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DEVELOPMENT OF A HIGH EFFICIENCY 2-CYLINDER ROTARY COMPRESSOR FOR ANNUAL PERFORMANCE FACTOR

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ABSTRACT

Recently, residential air conditioner power consumption reduction has been increasingly required in terms of global warming prevention. In Japan, the energy saving guideline index for air conditioners has been changed from the coefficient of performance (COP) measured during rated operation to the annual performance factor (APF), closer to the actual usage condition.

We have made improvements, with APF efficiency enhanced by 6% compared with our conventional 2-cylinder rotary compressor. This paper explains development details of the highly efficient 2-cylinder rotary compressor. To improve efficiency, we optimized the ratio of the cylinder height H to the cylinder bore diameter ΦD (H/ΦD), and reduced the leakage loss from the compression chamber to the suction chamber. Additionally, we adopted a suction piping structure whereby a suction pipe is connected to the thick partition plate splitting the suction gas flow with Y-shaped respectively to the upper cylinder and to the lower cylinder (Y-shaped suction flow split structure). To retain reliability, we designed the high rigidity crankshaft, and were able to reduce friction loss.

INTRODUCTION

The power consumption of residential air conditioners is the leading element of power consumption, constituting 1/4 of household power consumption, meaning achieving savings in such power is vital with global environmental protection in mind (CO_2 emission reduction). In response, the top runner program has been introduced in Japan, based on the 1999 revision of the Law Concerning the Rational Use of Energy, greatly promoting improvement of the coefficient of performance (COP) in cooling and heating rated capacity operations. Recently, the annual power consumption of residential air conditioners has been emphasized, which is important to enhance the annual performance factor (APF) that takes the actual operating time of air conditioners into account. To resolve this issue, the enhanced efficiency of the compressor that constitutes the majority of the power consumption of residential air conditioners is important, while improving efficiency in intermediate capacity operation that is most frequently used during actual operations is most desirable. We adopted new compressor structure/element technologies that are ready for such changes, and achieved higher efficiency over the entire capacity range, including the half-capacity operation resulted an R410A 2-cylinder rotary compressor.

MEASURING CONDITION AND METHOD

The regulations have been changed from COP during rated capacity operation to APF that is closer to actual usage regarding the index of energy saving. Fig. 1 shows the differences in the definition of these energy saving indices. To improve the APF, efficiency improvement needs to be achieved within the actual operation range. In other words, efficiency improvement in the half-capacity operation is essential. For example, if an efficiency improvement of 1% can be obtained in the measurement conditions, the contribution ratio to APF improvement is as shown in Fig. 2 (for our conventional model). The conditions indicate rated and half capacity operations of heating-and-cooling type air conditioner with a cooling capacity of 4.0kW, as shown in Table 1. In particular, the efficiency of the heating half-capacity operation has a high contribution ratio to APF, constituting 50% of the total contribution ratio. As measures to reduce the loss in compressors, higher motor efficiency has been focused upon, such as the adoption of rare-earth magnets, and inverter drive technology.

To enhance efficiency, new ideas for efficiency improvement are required. As one such new idea, we focused on the friction loss and leakage loss in the compression chamber, working toward technological development to improve both mechanical and compression efficiency.

