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Basic Study on Application of Magnetic Nano-oil to Scroll Compressor - Measurement of Friction and Leakage -

Takanobu Kikuchi

Mitsuhiro Fukuta

Masaaki Motozawa

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~ Measurement of Friction and Leakage ~

Takanobu KIKUCHI[1], Masaaki MOTOZAWA[2]*, Mitsuhiro FUKUTA[2],

[1]Graduate School of Integrated Science and Technology,
Shizuoka University, Hamamatsu, Shizuoka, Japan

[2]Department of Mechanical Engineering,
Shizuoka University, Hamamatsu, Shizuoka, Japan
+81-53-478-1058, motozawa.masaaki@shizuoka.ac.jp

* Corresponding Author

ABSTRACT

Since the improvement of efficiency of the refrigerant compressor for reducing energy consumption faces the limitation, the innovative technologies which is different from the existing technology, are strongly required. We propose the application of magnetic nano-oil, which is a dispersion of ferromagnetic nanoparticles stably dispersed in a refrigeration oil, to a refrigerant compressor for improvement of the efficiency. In this proposal, the magnetic nano-oil holds at only the sliding surface in the compressor by magnetic field, and it is expected that both friction on the sliding surface and leakage of refrigerant are reduced simultaneously in the refrigerant compressor. To conduct this feasibility study, both friction and leakage are evaluated by using the model test apparatus which is simulated the orbiting motion of a scroll compressor in this study. This model test apparatus can evaluate the gas leakage from the sliding surface and the frictional force at the sliding surface simultaneously or separately. Magnetic nano-oil is held at the sliding surface of the test piece by a neodymium magnet mounted in the test piece. Three kinds of model tests which are friction single test, leakage single test, and friction and leakage simultaneous test to investigate the influences of pressing force, rotational speed and upstream pressure on the gas leakage from the sliding surface and the friction at the sliding surface are examined. The results showed that the friction slightly decreased in the Stribeck curve by using the diluted the magnetic nano-oil comparing with the base oil in the friction single test. However, the remarkable difference in the friction and leakage between magnetic nano-oil and the base oil under the orbiting motion was not observed in the friction and leakage simultaneous test in this stage.

1. INTRODUCTION

Refrigeration and air conditioning equipment is utilized all over the world, and its demand continuously increases. Therefore, the energy consumption by refrigeration and air conditioning equipment occupies the large part of total energy consumption, and the improvement of the efficiency is strongly required. Particularly, a refrigerant compressor, which is a component of refrigeration and air conditioning equipment, consumes about 80% of the total energy of the refrigeration cycle. The improvement of the efficiency in the refrigerant compressor directly leads to the energy saving in the refrigeration and air condition equipment. There are a lot of studies on improvement of efficiency in the refrigerant compressor for reducing energy consumption for long time (Hirayama *et al.* (2018), Sato *et al.* (2018) etc.), and the improvement faces the limitation. Therefore, the innovative technologies which is different from the existing technology are strongly required for higher efficiency of the refrigerant compressor.

Refrigerant compressor is a device to compress refrigerant and discharge it at high pressure by reciprocating motion of piston or rotary motion of blade and rotor. To improve the efficiency in compressor, it is necessary to reduce friction on the sliding surface and leakage of refrigerant in compressor. However, if the sliding surface is pressed hard, leakage of refrigerant in compressor can be reduced while the friction should increase. Generally, there is trade-off relationship between leakage of the refrigerant and friction on the sliding surface in compressor. In our proposal of this present study, a magnetic nano-oil, which is a dispersion of ferromagnetic nanoparticles stably dispersed in a refrigeration oil, is applied to refrigerant compressor to solve this trade-off problem and improve the efficiency.

The magnetic nano-oil is a kind of a magnetic fluid which is the dispersion of ferromagnetic nanoparticles in base liquid such as water or kerosene. Therefore, the magnetic nano-oil has similar characteristics to the magnetic fluid, and reacts by applying magnetic field. The magnetic fluid has unique characteristics under the magnetic field; change in the physical properties such as viscosity, react and keep by the magnetic field, etc. By applying these unique properties, the magnetic fluid is actual use for sealing technology.

Refrigeration oil is generally used in refrigerant compressor for lubrication. In the refrigerant compressor, oil film is formed on the contact surface by refrigeration oil, and this oil film works effectively to reduce friction on the sliding surface, abrasion of the base plate and leakage of refrigerant. In this decade, a nano-oil, which is a dispersion of nano-particles in base lubrication oil, is investigated to aspire further improvement of energy consumption of the refrigerant compressor. Especially, the following effect can be expected by using nano-oil in the refrigerant compressor; tribological effect at the sliding surface and sealing effect of leakage of refrigerant. For instance, Lee et al. (2009) evaluated the lubricity of nano-oil containing fullerene nanoparticles, and reported that the lowering of friction coefficient was confirmed. They concluded that the cause of the lowering of the friction coefficient was the polishing effect generated between the nanoparticle and the sliding surface. Ashwin et al. (2013) prepared Al_2O_3 nano-oil with different concentration, and carried out the thrust ring friction test. The results showed that there was an optimum particle concentration for friction reduction effect.

