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MEASUREMENT OF CONTACT CONDITIONS BETWEEN SWASHPLATE AND SHOE IN THE AUTOMOTIVE SWASHPLATE COMPRESSOR

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ABSTRACT

In this paper, contact conditions between a swashplate and shoes in the swashplate compressor for automotive air conditioning use are investigated experimentally. The conditions are measured with the electric resistance method that utilizes the swashplate surface and the shoe surface as electrodes respectively. The instrumented compressor is connected to an experimental gas cycle with R134a, and is operated under various operating conditions of pressure and rotational speed. It is indicated by the measurement that the voltage of the contact signal decreases generally, which means better lubricating condition, with the increase of the rotational speed and with the decrease of the compression pressure. The relationship between the contact voltage and the Sommerfeld number is examined in order to evaluate the lubricating condition. The contact voltage is also related to the value of clearance between the contact surfaces experimentally under the static condition with and without oil between the surfaces.

1. INTRODUCTION

Lubricating condition in refrigerant compressors has great influence on the compressor performance and reliability. If a film of oil at a sliding portion in the compressor breaks down, metallic contact occurs and leads to wear and seizure of the sliding surfaces. It is important to monitor the contact condition between the sliding surfaces in actually operating compressors and to make clear the relationship between the compressor operating condition and lubricating condition.

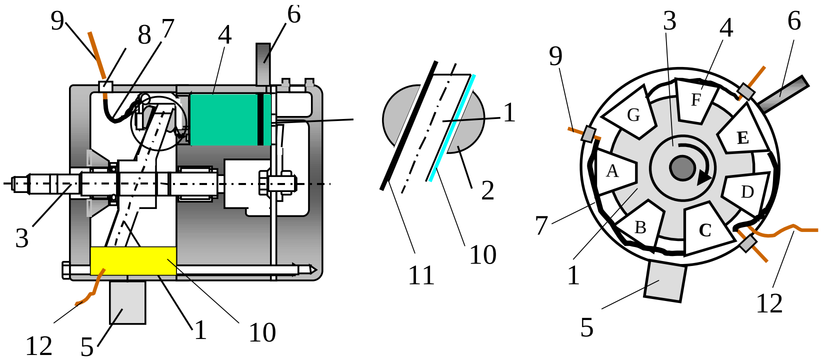
Swashplate compressors are favorably used for automotive air conditioning systems. The sliding contact between the swashplate and the shoe is one of the most severe lubricating locations in the swashplate compressor and it becomes extremely severe under starting-up and slugging conditions. There have been some studies that monitor the lubricating condition between the swashplate and the shoe. Inoue *et al*. (1999) measured successfully oil film thickness between the swashplate and the shoe with an optical method and an electric resistance method. Their results verified good lubricating condition of their swashplate compressor under the steady state operating condition. Chappell *et al*. (2000) and Drozdek *et al*. (2000) monitored the lubricating condition between the swashplate and the shoe with a contact resistance method, and showed the effectiveness of the method to indicate the degree of metal-to-metal contact between the sliding surfaces under the practical operating condition of the compressor.

In this study, the contact condition between the swashplate and the shoe of a swashplate compressor (Jingu, 2000) is monitored using the electric resistance method under different pressure and rotational speed conditions. The contact voltage using a right-angled plate instead of the swashplate is also investigated. The relationship between the contact voltage and the Sommerfeld number is examined in order to evaluate the lubricating condition. The contact voltage is related to the value of clearance between the contact surfaces experimentally under the static condition with and without oil between the surfaces.