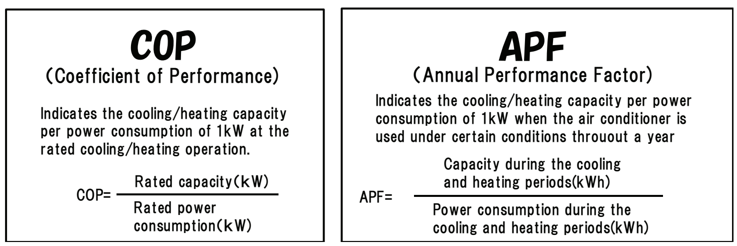


Fig.1: Definition of COP and APF

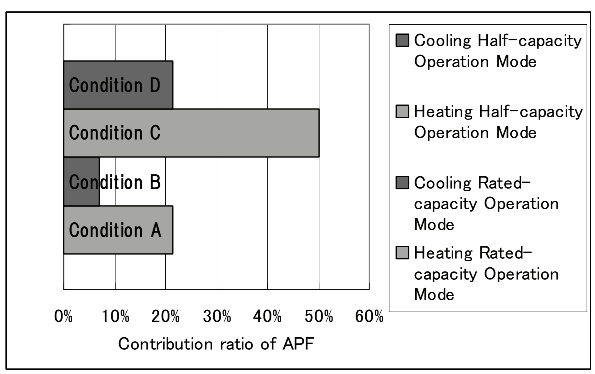


Fig.2: Contribution ratio of APF

Table 1: Calorimeter Test Condition

Air-conditioner operation mode	Heating	Cooling	Heating	Cooling
	Rated-capacity	Rated-capacity	Half-capacity	Half-capacity
Condition	A	B	C	D
Compression ratio	2.8	2.6	2.2	1.8
Revolution [s^{-1}]	59	50	28	18

STRUCTURE AND OVERVIEW OF DEVELOPED COMPRESSOR

Table 2 shows the specifications of the developed 2-cylinder rotary compressor, while Fig. 3 show the cross sections of the structure. The compression mechanical part adopts 2-cylinder rotary structure and in the motor part, a brushless DC motor consisting of a concentrated winding type stator and a rotor embedded with rare earth permanent magnets is applied. The major elemental technologies and features that have been newly developed are as follows:

(1) A thin cylinder with a reduced the ratio of the cylinder height H to the cylinder bore diameter ΦD (hereafter H/ΦD) is adopted. Mechanical efficiency is improved by reducing the friction loss of the crankshaft while retaining the reliability by reducing the axial load.

(2) As a result of adopting the thin cylinder, the compression efficiency is improved by reducing the leakage loss from the radial clearance between the cylinder and rolling piston, and by reducing the top clearance volume of the discharge port.

(3) A suction piping structure whereby a suction pipe is connected to the thick partition plate splitting the suction gas flow with Y-shape respectively to the upper cylinder and to the lower cylinder (Y-shaped suction flow split structure) is adopted. The Y-shape in the partition plate is optimized so that the refrigerant gas can smoothly flow into each of the compression chambers.

Table 2: Specifications of Compressor

Compression type	Hermetic Rotary
Refrigerant	R410A
Displacement	12.8 cm3/rev.
Rotational speed range	9 - 120s-1
Rated-capacity (60s-1)	4.0kW
Nominal power	1.1kW
Inverter	Vector control
Motor type	Brushless DC motor
Pole	4
Motor rotor magnet	Rare-earth (Nd-Fe-B)
Weight	9.5kg
Outside diameter×Height	Φ116×282mm

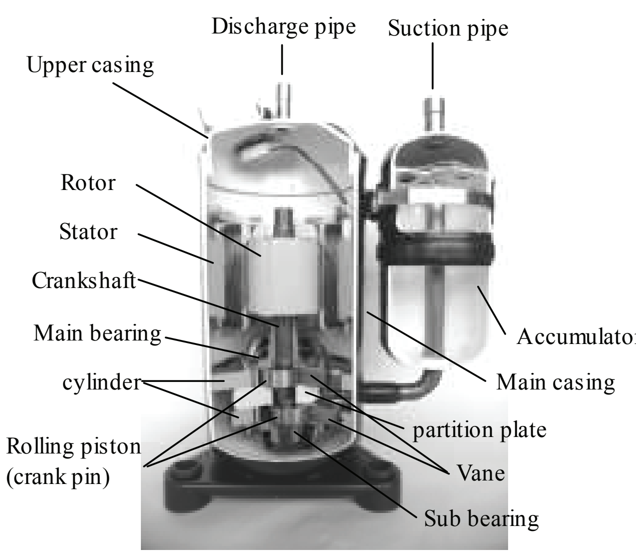


Fig.3: Cross section of developed compressor

DESIGN OF DEVELOPED COMPRESSOR

Mechanical Efficiency Analysis

Figure 4 shows the calculation values of friction loss in our conventional model. The friction loss of each slide part is obtained by the following equation (1).

$$L=\mu\times F\times V \tag{1}$$

Where, L: the friction loss, μ: the coefficient of friction, F: the load, V: the velocity. μ is affected by the lubricant viscosity, load, rotational speed, and clearance, etc, hence our empirically-estimated data is used. In particular, coefficient of friction is corrected for the crank-pin, according to the McKee formula(1) considering that the crank-pin diameter ΦDcr is large compared to the crank-pin length Lcr. The McKee formula indicates that μ rapidly increases as Lcr/ΦDcr becomes smaller than about 0.6. Fig. 4 indicates that the friction loss of the crank-pin constitutes about 55% of the total, implying that reducing the friction loss of the crank-pin would lead to an effective improvement in mechanical efficiency.