On the basis of this background, we propose that magnetic nano-oil is applied to refrigerant compressor to aim further improvement of the efficiency in refrigerant compressor compared with the existing technologies. Concretely speaking, the magnetic nano-oil holds at only the sliding surface in the compressor by magnetic field, and simultaneous reduction of both friction on the sliding surface and leakage of refrigerant is expected by the tribological effect and sealing effect of magnetic nano-oil under magnetic field. In addition, if the lubricating oil can be held at only necessary part in the compressor, the oil circular system could be unnecessary in the actual refrigeration cycle, and the oil circulation loss in the system can be reduced.

Regarding magnetic nano-oil, Li *et al.* (2020) arranged the micro magnet array on the friction surface, and tested the bearing force and lubrication behavior of the magnetic nano-oil. They reported that the hydrodynamic lubrication state was obtained under the condition of the load less than the bearing force, and the low friction coefficient could be realized especially in the high rotational speed region by the effect of shear fluidization. Wei *et al.* (2011) reported that there were appropriate magnetic field distribution and, saturation magnetization to reduce effectively the friction coefficient by comparing a base oil with a magnetic nano-oil under an external magnetic field. The existence of appropriate particle concentration is also considered for the magnetic nano-oil.

In this study, to conduct this feasibility study, both friction and leakage are evaluated by using the model test apparatus which is simulated the orbiting motion of a scroll compressor. This model test apparatus can evaluate the gas leakage from the sliding surface and the frictional force at the sliding surface simultaneously or separately. Magnetic nano-oil is adhered to only the sliding surface of the orbiting metal piece incorporating neodymium magnet. The influences of pressing force, rotational speed and upstream pressure on the gas leakage from the sliding surface and the friction at the sliding surface which adheres the magnetic nano-oil are examined.

2. EXPERIMENT

2.1 Consideration of Application of Magnetic Nano-oil to Compressor

Compressors used for vapor-compressing refrigeration system can be classified into reciprocating type, rotary type, scroll type, screw type, and so on. Among them, scroll compressors are used for many air conditioners because they have high efficiency and are silent. The scroll compressor consists of a pair of a fixed scroll and an orbiting scroll with spiral-shaped blade, and the refrigerant in the compression chamber is compressed by the rotating motion of the orbiting scroll. The scroll compressor has many compression chambers from the suction chamber to the discharge chamber, the leakage and friction occurs at the sliding surface of the spiral-shape blade between each chamber.

Therefore, we focused on the scroll type compressor and considered magnetic nano-oil is held at only the sliding surface of the spiral shape-blade between chamber by magnetic field in this study.

In addition, refrigerant leakage in the scroll compressor can be classified into radial leakage at the scroll sliding surface and tangential leakage of the scroll side surface. Kitamura et al. (2016) compared the radial leakage through the bottom surface of the tip seal with the tangential leakage through the blade side, and reported that the radial leakage through the bottom surface of the tip seal is dominant. In this study, we measured the radial leakage and the friction at the sliding surface of the blade tip of the scroll wrap with keeping magnetic nano-oil at this sliding surface in model experiment.

2.2 Experimental Apparatus

Figure 1 shows an outline of the experimental setup. The experimental apparatus is simulated the orbiting motion of a scroll compressor, and can evaluate the gas leakage and the friction at the sliding surface simultaneously with changing pressing force, rotational speed, and upstream pressure. A base plate is set on an orbiting plate which is simulated the orbiting motion of the scroll compressor. The orbiting plate rotates by the inverter-controlled induction motor through the crankshaft and coupling, and the rotational speed can be controlled by inverter. A test piece is mounted on the base plate by a center pin and pressed by a cantilever via linear rod. The vertical force applied to the test piece can be measured by the load cell mounted between cantilever and linear rod. The center pin is designed to contact with the gravity center of the test piece holder, and the test piece can be, therefore, pressed to the base plate uniformly and parallelly.

Figure 2 shows the detailed diagram of the holder for holding the test piece and measurement of friction force. The test piece is held under this holder and is pressed by center pin from the upper side of the holder as shown in Fig. 1. This holder is sandwiched by the micrometers and lock bolts via the loadcells in the *X*-direction and *Y*-direction separately. The micrometers and lock bolts are used to adjust the test piece to the center position. The friction force of the sliding surface between the test piece and the base plate can be measured directly by load cells attached on this holder. A linear guide is installed between the holder and the load cell to cancel the tangential force. Three load cells are set in *Y* axis to confirm the rotational moment in *Z*-axis is zero.