2. EXPERIMENT

Figure 1 shows a schematic view of an experimental swashplate compressor, having 7 cylinders with total stroke volume of 180 cm^3/rev, for automotive air conditioning use. In order to monitor the contact condition between the swashplate and the shoe under the practical operating condition, the electric resistance method that employs the swashplate and the shoe as electrodes is applied. As the swashplate is pressed harder by the shoe on the piston side than the shoe on the other side, the contact condition of the piston-side shoe with the swashplate is paid attention in this study. In order to monitor the electric resistance between the swashplate and the shoe, the swashplate and the shoe must be insulated electrically except for the relevant contact point. For that purpose, a PET sheet of 0.3 mm is placed on the anti-piston-side surface of the swashplate, and the height of the anti-piston-side shoes is decreased by the sheet thickness. The piston-side shoe of concern is electrically connected to the piston by a hairspring attached to the shoe pocket of the piston, as shown in Figure 2. The insulation between the piston and the cylinder is assured by the resinous coating that is originally painted on the piston surface for the anti-wear purpose. The piston is connected with an insulated flexible wire to a terminal mounted on the casing. Figure 3 shows an schematic electric circuit to monitor the contact resistance between the swashplate and the shoe. When the two parts contact with each other and the electric current flows through the circuit, the voltage across a resistance of 500 Ω changes. In this study, the circuit is arranged as that the voltage becomes 2 V when the two parts contact perfectly while it is 0 V when they separate totally. In the experimental compressor, the actual electric circuit is composed of the casing, the shaft, the swashplate, the piston-side shoe, the hairspring, the piston and the flexible wire.

In this study, the contact conditions between the swashplate and three shoes of piston C, E and G shown in Figure 1 are monitored with three individual electric circuits. At the same time, pressure in the cylinder E is measured with a piezoelectric pressure transducer. In addition to the experiments, special experiments using a right-angled plate instead of the swashplate are executed under the condition that appropriate pressure is exerted on the piston head.



1: Swashplate	2: Shoe	3: Shaft	4: Piston
5: Viscometer	6: Pressure sensor	7: Flexible wire	8: Terminal
9: Lead wire	10: Oil	11: PET film	12: Thermocouple

