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Estimation, of the Starting Torque, of Refrigerant Rotary Compressors

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ABSTRACT

Estimation of starting torque is very important for motor design and for improvement in compressor efficiency. Especially, when compressors are restarted after a period of inoperation, motors sometimes meet large starting torque. The assumed reasons are as follows. The compressors temperature is sometimes lower than any other parts of the refrigerant cycle. In this case, the refrigerant tends to collect in the compressor and is condensed there. So, the oil between the lubricated surface is dissolved in the refrigerant and removed by this refrigerant liquid. Furthermore, the unbalanced magnetic pull force in induction motors makes the starting torque larger.

An experimental model has been developed for measuring torque. Using this apparatus, torque was measured at various pull forces, various oil conditions, and with variously treated shafts. A mathematical model was made for analyzing the starting torque. Based on this analysis, it is possible to predict individual torques under various conditions, using the value of friction coefficients obtained from experimental data, and the value of pull force. The theoretical analysis, based on the mathematical model for starting torque, agrees fairly well with experimental data obtained from using actual compressors. The influences of compressor dimension, shaft surface treatment, mechanical air gap in the motor, compressors blade spring on starting torque are found qualitatively and quantitatively by this study.

INTRODUCTION

An air conditioning unit consists of four elements, those are, a compressor, condenser, capillary (or expansion valve) and evaporator, as shown in Fig. 1. As the thermal capacity of the compressor is usually larger than any other parts of the refrigerant cycle, the presence of sunlight always causes large quantities of refrigerant to migrate into the compressor and dilute the oil. The migration path of refrigerant in the rotary compressor is shown in Fig. 2. There is no restriction between the condenser and the compressor case, so the refrigerant can easily migrate into the compressor. The liquid level is often two or three times as much as oil level in running. As the refrigerant dilutes the oil between the lubricated surfaces, the friction coefficients in moving parts become larger. Accordingly, compressor motors require large starting torque.

Little information is available concerning the starting torque for rotary compressors. So, the starting torque has been clarified by using rolling piston type hermetic rotary compressors. To analyze the starting torque mechanism in several conditions, a mathematical model was made up. This model includes factors concerning compressor dimension, motor pull force, blade spring force and the weight of moving parts. Test apparatus to measure the rotating torque was developed and confirmed to be very useful in estimating the starting torque for the rotary compressor.
mechanism. Furthermore, it was found that the friction coefficients for shafts and motor pull force are very important in determining the starting torque. Their details are discussed in the following.

MATHEMATICAL MODEL

A schematic model of the starting torque for a rolling piston type rotary compressor is shown in Fig. 3. Following assumptions are used for simplicity to calculating the starting torque.

1. Inertia forces for moving parts are neglected, because interest is focused on the instantaneous movement at low speed in starting.
2. The force needed to compress the refrigerant is neglected, because the suction pressure is nearly equal to the discharge pressure just before starting.
3. A shaft is assumed to be rigid and has no deflection.
4. Friction forces of roller and blade are neglected since they are very small.
5. There is no force considered due to gravity between the roller and the crank.
6. The shaft contacts two points, the upper end of the main bearing (B in Fig. 3) and the lower end of the sub bearing (A in Fig. 3). The motor pull force ($F_{mol}$) is larger than the blade spring force ($F_v$).

On the above assumptions, the starting torque is calculated by using the motor pull force, spring force and gravity of the motor and shaft. Spring force ($F_v$) is shown as a function of blade displacement ($y$).

\[ F_v = ky + F_{v0} \]  
\[ y = e(1 + \cos \theta) \]

where:
- $k =$ spring constant
- $F_{v0} =$ spring force at the bottom dead center
- $e =$ eccentricity of the crank
- $\theta =$ crank angle from blade position

The motor pull force acts upon the center of the motor in radial direction of the smallest gap. The reaction forces for main bearing ($R_1$) and sub bearing ($R_2$) are gained by solving the force and momentum equations in each of two mutually perpendicular direction.

\[ R_1 = \frac{F_{mol}}{L - \frac{L}{k_1}} \sqrt{1 + 2C_1 \cos \theta + C_1^2} \]  
\[ R_2 = \frac{L}{L - \frac{L}{k_1}} F_{mol} \sqrt{1 + 2C_2 \cos \theta + C_2^2} \]

Fig. 2 Migration Path of Refrigerant

Fig. 3 Schematic Model of Starting Torque
CHARACTERISTICS OF MOTOR

It is known that the radial magnetic pull (RMP) occurs in eccentric direction due to rotor eccentricity. RMP studies have mainly concentrated upon (1) Intensity of structure, that is, shaft deflection, gap beat etc. (2) Vibration, noise and durability of bearing. However, it was found to strongly affect the starting torque for compressors.

Using a strain gage put on the main-bearing, the motor pull force was measured. The relation of RMP and rotor eccentricity gained by this method is shown in Fig. 4. It is known that the pull force is proportional to the rotor eccentricity. When rotor eccentricity for an induction motor is small, these relations are shown by the following equation.

\[ F_{m0} = C_m \Delta \delta/\delta \]  

where:

- \( C_m \): constant
- \( \Delta \delta \): eccentricity
- \( \delta \): mechanical air gap

As the rotor eccentricity occurs due to parts inaccuracy and mounting inaccuracy, RMP acts upon the rotor when compressors start.