Because the base plate has the orbiting motion, the measured friction force in *X*-direction and *Y*-direction has sinusoidal change and 90° of the phase differences. The friction force generated between the test piece and the base plate can be calculated by the following Equation (1).

$$F = \sqrt{{F_x}^2 + {F_y}^2} \tag{1}$$

where, F_x and F_y are the friction force in *X*-direction and *Y*-direction, respectively.

This experimental apparatus also reproduces the pressure chamber of the scroll compressor by pressurizing the inside of the test piece with nitrogen gas. The nitrogen gas is supplied from the gas cylinder to the inside of the test piece via the gas supply hole shown in Fig. 2, and the outside of the test piece is atmospheric condition. The gas pressure inside the test piece is controlled by the regulator, and the gas leakage from the sliding surface between the test piece and the base plate is measured by flow meter attached downstream of the gas cylinder.

2.3 Test Piece and Holding Method of Magnetic Nano-oil

Figure 3 shows a cross-sectional diagram of the test piece. The bottom plate in this figure corresponds to the base plate as explained above. The part protruded downward from the bottom side of the test piece is pressed to the base plate and become the sliding surface. Both the test piece and the base plate are made by SUS303 which is the non-magnetized stainless, because magnetic nano-oil should be held at only the sliding surface and other part must not react by magnetic field. To hold magnetic nano-oil at only the sliding surface, the circular groove was dug at the upper point of the sliding surface, and a neodymium ring magnet was arranged to this groove with using magnetized yoke which is made by SUS430 as shown in Fig. 3. Magnetized yoke is a cap of the neodymium magnet and has a role to concentrating the magnetic gradient at only the sliding surface of the test piece. Thus, Fig. 4 shows a photograph of the actual application of magnetic nano-oil on the sliding surface of the test piece. It can be confirmed that the magnetic nano-oil is held at only the sliding surface by the magnetic force. The magnetic field intensity at the sliding surface is 56.2 mT.

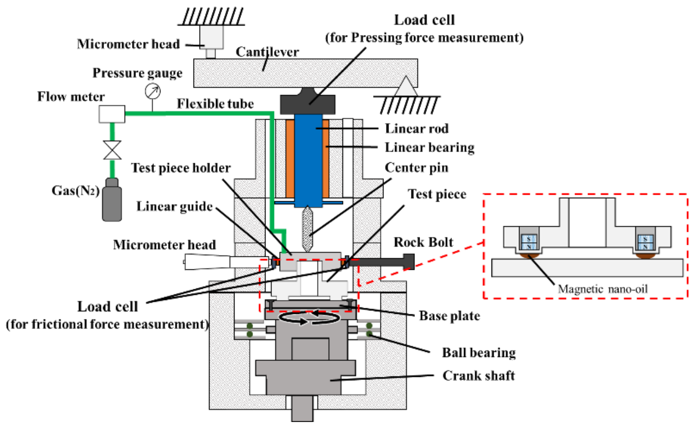

Figure 1: Experimental apparatus.

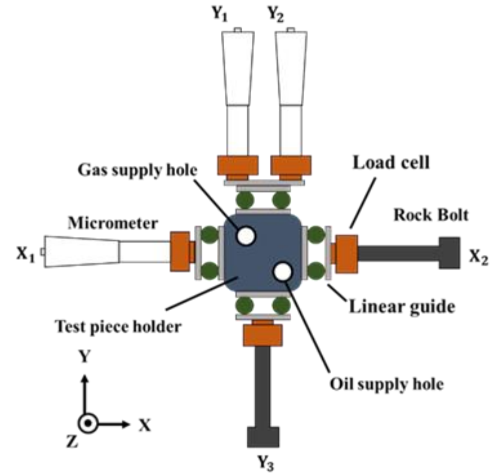

Figure 2: Detailed diagram of the test piece holder.

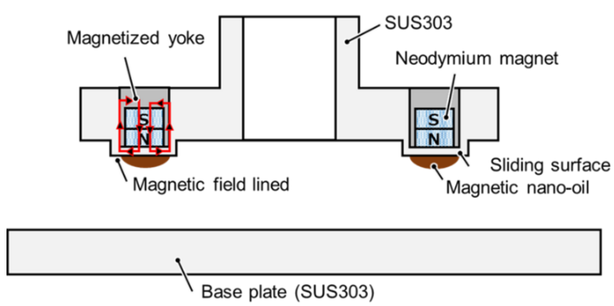

Figure 3: Test piece.

Figure 4: Application of magnetic nano-oil to the test piece.

2.4 Test fluid

Poly Alpha Olefin (PAO) and PAO-based magnetic nano-oil were used as test fluids in this study. PAO-based magnetic nano-oil is produced by a magnetic fluid manufacturer, and thus, this test magnetic nano-oil has good long-time stability. PAO is a synthetic oil which has similar characteristics to a mineral oil. Although PAO is not used as a refrigeration oil in general, the test magnetic nano-oil has excellent dispersion of magnetic nano-order-particles in base oil. Therefore, we used these test fluids in this model test.