To reduce the friction loss of the crank-pin, reduction of the crank-pin diameter ΦDcr is effective because μ and the slide speed can be reduced. However, when the crank-pin diameter ΦDcr is reduced, the sub bearing diameter must also be reduced in order to build the rolling piston into the crankshaft, affecting the reliability of the sub bearing. To resolve this, we maintained the sub bearing reliability and reduced the crank-pin diameter simultaneously; reducing the axial load by adopting the aforementioned thin cylinder and enlarging the crank eccentricity. Fig. 5 show the calculation values of the friction loss of the developed model compared to the conventional model. The friction loss of the crank-pin is reduced by 30% compared to the conventional model in any condition. A reduction of 20% compared to the conventional model can also be expected for the total friction loss.

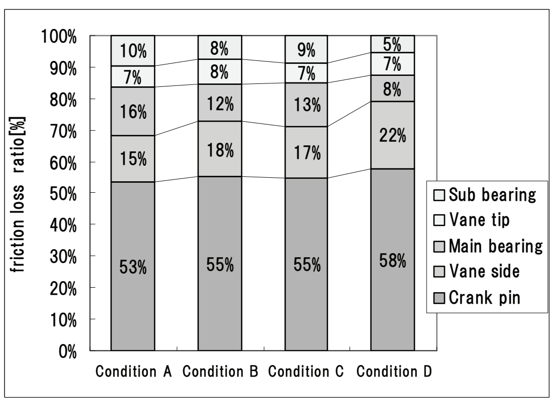


Fig.4: Friction loss ratio of conventional model

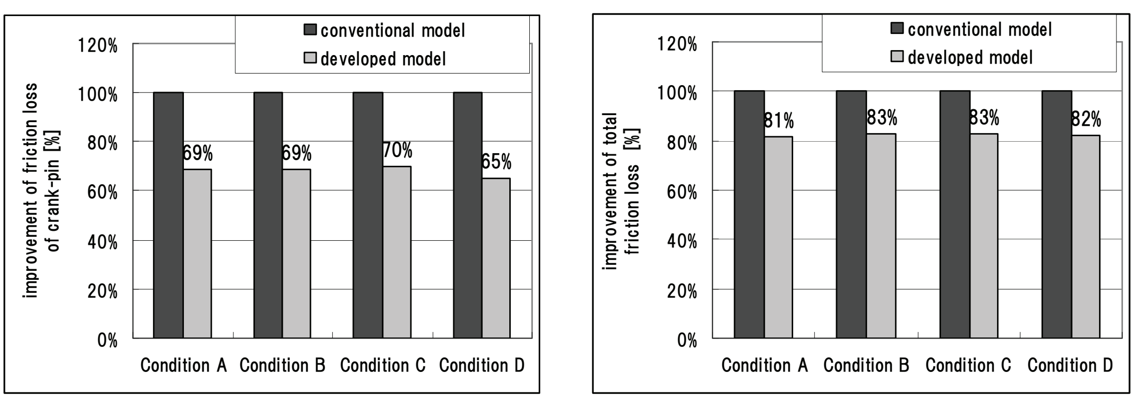


Fig.5: Improvement of friction loss

Compression Efficiency Analysis

The thin-shaped cylinders are also effective in improving compression efficiency by reducing the leakage losses. The leakage losses in the compression chamber can be divided into the following 3 types:

(1) Leakage loss from the radial clearance between the cylinder and rolling piston
(2) Leakage loss from the axial clearance between the bearing and rolling piston
(3) Leakage loss from the axial clearance between the bearing and vane

The above-mentioned set clearances are appropriate values with reliability in mind, and hence cannot generally be reduced to decrease the leakage loss. In addition, the relation of the leakage loss above can be defined as (1):(2):(3)=6 : 1: 1 approximately[2], while the leakage loss from the radial clearance between the cylinder and rolling piston is dominant and represents about 75% of the total. The leakage can be reduced in proportion to the cylinder height H, achieving an effective improvement in compression efficiency. Furthermore, we reduced the top clearance volume in the discharge port part by 66% compared to the conventional model. We achieved this by reducing the valve seat thickness, moving the discharge port position to the interior of the compression chamber.

