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DEVELOPMENT OF DUAL-STAGE COMPRESSOR FOR AIR CONDITIONER WITH R410A

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ABSTRACT

In recent years, residences with high heat insulation have been increasing in number in Japan. Air conditioners in these residences are therefore often operated with a comparative small air-conditioning load. Moreover, air conditioners are operated more often in spring and autumn in minimal capacity to remove accumulated indoor heat from home electric or lighting equipments. In response to these changes in housing characteristics, we have developed a dual-stage compressor adopting the variable-cylinder system first in the world. The system enables one of two compression chambers of 2-cylinder rotary compressor to pause with the other kept running. A combination of this new technology with the inverter realizes efficient compressor operation at low loads, and significantly improves energy saving along with air-conditioning performance. This technology, developed as a new variable capacity mechanism with minimal losses, is also applicable to fixed-speed compressors and will improve the air-conditioning performance as well.

1. INTRODUCTION

From the standpoint of global environmental conservation, the air conditioner industry is developing new products with enhanced energy saving. Compressors for residential air conditioners in Japan have changed from a fixed-speed type to an inverter-driven variable speed type.

In Japan, as in Europe and North America, residences with high heat insulation (hereinafter “energy saving residences”) have been increasing in number. We surveyed about 60% of houses in Japan are now energy saving residences meeting the building heat insulation characteristics of a seasonal power consumption evaluation standard by JIS (Japanese Industrial Standards). These residences have greatly changed the energy efficiency characteristic required of compressors, making it difficult for the inverter capacity variable type to cope with.

We have developed a dual-stage compressor, the first in the industry that meets these residences characteristics, using a new mechanism to cope with them. This paper presents an overview of the new compressor and describes its features and functions.

2. BACKGROUND OF DEVELOPEMENT

The distribution of annual air-conditioning load and conventional compressor efficiency in an energy saving residence are plotted in Fig. 1. This residence is a wooden house built using the two-by-four construction method installing an air conditioner of 2.8 kW cooling capacity for about 40 m³ room (The measuring condition of the compressor was in accordance with the nominal cooling condition in our air conditioner.) In cooling operation during summer, the compressor capacity to keep the room temperature is small after the room temperature reaches the set temperature, because of excellent room heat insulation characteristics. Moreover, air conditioners are operated more often in spring and autumn in minimal capacity to remove accumulated indoor heat from home electric appliances, lighting equipments and human bodies. This shows that the compressor is used mostly in the small capacity region except when the air conditioner operation is started. Energy efficiency of the conventional compressor is significantly lower in the small capacity region. (Region A) This is influenced by energy losses of the motor inverter, leakage losses of the compressor etc. The capacity variable range by the inverter is limited and room temperature is adjusted by repeating on-and-off operations, which increase losses, after room temperature reaches the set temperature during operation at minimal capacity. (Region B) This intermittent operation mode not only deteriorates the energy efficiency, but also causes room temperature fluctuations, sometimes causing

discomfort. However, rapid cooling and heating is still required at the start of air conditioner operation, and enhanced energy efficiency in the large capacity region is also necessary.

The system illustrated in Fig. 2 solves these problems by installing two inverter type compressors in the air conditioner, small and large capacity compressors, to select and use the compressor with higher efficiency. However, this system requires two compressors and inverters. Additionally, complicated control system is required and more space is needed for this scheme.

The new technology is aiming at improving efficiency in the small capacity region and expanding the minimum capacity operation region by combining the conventional inverter and a new variable capacity mechanism. The new capacity variable mechanism was designed to meet the following requirements:

- (1) A capacity variable ratio of 60% or less.
- (2) Loss minimum during mechanism operation.
- (3) Loss minimum in the large capacity region (when the mechanism is not in operation).
- (4) Simple mechanism and low cost.