The original test magnetic nano-oil has 45 wt% weight concentration of magnetic particles. We used also diluted the test magnetic nano-oil which has 20 wt% in this study. These test fluids under no magnetic field are named as “Base-oil,” “Mag-oil 45wt n/m,” and “Mag-oil 20wt n/m”. The “n/m” indicates no magnetic field, while “w/m” means with magnetic field, and we expressed as “Mag-oil 45wt w/m” and “Mag-oil 20wt w/m” if the magnetic field is applied to the magnetic nano-oil. The volume fraction, viscosities of each test fluid are listed in Table 1. The viscosity of magnetic nano-oil under no magnetic field was estimated by the following Equation (2).

$$\frac{\eta}{\eta_s} = \left(1 - \frac{5}{2}\phi_v + b\phi_v^2\right)^{-1} \tag{2}$$

η_s is viscosity of the solvent, and ϕ_c is particle volume concentration. where b is given by the following Equation (3):

$$b = \frac{\frac{5}{2}\phi_c - 1}{\phi_c^2} \tag{3}$$

here, ϕ_c is the critical volume concentration, and the viscosity of the magnetic fluid increases with the volume concentration of the dispersed magnetic particles under no magnetic field.

In the case of magnetic nano-oil (i.e. magnetic fluid), the viscosity increases apparently when the external magnetic field is applied to the magnetic nano-oil. The apparent viscosity increases depending on the share rate when magnetic fluid flows. When the shear rate is sufficiently small and the external magnetic field is applied perpendicular to the flow direction, the increase value of the apparent viscosity $\Delta\eta$ of the magnetic fluid is expressed by the following Equation (4). (Odenbach et al., 2002)

$$\eta_r = \frac{3}{2}\phi'\eta_0 \frac{\alpha - \tanh\alpha}{\alpha + \tanh\alpha}\langle \sin\beta^2 \rangle \tag{4}$$

Where, ϕ' is the volume concentration of the particles in the fluid, η_r is rotational viscosity, η_0 denotes the viscosity of the fluid, and β is the angle between vorticity and field direction, and α is the ratio of magnetic torque and thermal energy under the magnetic field given by,

$$\alpha = \frac{\mu_0 mH}{kT} \tag{5}$$

Here, μ_0 is permeability in vacuum space, m is the magnetic moment of the particle, H is applied magnetic field intensity, k is the Boltzmann constant and T is temperature. The apparent viscosity of the magnetic nano-oil under the magnetic field was estimated by the upper equations, and listed in Table 1.

Table 1: Viscosities of base-oil and magnetic nano-oil

	Base-oil	Mag-oil 45wt n/m	Mag-oil 45wt w/m	Mag-oil 20wt n/m	Mag-oil 20wt w/m
Viscosity	5	27	34	12	15
Particle mass concentration [%]	-	45		20	
Particle volume concentration [%]	-	11.8		5.0	

3. RESUITS AND DISCUSSIONS

3.1 Pre-conditioning Interim Operation

In the experiments, three kinds of model tests were conducted; Friction single test, Leakage single test, Friction and leakage simultaneous test. Before each model test, pre-conditioning interim operation was carried out for 180 minutes to satisfy the initial condition for each model tests.

Figure 5 shows the time series change in the friction coefficient during the pre-conditioning interim operation. The horizontal axis is elapsed time from the start of the pre-conditioning test, and the vertical axis is friction coefficient. The preconditioning interim operation was conducted under the contact load of 500 N lubricated the sliding surface with base oil and magnetic nano-oil with applying magnetic field. The results of three same pre-conditioning tests for base oil and 45 wt% of the magnetic nano-oil under magnetic field are shown in this figure. This figure indicates that the initial friction of the beginning of the pre-conditioning operation is rather large, but rapidly decreases and then is saturated at small value for the base oil, while the initial friction is small and hardly changes with elapsed time for 45 wt% magnetic nano-oil applied magnetic field. Also, 20 wt% magnetic nano-oil under magnetic field has same tendency with 45 wt% magnetic nano-oil. Regarding the tendency of the base oil, this seems that the contact pressure and the friction decreases due to the increase of the real contact area by the elastic deformation or plastic deformation of the protrusion of the sliding surface microscopically with elapsed time. After enough time, the microscopic deformation of the contact surface converges and the friction coefficient becomes stable. In contrast, in the case of magnetic nano-oil, the configuration that the friction hardly changes with elapsed time means that the wear is less likely to occur because magnetic nano-oil is held at only the sliding surface and protects effectively the surface from the wear.