Figure 1: Experimental compressor

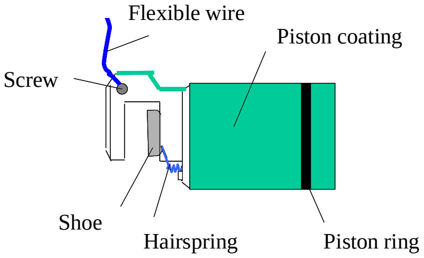


Figure 2: Connection between shoe and piston

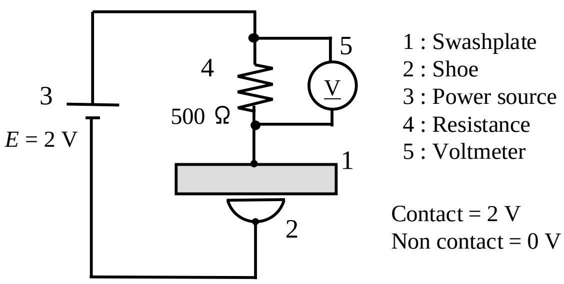


Figure 3: Electric circuit

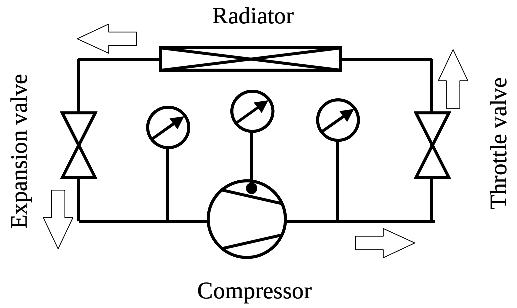


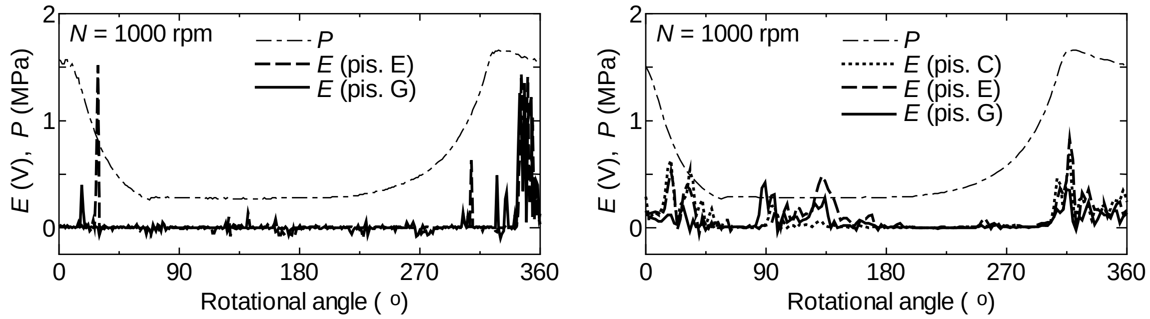
Figure 4: Experimental gas cycle

The experimental compressor is connected to an experimental gas cycle working with HFC134a as shown in Figure 4. The compressor is belt-driven by an inverter controlled variable speed motor. Operating conditions of the compressor are rotational speed: N = 1000 - 3000 rpm, suction pressure: P_s = 0.1 - 0.3 MPa[abs], discharge pressure: P_d = 0.9 - 1.6 MPa[abs] and suction temperature: T_s = 10 ^{o}C. They are controlled by two throttling valves, heat rejection at the radiator and charge amount of refrigerant. The rotational speed of the compressor is controlled by the inverter frequency, and the rotational angle of the compressor shaft is detected with an eddy current sensor.

3. RESULTS AND DISCUSSION

3.1 Processing of Contact Signals

Figure 5 shows signals of contact voltage E and pressure P in the cylinder against the rotational angle of the compressor under the operating condition of the rotational speed N = 1000 rpm, the suction pressure P_s = 0.3 MPa[abs] and the discharge pressure P_d = 1.6 MPa[abs]. Figure 5 (a) illustrates instantaneous signals during one revolution of the compressor. The voltage signals have many spikes especially during the discharge process where the shoe is pressed hard against the swashplate. On the other hand, Figure 5 (b) illustrates averaged signals over one-hundred revolutions of the compressor. The location of peaks in each voltage signal in Figure 5 (b) is similar to that in Figure 5 (a), but the height of the peaks in Figure 5 (b) is less than that in Figure 5 (a). This is because the instantaneous signal consists of spikes whose locations are slightly different from revolution to revolution of the compressor and the spikes tend to be moderated when they are averaged over many revolutions. The averaging treatment can eliminate unstable fluctuation of signals, uncertainty, electric noise, inappropriate and irregular signals caused by the unexpected contact. The averaging number more than fifty revolutions was enough to obtain the stable averaged signals, and the averaged signals over one-hundred revolutions are used in the following results and discussion if it is not mentioned specifically.



(a) Instantaneous signals (b) Averaged signals

Figure 5: Signals in one revolution (P_s = 0.3 MPa, P_d = 1.6 MPa)

3.2 Contact Signals under Different Rotational Speeds

Figure 6 shows the contact signal *E* and the cylinder pressure *P* against the rotational angle under the pressure conditions of suction pressure P_s = 0.3 MPa[abs] and discharge pressure P_d = 1.6 MPa[abs] with different rotational speed *N* = 1000, 2000 and 3000 rpm. At each rotational speed, the contact voltage becomes high in the high pressure range i.e. the compression and discharge processes. With the increase of rotational speed, the contact signals show lower peaks, which means that the lubricating condition becomes better with higher rotational speed. Though some peaks of the contact signals are included in the suction process in Figure 6, it is supposed that the peaks are caused not by the hard contact between the swashplate and the shoe but by the unstable behavior of the shoe under the unloaded condition.