3. NEW VARIABLE CAPACITY MECHANISM

The 2-cylinder rotary compressor has two compression chambers, and their compression works are done simultaneously but independently by one shaft connected to the motor rotor. Considering these two independent compression chambers as two small compressors, we developed new variable capacity mechanism (hereinafter “variable cylinder system”) that operates two compression chambers in the large capacity region (2-cylinder operation: capacity 100%) and one compression chamber in the small capacity region (1-cylinder operation: capacity 50%). Figure 3 illustrates switched operation of this compressor. The variable cylinder system is composed of a 3-way valve connected to the lower compression chamber and a small permanent magnet to hold the vane. Holding the vane by the small magnet enables the lower chamber to pause compression when a capacity is cut by half.¹⁾ There can be several options as the means to hold the vane. Holding by a stopper is one of the option,²⁾ but it has disadvantages in respect of cost and efficiency because it requires an actuator of the stopper inside the shell and special machining on the vane etc. There may be another option for the purpose to cut capacity by half. Shutting a suction tube down by an electric valve can be the one to satisfy the purpose,³⁾ but it has disadvantage in respect of efficiency because it can be accompanied by the leakage loss to the vacuum chamber. Therefore we selected the magnet method mentioned above. 2-cylinder and 1-cylinder operation modes are described below.

3.1 2-cylinder operation

2-cylinder operation using the two compression chambers is performed when a large capacity is needed such as at the start of air conditioner operation. In the conventional 2-cylinder rotary compressor, one coil spring is provided on the back of the vane of each chamber so that the vane is pushed to the rolling piston even when there is no pressure difference between suction and discharge side after starting operation, therefore each chamber starts compression immediately. In the dual-stage compressor, only the upper chamber has a coil spring on the back of its vane so that only the upper chamber starts compression immediately after starting operation. (See Fig. 3 (1).) However, the pressure inside the shell rises as a result of compression in the upper chamber and the vane of the lower chamber is soon pushed to the rolling piston to start 2-cylinder operation.

3.2 1-cylinder operation

As illustrated in Fig. 3 (2), in the small capacity region such as the room temperature is near set temperature, the 3-way valve is switched to introduce a high-pressure from the air conditioner cycle into the lower chamber, to achieve a pressure balance between the shell inside and lower chamber. This detaches the vane, which was attached to the rolling piston by pressure difference, and the vane is attracted and held by the small magnet installed near the back of the vane. This series of operations leaves the lower chamber idle and enables only the upper chamber compresses to perform 1-cylinder operation.

Both 1-cylinder operation and 2-cylinder operation can be switched freely by selecting the pressure from the cycle communicating to the lower chamber.

3.3 Optimization of Magnet design

The design of the magnet that attracts and holds the vane in the 1-cylinder operation mode needs to satisfy two opposite requirements. The first requirement is “a stronger magnet is suitable” to hold the vane during 1-cylinder

operation. The second requirement is “a weaker magnet is suitable” to switch easily from 1-cylinder operation to 2-cylinder one. Comparison of the vane holding force (magnet force) F_1 and the another vane working force F_2 in four operation modes is shown in Fig. 4. Suitable design is needed as the vane holding force F_1 varies greatly according to the distance from the magnet. In the diagram, the relationship of $F_2 > F_1$ is established in Operation Modes 1 and 2, allowing continuation of 2-cylinder operation or switch to 2-cylinder operation as desired. The relationship of $F_1 > F_2$ is established in Operation Modes 3 and 4, similarly allowing continuation or switch. Optimization of the magnet design and the parts design has accomplished desirable mechanism operation in each operation mode.

4. ENERGY SAVING OF DUAL-STAGE COMPRESSOR

Figure 5 shows the cross section of the newly developed dual-stage compressor. This compressor is the brushless DC 2-cylinder rotary compressor driven by the vector control inverter, packaging a variable cylinder system. This name originated from two operation modes by the variable cylinder system. It is for a R410A residential air conditioner with a cooling capacity of 2.2 to 7.1 kW class. Table 1 shows specifications of the dual-stage compressor. The largest feature of the compressor is the variable cylinder system, and this mechanism enables one of two compression chambers to pause compressing refrigerant with the another kept doing it, achieving a wide variable capacity range and high efficiency operation in the small capacity range. Additionally, the efficiency over the entire capacity range has been enhanced and low noise is attained by using a rare-earth magnet motor rotor with slits and by optimizing mechanical parts dimension.