3.2 Friction single test

As the friction single test, the friction at sliding surface under the orbiting motion was measured without pressurized condition. Fig. 6 show relationship between the friction coefficient and contact force when the sliding surface is

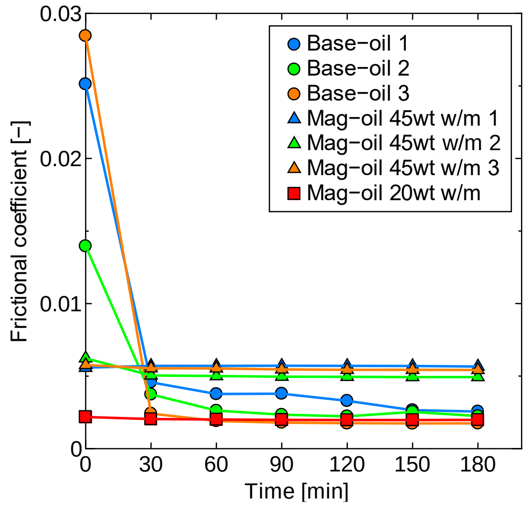

Figure 5: Time series difference of the frictional coefficient for the pre-conditioning interim operation.

lubricated with base oil, 20 wt% and 45 wt% of magnetic nano-oil under the magnetic field. The rotational speed was kept at 300 rpm, the contact force was varied 50, 150, 250, 350 and 450 N. Friction experiments are carried out 3 times for base oil and 45 wt% of magnetic nano-oil, and it is confirmed that the results have good repeatability. The friction coefficient decreases with increasing the contact force. This tendency is the common feature in the frictional test for the hydrodynamic lubrication regime. The frictional coefficient of 45 wt% magnetic nano-oil under magnetic field is larger than that of base oil. This is because the viscosity of magnetic nano-oil is larger than that of the base oil, and the viscosity of magnetic nano-oil increases apparently by applying magnetic field. In contrast, although the viscosity of 20 wt% magnetic nano-oil is larger than that of base-oil, the frictional coefficient of 20 wt% of magnetic nano-oil is consistent to the base oil. This means that the 20 wt% magnetic nano-oil with magnetic field effectively works to reduce the frictional coefficient without the influence of the viscosity. It is also considered that an optimum particle concentration exists for maximizing the effect of magnetic nano-oil. Therefore, to compare the effect of both base oil and magnetic nano-oil under magnetic field fairly, it is necessary to evaluate the friction with canceling the influence of viscosity. Moreover, although the results are not displayed here, the friction single experiments carried out by changing the rotational speed of 225, 375, and 450 rpm, and these results have almost similar tendency to the result for 300 rpm as explained above.

To evaluate the tribological feature, the Stribeck curve is commonly used. The Stribeck curve is the relationship between the frictional coefficient and Sommerfeld number, and makes it possible to discussion about the tribological feature and classify the lubrication regimes. The Sommerfeld number for the lubricating condition with a line contact is defined as;

$$S = \frac{\eta V}{F_c / L} \tag{6}$$

where, η is oil viscosity, V is turning speed, and F_c is contact force, and L is sliding surface length, respectively.

Figure 7 shows the Stribeck curve described by the all experimental results of the friction single test including other rotational number such as 225, 375, and 450 rpm. This figure indicates that the lubrication regime of the base oil is the mixed lubrication state where the Sommerfeld number is comparatively small, and it shifts to the hydrodynamic lubrication state with increasing the Sommerfeld number corresponding to the large contact force and the high sliding speed. In the case of 45 wt% magnetic nano-oil with magnetic field, it can be seen that the lubrication regime is thorough out the hydrodynamic lubrication state in this experimental condition, and the configuration of results ranges along the results of the base oil with almost same inclination in the large Sommerfeld number region.

On the other hand, in the case of 20 wt% magnetic nano-oil with magnetic field, this figure clearly indicates that the lubrication regime is also the hydrodynamic lubrication state same as 45 wt% magnetic nano-oil, and the frictional coefficient of the 20 wt% magnetic nano-oil is quite smaller than that of base oil and 45 wt% magnetic nano-oil at the same Sommerfeld number. Therefore, we can confirm the effect of the magnetic nano-oil on the friction by comparing in the Stribeck curve.

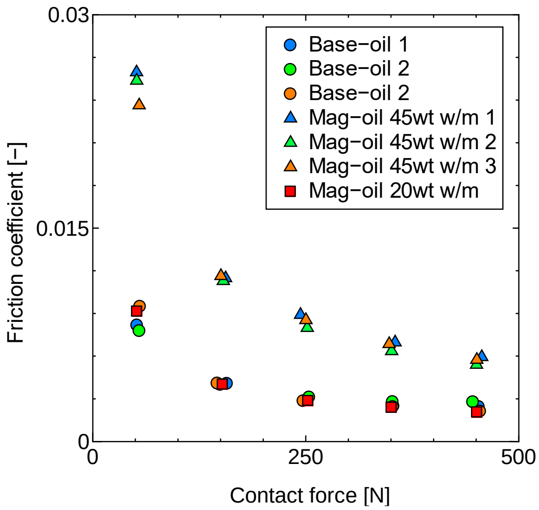

Figure 6: Relationship between contact force and friction coefficient at 300 rpm.