3.3 Contact Signals at Low Pressure Condition

Figure 7 shows the contact signal *E* and the cylinder pressure *P* against the rotational angle under the lower pressure conditions of suction pressure P_s = 0.1 MPa[abs] and discharge pressure P_d = 0.9 MPa[abs] with different rotational speed *N* = 1000, 2000 and 3000 rpm. At *N* = 1000 and 2000 rpm, high peaks that was shown in Figure 6 are not observed in Figure 7 because of the lighter contact force between the swashplate and the shoe. But at *N* = 3000 rpm, some peaks are recorded. This may be caused by the unstable behavior of the shoe that is pressed to the swashplate with lighter contact force at higher speed.

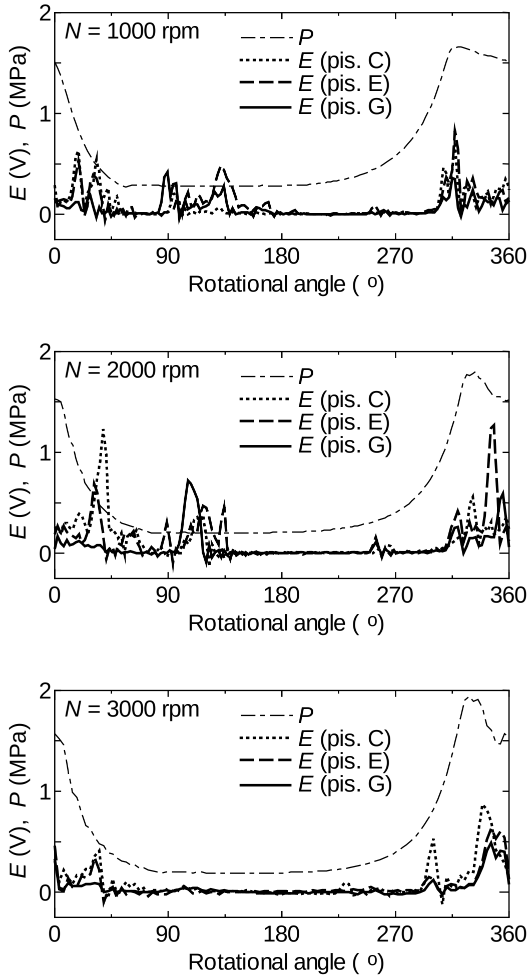


Figure 6: Averaged curves under different rotational speed (P_s = 0.3 MPa, P_d = 1.6 MPa)

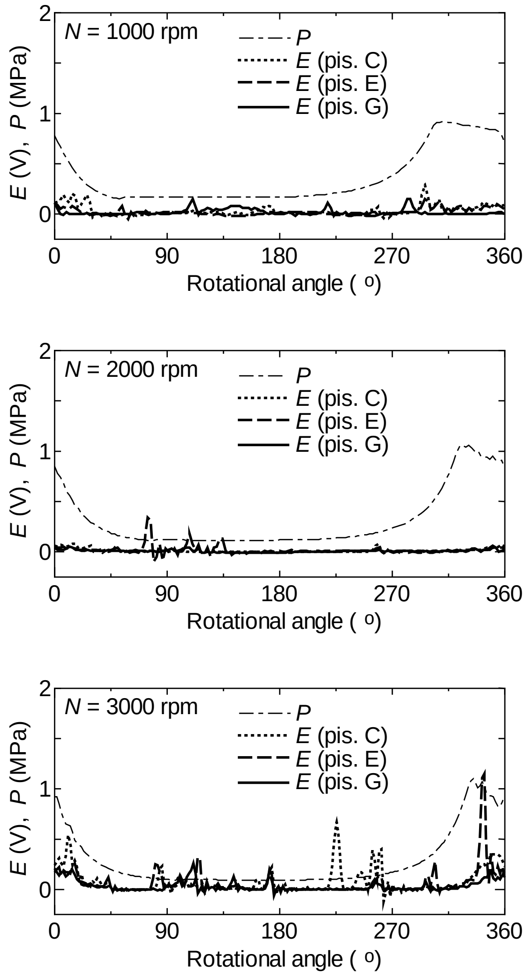
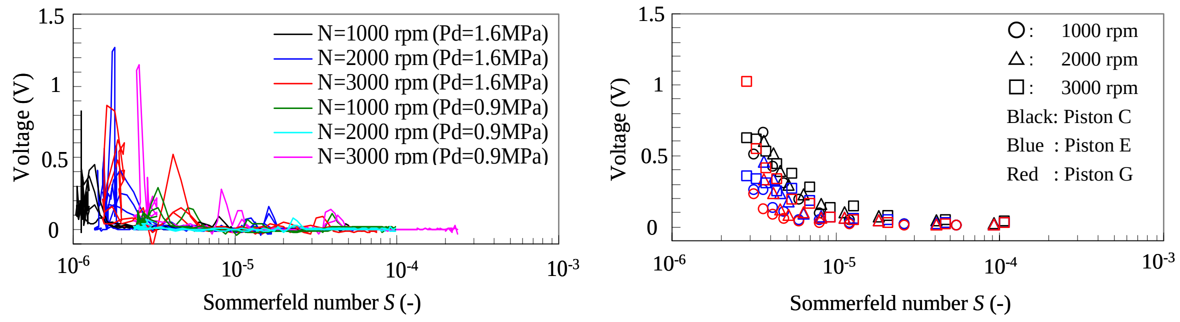


