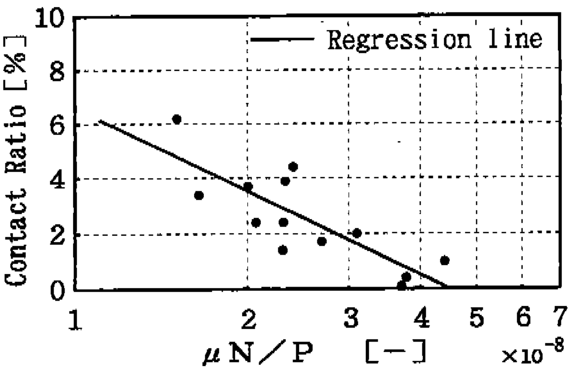

Fig.10 Contact ratio characteristics (CFC-12)

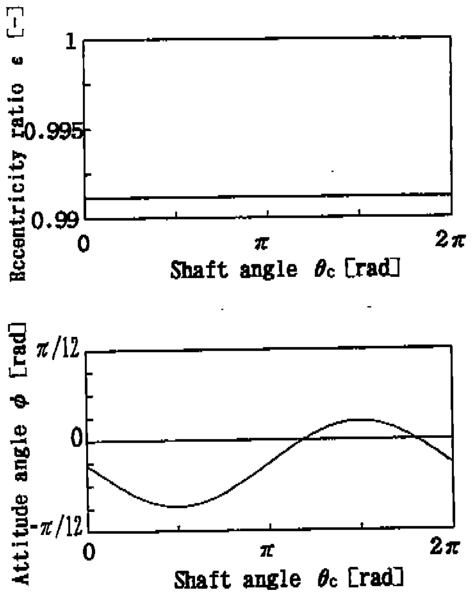

Fig.11 Theoretical characteristics of small end bearing (HFC-134a, 60Hz, Pe=85kPa, Pc=1015kPa, oil 80℃)

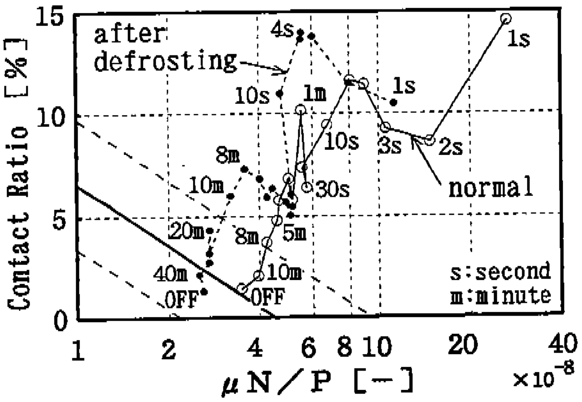

Fig.14 Contact ratio characteristics under transient conditions (CFC-12, on refrigerator, 60Hz, ambient temp. 30℃)