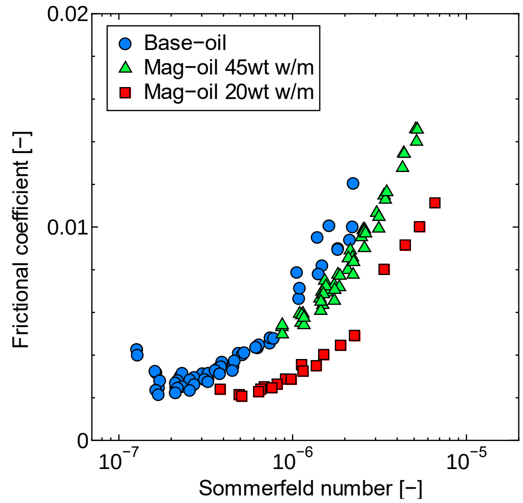

Figure 7: Stribeck curve for friction single test.

3.3 Leakage Single Test

As the leakage single test, the leakage from the sliding surface without the orbiting motion of the base plate was measured. First of all, when the pressure is applied to the inside of the test piece, the contact force should be calculated with considering the influence of the pressure. The conceptual model for calculating the contact force is shown in Fig. 8. When the nitrogen gas is supplied inside the test piece, the contact force on the sliding surface between the test piece and the base plate can be obtained by subtracting the pressure force acting in the test piece from the vertical force F_z measured by the load cell attached on the linear rod. The pressure force acting on the test piece F_{pb} is calculated by sum of the pressure force acting inside of the test piece and the sliding surface. The pressure distribution on the sliding surface is assumed to decrease linearly from the inside pressure to the atmospheric pressure. Therefore, the contact force F_c acting on the sliding surface is obtained by the following Equation (7).

$$F_c = F_z - F_{pb} = F_z - \left\{ P\frac{\pi}{4}d_{in}^2 + \frac{P}{2}\frac{\pi}{4}(d_{out}^2 - d_{in}^2) \right\} \tag{7}$$

where, P, d_{in}, and d_{out} are the upstream pressure, the inside diameter of the sliding surface, and the outside diameter of the sliding surface, respectively. In this experimental apparatus, since the downstream of the sliding surface is opened to the atmospheric pressure, the average pressure of upstream and downstream is obtained as 1/2 of the upstream pressure.

Figures 9, 10 and 11 show the relationship between contact force and the flow rate of leakage at upstream pressures of 0.2, 0.3 and 0.4 MPa, respectively. In these figures, the legend “No-lubricant” indicates the state which lubrication oil is not used. These figures clearly indicate that the leakage occurs even under the large contact force condition if the lubrication oil is not used, while the leakage is less likely to occur under the small contact force by using lubrication oil. This is the common situation. Comparing base oil with the magnetic nano-oil, in the case of small upstream pressure such as 0.2 MPa, there are no leakage for both base oil and magnetic nano-oil. On the other hand, in the case of larger upstream pressure such as 0.3 and 0.4 MPa, the gas leakage occurs at almost same contact force. Therefore, we can not confirm the remarkable sealing effect by using magnetic nano-oil adhered the sliding surface in this stage. This is because although magnetic fluid is used to the sealing technology, the pressure resistance is relatively small because of small saturated magnetization.

3.4 Friction and Leakage Simultaneous Test

Finally, we would like to discuss the leakage and friction under the orbiting motion when the magnetic nano-oil is applied to the sliding surface. The friction and leakage simultaneous tests were carried out with decreasing the contact force less than 200 N under the condition which is the upstream pressures of 0.1 MPa, 0.2 MPa, 0.3 MPa and 0.4 MPa, the rotational speeds of 225 rpm, 300 rpm, 375 rpm and 450 rpm.

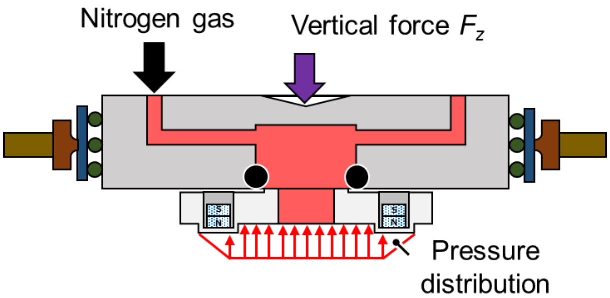

Figure 8: Conceptual model of the pressure distribution for calculation of pressure force.