Figure 7: Averaged curves under lower pressure condition (P_s = 0.1 MPa, P_d = 0.9 MPa)



(a) In practical compressor (b) Using right-angled plate

Figure 8: Relationships between voltage and Sommerfeld number

3.4 Evaluation of Lubricating Condition by Sommerfeld Number

In general, Sommerfeld number is a non-dimensional number used for the evaluation of lubricating condition of sliding bearings. In this study the number S is defined for the sliding condition between the swashplate and the shoe as follows;

$$S = v \cdot \eta / f_w \quad (1)$$

where, v is the sliding velocity [= (angular velocity of the swashplate)×(pitch radius of the shoe)], η is the viscosity of the lubricating oil, and f_w is the contact force per unit length [= (shoe load)/(shoe diameter)]. Smaller S corresponds to larger contact load and smaller sustainable force of oil film, which means worse lubricating condition.

Figure 8 (a) shows relationships between the contact voltage and the Sommerfeld number S during the compression and discharge processes in practical compressor experiments. When S becomes smaller than about 5×10^{-6}, the contact voltage increases, which means that the lubricating condition becomes severe. On the other hand, Figure 8 (b) shows relationships between the contact voltage and the Sommerfeld number S in experiments using right-angled plate instead of the swashplate under the condition that appropriate pressure was exerted on the piston head. The relationships in Figure 8 (b) are similar to those in Figure 8 (a), which indicates that the lubricating condition between the swashplate and the shoe in the practical compressor can be evaluated by the experiment using the right-angled plate with steady force of the shoe.

3.5 Relationship between Contact Voltage and Oil Film Thickness

In order to investigate the relationship between the contact voltage and the oil film thickness, a static model apparatus, which consists of a fixed plate and a rod (ϕ 10 mm) mounted on a sliding stage, was set up as shown in Figure 9. The plate and the rod are connected to the same electric circuit as shown in Figure 3. The distance or clearance between the plate and the rod-end face is increased and decreased step by step, and then the force to press