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Minimum voltage required to start compressors is usually measured to check the starting torque. Figure 5 shows the relation of the starting voltage and torque. In this example, to start at 85 volts, mechanism torque needs to be below 5.6 kg·cm with Starting Capacity (SC), but 3.6 kg·cm without SC. When friction coefficients for moving parts are 0.25, motor pull force for starting should be below 5 kg·cm and rotor eccentricity should be below 0.14 mm. As shown in the above example, rotor eccentricity influences the magnetic pull force and the starting torque for rotary compressors.

**COEFFICIENT OF FRICTION IN COMPRESSOR PARTS**

In estimation of the starting torque, one of the important factors is coefficient of friction in the moving parts of compressors, particularly between the shaft and the bearing. In order to estimate it, two kinds of shaft treated with phosphoric acid chloride (Specimen A, B) and a shaft coated with solid film lubricant (Specimen C) have been prepared. The former is MnHPO₄ generally used for protecting from abrasion. The latter is MoS₂. The test shafts were made from cast iron with surface finish of about 1.6 μm Rₐ and these surfaces were treated. SEM photographs and profiles of test shaft surfaces are shown in Fig. 6. For these shafts, coefficient of friction values were measured with the bearing combined with and without refrigerant oil (viscosity is 50 cp at 40°C). Figure 7 shows the test results under several loads. The coefficients of friction in either shaft is mostly less than 0.2 with oil. However, when oil is not used these coefficients have a tendency to be large. In case of shaft A, coefficient from 0.25 to 0.3, are 50 percent larger without than with oil. On the other hand, shaft C gives the best results, which are as low as 0.15, with and without oil. In addition, coefficient of friction values in the other moving parts of compressors were measured and the same tendency as that for shaft A was obtained.
EXPERIMENTAL APPARATUS FOR TORQUE AND TESTING METHOD

An experimental apparatus for measuring the rotating torque, as shown in Fig. 8, has been produced. A rotary compressor mechanism that consists of a cylinder, a roller, a blade, a shaft and bearings is set upside down differing from actual setting in center of the apparatus. The rotating torque is measured by a load transducer as reaction force of a driving motor. Generally, it is known that friction force depend on rotation speed. However, driving motor is set up at constant low speed of 1 r.p.m., because it seems that the starting torque concerns with static friction force. Moreover, a spring force is used instead of radial magnetic pull on the center of axial direction. Using this apparatus, the rotating torque is recorded at the rotation angle obtained by a potentiometer on an X-Y recorder. A schematic diagram of the torque measuring system is shown in Fig. 9.

EXPERIMENTAL RESULTS OF TORQUE

Figure 10 shows typical torque curves for Specimen A, where (a) is with and (b) is without oil, and theoretically calculated results, where coefficients of friction in every moving part are assumed to be 0.25 or 0.16 constant. As the experimental curves agree fairly well with theoretical analysis, it seems that the torque can be predicted by the theoretical analysis.

Then, the torque values were measured under several conditions. The measured torque variations, with or without oil, are shown in Fig. 11, plotted against the specific pull force. Values obtained are compared with theoretical results. In this case, the maximum values are selected as the torque. Individual experimental results are in proportion to coefficients of friction in shafts and the pull force, which are apparently important factors in estimating starting torque. The plotted data are in limits from 0.1 to 0.2 as coefficients of friction with oil, versus from 0.2 to 0.3 without oil. Accordingly, the torque is effected by the oil condition.
Moreover, in order to simulate the migration of refrigerant, it was attempted to sink a compressor mechanism filled with oil in refrigerant R113. The relation between the torque and time was investigated. As shown in Fig. 12, the torque, which was as large as the value with oil at first, increased and reached a value as large as that without oil. These phenomena show that the oil between the lubricated surfaces is easily removed by refrigerant. In starting a compressor, it is important to consider the migration of refrigerant sufficiently.

STARTING TEST ON ACTUAL COMPRESSORS

Finally, in order to prove whether the developed method to estimate the starting torque is proper or not, the starting test on actual compressors have been carried. So, the effect of motor eccentricity on the starting voltage was investigated, using the coefficient of friction and oil condition as parameters. As shown in Fig. 13, starting voltage tends to increase in proportion to the motor eccentricity and is effected by the coefficient of friction and oil condition. Accordingly, a characteristic of motor can be determined by the dimensions, the coefficient of friction in the moving parts of compressor and the lubricant condition.

CONCLUSION

Several conclusions have been reached as follows:

1. The starting torque is effected by the coefficient of friction in the moving parts of compressors, the lubricant condition and the radial magnetic pull for motors.

2. The theoretical analysis, based on the mathematical model for starting torque, agree fairly well with the experimental date using actual compressors.
(3) The starting mechanism, when compressors are restarted after a period of inoperation, is concerned with the migration of refrigerant. This has been confirmed experimentally.

(4) It has been confirmed experimentally that the radial magnetic pull increases approximately in proportion to motor eccentricity.

(5) It is obvious that, using the estimating method developed in this paper, the starting mechanism in actual compressors is well explained.

(6) This method is effective to design motor and compressor mechanisms.

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