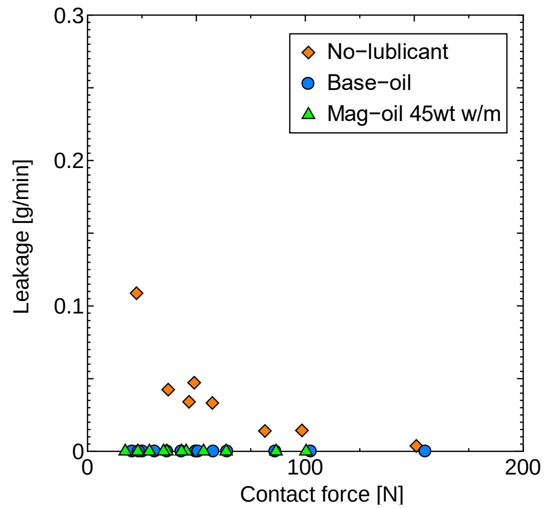

Figure 9: Relationship between contact force and gas leakage at 0.2 MPa.

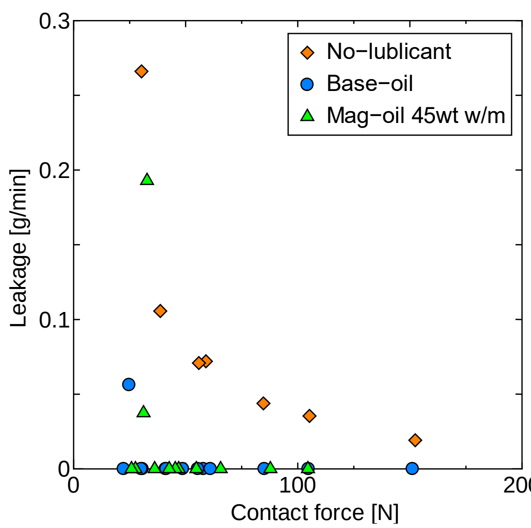

Figure 10: Relationship between contact force and gas leakage at 0.3 MPa.

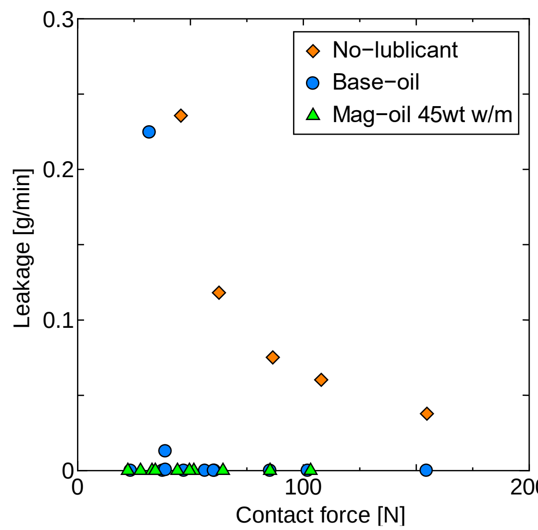

Figure 11: Relationship between contact force and gas leakage at 0.4 MPa.

Figure 12 shows the relationship between the gas leakage and contact force under the orbiting motion. When the upstream pressure is 0.3 MP and 0.4 MPa, the gas leakage occurs for both the base oil and the magnetic nano-oil with magnetic field at the almost same contact force. Therefore, the remarkable difference in the gas leakage is not observed under the orbiting motion. Moreover, the gas leakage under the orbiting motion occurs more easily compared with the gas leakage without orbiting motion as described in previous section because the apparent gap of the sliding surface continues to change by the movement of the seal point.

Figure 13 shows the relationship between the frictional coefficient and the contact force at 300 rpm of the rotational speed. This figure indicates that the similar tendency shown in Fig. 6 is obtained under the orbiting motion, but the fluctuation of the obtained frictional coefficient is relatively large because the base plate continues to move. In addition, when the gas leakage occurs, the frictional coefficient becomes very small because the test piece floats due to the pressure force. Fig. 14 shows the Stribeck curve for friction and leakage simultaneous test. As shown in this figure, it can be seen that the configuration of the Stribeck curve is similar to the results of the friction single test as shown in Fig. 7. Only when the gas leakage occurs, the frictional coefficient becomes small for both base oil and magnetic nano-oil. In this stage, the remarkable difference in the friction also is not observed.

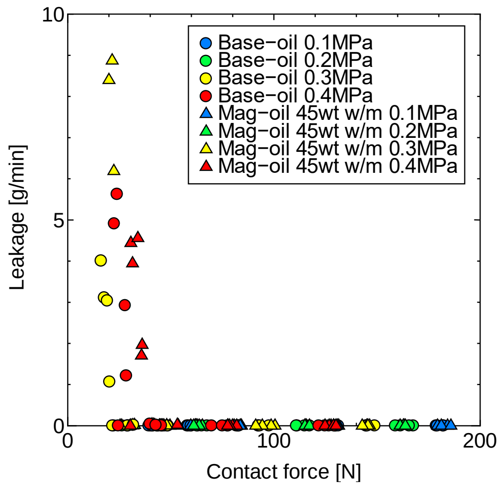

Figure 12: Relationship between contact force and gas leakage by friction and leakage simultaneous test.