Maximum Capacity Performance

In inverter control, the supercharge effect caused by the gas inertial motion is generally used to maintain the maximum capacity of the air conditioner[3]. However, for the Y-shaped suction flow split structure, we can't use the supercharge effect because the pressure pulsation is too small. Fig. 6 shows the change of volumetric efficiency due to the compressor rotational speed change in the suction piping structure. In the conventional suction piping structure where each suction pipe is placed on the cylinders, the volumetric efficiency increases dramatically due to the supercharge effect as the compressor rotational speed increases. On the other hand, in the Y-shaped suction flow split structure, the volumetric efficiency does not increase, and stays almost flat, due to the extremely small pressure pulsation.

Consequently, we enlarged the compression chamber volume to compensate for the insufficient maximum capacity due to the supercharge effect for adopting the Y-shaped suction flow split structure. However, small pressure pulsation is intrinsically advantageous in terms of efficiency due to the small suction loss. Therefore, we will be examining measures using higher rotational speed in future.

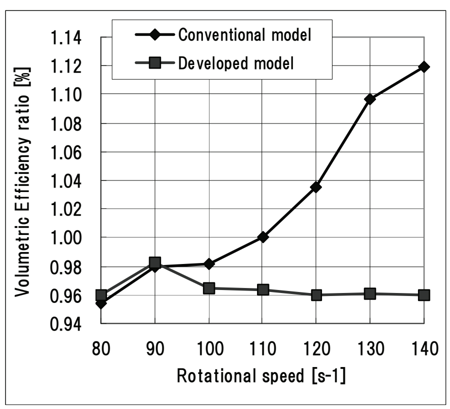


Fig.6: Volumetric efficiency

High Efficiency Motor

The developed motor realized both resources saving and higher efficiency. Fig.7 shows the developed rotor and a conventional rotor. The characteristic of this motor is as follows.

(1) Compact and highly efficient
We reduced the volume by 10% while maintaining the same level of efficiency compared to a conventional model. We changed the magnet layout and its shape so as to gain necessary magnetic force with space constraints.

(2) Resources saving
The insulation between the motor core's slot and coil, film insulation is used, meaning the amount of molded insulation used, which are technically difficult to recycle, can be reduced by 24%.

(3) Selection of a number of turns of winding suitable for half-capacity operation
The number of turns of winding was adjusted so that the maximum motor efficiency can be obtained in the targeted heating half-capacity operation.

By integrating these technological developments, we achieved an efficiency improvement of about 2% compared to the conventional model.

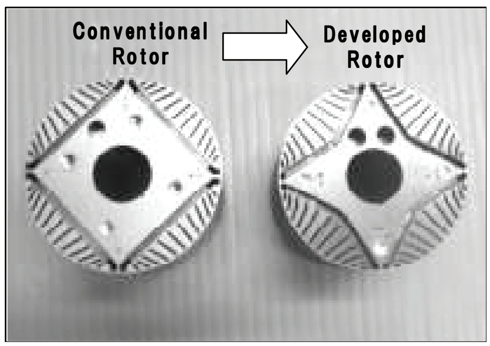


Fig.7 : Features of developed rotor

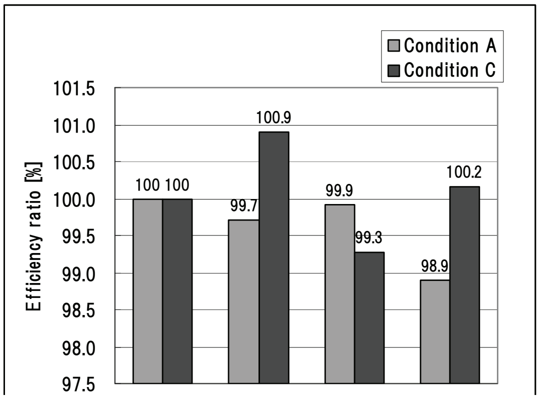
EXPERIMENTAL RESULTS

Efficiency of the Y-shaped suction flow split structure

There have been many research papers focusing on the reduction of the H/ΦD[4], but few commercialized compressors exist. The simplest structure would have each suction pipe is placed on the cylinders in terms of the structure of the rotary compressor, and the reduction of the cylinder height H is restricted to retain the required suction pipe diameter. To resolve this problem, we adopted a suction piping structure whereby a suction pipe is connected to the thick partition plate splitting the suction gas flow with Y-shape respectively to the upper cylinder and to the lower cylinder (Y-shaped suction flow split structure). The three advantages of this structure are as follows:

(1) The optimum suction pipe diameter can be obtained, regardless of the H/ΦD.
(2) Pressure pulsation can be reduced by alternate suction in the two cylinders, which may be effective for reducing the suction pressure loss and gas flow noise.
(3) Even when the thin cylinder is adopted, the fastening with bolts between the bearing and cylinder can be placed on thick partition plate, achieving a stiff compression unit.

In addition, we optimized the branch shape in this structure in order to further reduce the suction pressure loss. We compared the performance of the shapes (B) - (D) with the assigned suction port diameter before branching ΦD1, suction port diameter after branching ΦD2, and branch angle θ with respect to the conventional shape (A). Fig. 8 show the shape parameters. In the commercialized shape (B), we achieved an efficiency improvement of 1% in the targeted heating half-capacity operation (Condition C).



	(A)	(B)	(C)	(D)
ΦD1	Φ8.0	Φ11.5	Φ11.5	Φ11.5
ΦD2	Φ8.0	Φ8.0	Φ6.5	Φ8.0
θ	—	40deg	40deg	90deg

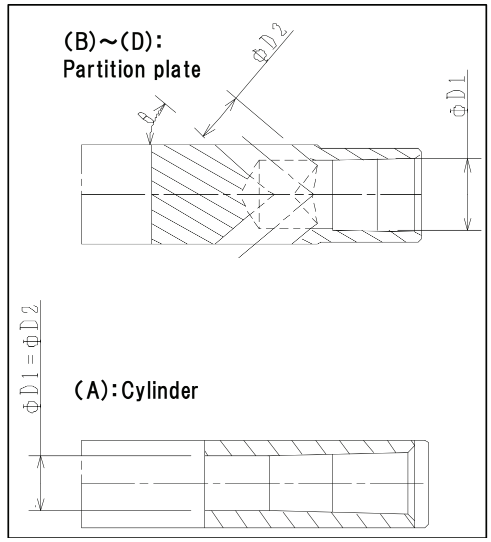


Fig.8: Difference in efficiency due to the branch shape

Performance Improvement

Figure 9 shows the result of efficiency improvement of the developed compressor. By developing these elemental technologies for higher efficiency, we achieved efficiency improvement of 4 to 7% compared to the conventional model of equivalent capacity. We achieved an efficiency improvement of 6.4% in the targeted heating half-capacity operation, as well as an improvement of 6% in the APF value calculated from these conditions.

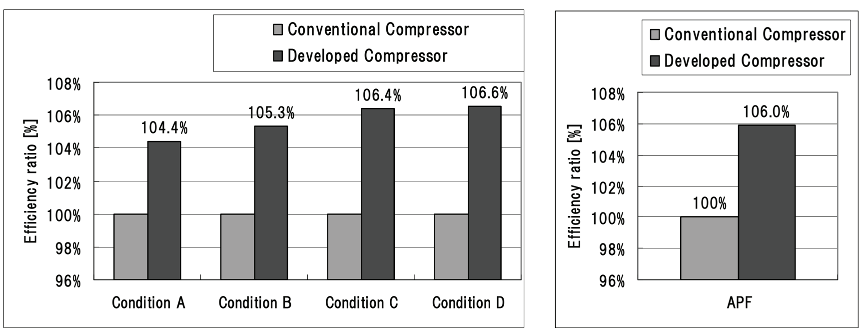


Fig.9: Improvement of performance

CONCLUSIONS

We succeeded in developing a high efficiency compressor compatible to the new index APF by developing and adopting elemental technologies, such as a thin cylinder, reduced crank-pin diameter, Y-shaped suction flow split structure, and reduced top clearance volume due to optimum arrangement of the discharge port, and motor design focusing on half-capacity operation in the developed R410A 2-cylinder rotary compressor. We achieved an efficiency improvement of 6.4% in the targeted heating half-capacity operation, as well as an improvement of 6% in the APF value calculated from these conditions.

We will work toward technological development for the development of environmentally-conscious products.

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