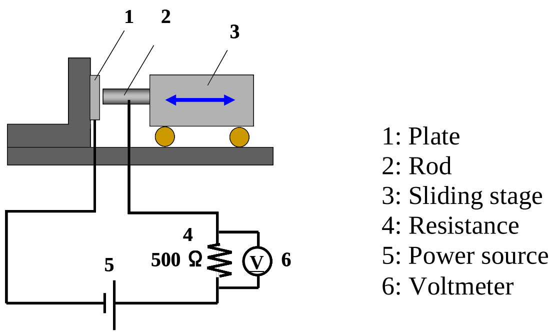
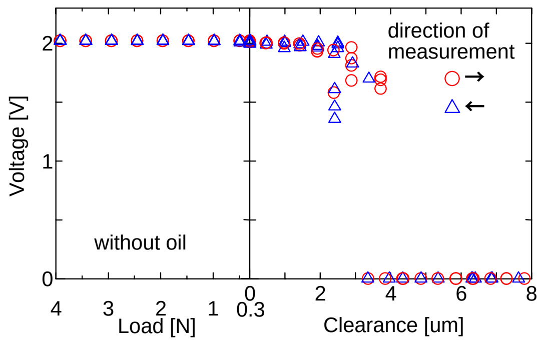
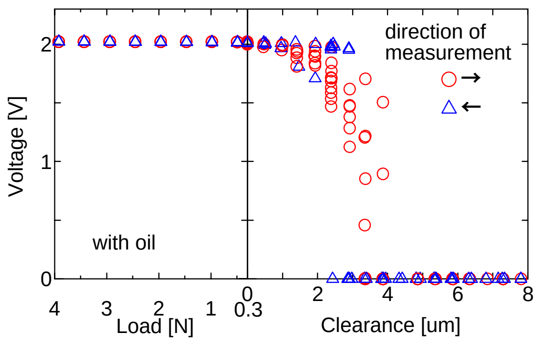


Figure 9: Experimental setup to examine the relationship between the contact voltage and the clearance



(a) Without oil



(b) With oil

Figure 10: Relationship between voltage and clearance/load

the rod against the plate is changed. Roughness of the surface was about 3 µm for the rod-end face and 0.4 - 0.8 µm for the plate. Because of these surface roughness, it was difficult to decide exactly the position of clearance '0' between the plate and the rod-end face. In this study, it was defined as the condition that the rod-end face is pressed to the plate with the force of 0.3 N (corresponding to 3.7 kPa). The clearance was measured from the '0' clearance position with a laser displacement sensor. In experiments, the contact voltage was measured while the clearance was increased and decreased step by step under the condition with and without lubricating oil between the plate and the rod-end face. The results are shown in Figure 10.

In the case of Figure 10 (a) without oil, the contact voltage begins to decrease when the clearance reaches 2 - 3 µm, and it becomes 0 V when the clearance exceeds 4 µm corresponding to the total surface roughness. The relationship between the voltage and the clearance is almost same when the clearance is decreased step by step. In the case of Figure 10 (b) with oil, the relationship between the clearance and the voltage is slightly different from those in Figure 10 (a) without oil. When the clearance increases in Figure 10 (b), medium voltage data appear in the clearance range of 2 - 4 µm. But when the clearance decreases, the medium voltage data does not appear. In both Figures 10 (a) and (b), the contact voltage is almost 2 V constant not depending on the contact load between 0.3 to 4 N.

The relationships shown in Figure 10 will be influenced by the surface roughness, the oil viscosity and the kind of oil. If it is assumed that the relationships in Figure 10 (b) based on the model experiment with oil can be applied to the evaluation of the practical compressor results of Figure 5 (a), the contact condition between the swashplate and the shoe of the experimental compressor is expected not to be severe under that operating condition because the instantaneous contact voltage does not reach 2 V.

4. CONCLUSIONS

In this study, the contact conditions between the swashplate and the shoe in the swashplate compressor for automotive air conditioning use were examined by the electric resistance method that used the swashplate and the shoe as electrodes. It was confirmed that the contact signal arose during the compression and discharge processes and it decreased with the increase of the rotational speed, which meant that the lubricating condition became better. The relationships between the contact voltage and the Sommerfeld number at the practically operating compressor were similar to those obtained in experiments using the right-angled plate with steady force of the shoe. The experiment using the model contact apparatus revealed that the contact could be detected in the range of the total surface roughness and that there existed a certain relationship between the voltage and the clearance.

In the next step of this study, an electrostatic capacitance method is applied to measure the oil film thickness between the swashplate and the shoe.

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