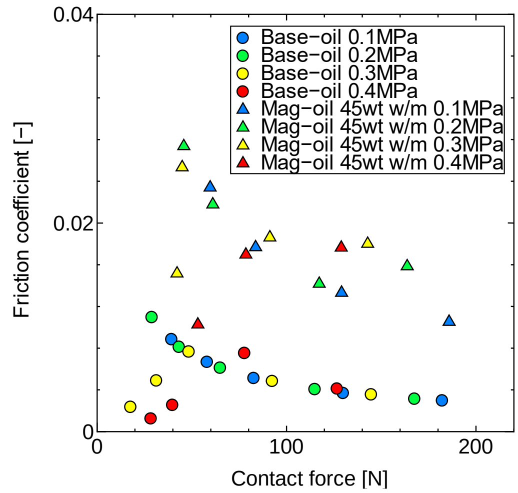

Figure 13: Relationship contact force and friction coefficient at 300 rpm by friction and leakage simultaneous test.

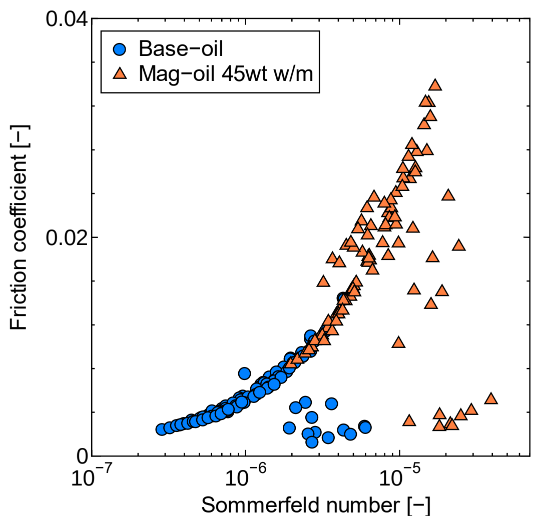

Figure 14: Stribeck curve by friction and leakage simultaneous test.

The simultaneous experiment by using the diluted magnetic nano-oil was not carried out because we have changed the holding method of the magnetic nano-oil and moved to the next experiments. However, taking the results of the single tests and simultaneous tests by 45 wt% of magnetic nano-oil into account, it is expected that the friction at the sliding surface can be reduced with considering the viscous effect similar to the friction single test, but it seems to be difficult to reduce the leakage by using 20 wt% of magnetic nano-oil.

In this stage, it is difficult to clarify the effect of the magnetic nano-oil on the friction and leakage under the orbiting motion like a compressor. However, since the merit of using magnetic nano-oil is that the lubrication oil keeps at only the sliding surface, not only the lubrication oil needs not to be supplied to the sliding surface but also it is possible that wear could be suppressed because of the elastic effect of the magnetic nano-oil under the magnetic field, and lubricating effect could keep for long time. Further experiments with changing holding method of magnetic nano-oil at the sliding surface, the base oil of the magnetic nano-oil and properties of the magnetic nano-oil such as concentration of magnetic nano-particles, viscosity and saturated magnetization are needed to improve the efficiency of the refrigerant compressor by using magnetic nano-oil in the future.

4. CONCLUSIONS

Magnetic nano-oil was applied to the refrigerant compressor for improvement of the efficiency. We propose that the magnetic nano-oil holds at only the sliding surface in the compressor by magnetic field, and model test for evaluation of friction at the sliding surface and the leakage from the sliding surface have been conducted. The following conclusions were obtained.

1. In the pre-conditioning interim operation, the initial friction of the beginning of the pre-conditioning operation is rather large, but rapidly decreases and then is saturated at small value for the base oil, while the initial friction is small and hardly changes with elapsed time for 45 wt% and 20 wt% magnetic nano-oils under magnetic field.
2. The result of the friction single test shows that the friction slightly decreased with considering the Stribeck curve by using the 20 wt% magnetic nano-oil under the magnetic field comparing with the base oil.
3. The result of the leakage single test shows that the leakage occurs even under the large contact force condition if the lubrication oil is not used, while the leakage is less likely to occur under the small contact force by using lubrication oil. However, the remarkable sealing effect by using magnetic nano-oil adhered the sliding surface in this stage is not observed comparing with the base oil.
4. From the friction and leakage simultaneous test, the remarkable difference in the friction and leakage between magnetic nano-oil under the magnetic field and the base oil was not observed under the orbiting motion in this stage. Therefore, further experiments with changing holding method of magnetic nano-oil at the sliding surface, viscosity and saturated magnetization of magnetic nano-oil are needed to optimize the application of the magnetic nano-oil to compressor in the future.

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