4.1 Variable Cylinder System

The variable cylinder system needs neither additional parts nor special machining inside the compression chambers. Therefore this mechanism can minimize losses during 2-cylinder operation and keep the high efficiency characteristic of the 2-cylinder rotary compressor. In 1-cylinder operation also, pressure inside the lower compression chamber is balanced to shell-inside, to idle the rolling piston under no load, so that losses of the mechanism (leakage loss, sliding loss, etc.) become almost zero. On the other hand, the revolution speed can be doubled to 2-cylinder operation speed under the same capacity, realizing high efficiency operation in the minimal capacity region. The efficiency characteristic of the dual-stage compressor is shown in Fig. 6. 1-cylinder operation has been selected for the small capacity region, in which the efficiency is greatly lowered in the conventional compressor. During 1-cylinder operation, the revolution speed is doubled, enabling operation at high efficiency. Compared with the conventional compressor, efficiency is increased by 30% at the maximum. The capacity range has been expanded to the small capacity region side as well, to realize continuous operation at a minimal capacity without intermittent operation that increases losses. As a result, not only energy saving but also comfort of the air conditioner is achieved at the same time. The energy efficiency could be improved by 4% in the medium to large capacity range also by incorporating the technologies described below.

4.2 Motor

A motor rotor with slits containing rare-earth magnets (neodymium-iron-boron) was developed for the dual-stage compressor to achieve a higher efficiency. Figure 7 shows the newly developed motor rotor and the conventional one. The motor has the following features.

(1) Compact and high efficiency

A rotary torque generated by variation of reluctance (magnetic resistance) of rare-earth magnets with a powerful magnetic field can be used. This achieves 23% reduction in weight and 1% efficiency improvement compared with a DC motor that uses a conventional motor rotor with ferrite magnets.

(2) Low electromagnetic noise

The slits of the newly developed motor rotor make the magnetic flux distribution uniform on the exteriors of the motor rotor, and make the induced voltage waveform close to the sine wave as illustrated in Figure 7. Consequently, electromagnetic noise decreases as shown in Figure 8.

4.3 Mechanical parts dimension

The mechanical parts dimensions were optimized to improve the efficiency in the medium to large capacity range, such as by expanding the compression chamber volume and by other means while fully utilizing the high

efficiency characteristic in the small capacity range of the dual-stage compressor. As a result, losses were reduced by about 18% compared with the conventional compressor.

5. CONCLUSIONS

The technologies incorporated into the dual-stage compressor have achieved not only energy saving of air conditioners in which it is installed, but have also enabled continuous minimal operation that can provide a comfortable indoor environment throughout the year. As a result, the capacity variable range in terms of maximum per minimum ratio was expanded to 27 compared to 18-for the conventional compressor. This compressor is applied to our residential air conditioner “DAISEIKAI NDR”⁴⁾ series.

This wide capacity variable range will greatly contribute to the future development of air conditioners. Moreover, in fixed-speed compressors also, the new technology will contribute to enhancing the performance of air conditioners and meeting the energy saving regulations in many countries as a new variable capacity mechanism with minimal losses. We will use these technologies as a base to make further contributions to global environment conservation and for the production of air conditioners that enable a comfortable indoor environment.

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Table. 1 Specifications of Dual-Stage Compressor and conventional compressor

	Dual-Stage Compressor	2-Cyl Rotary Compressor
Model	DA111A1FD series	DA91A1F series
Compression type	Hermetic Rotary	Hermetic Rotary
Used refrigerant	R410A	R410A
Displacement	11? 5.5 cm ³ (Switching)	9.1 cm ³
Inverter	Vector control inverter	Vector control inverter
Motor type	Brushless DC motor	Brushless DC motor
pole	4	4
Motor rotor magnet	Rare-earth (Nd-Fe-B)	ferrite
Max. / Min. capacity ratio	27	18
Weight	9.6 kg	10.2kg
Outside diameter × Height	f 116×282mm	f 116×282mm

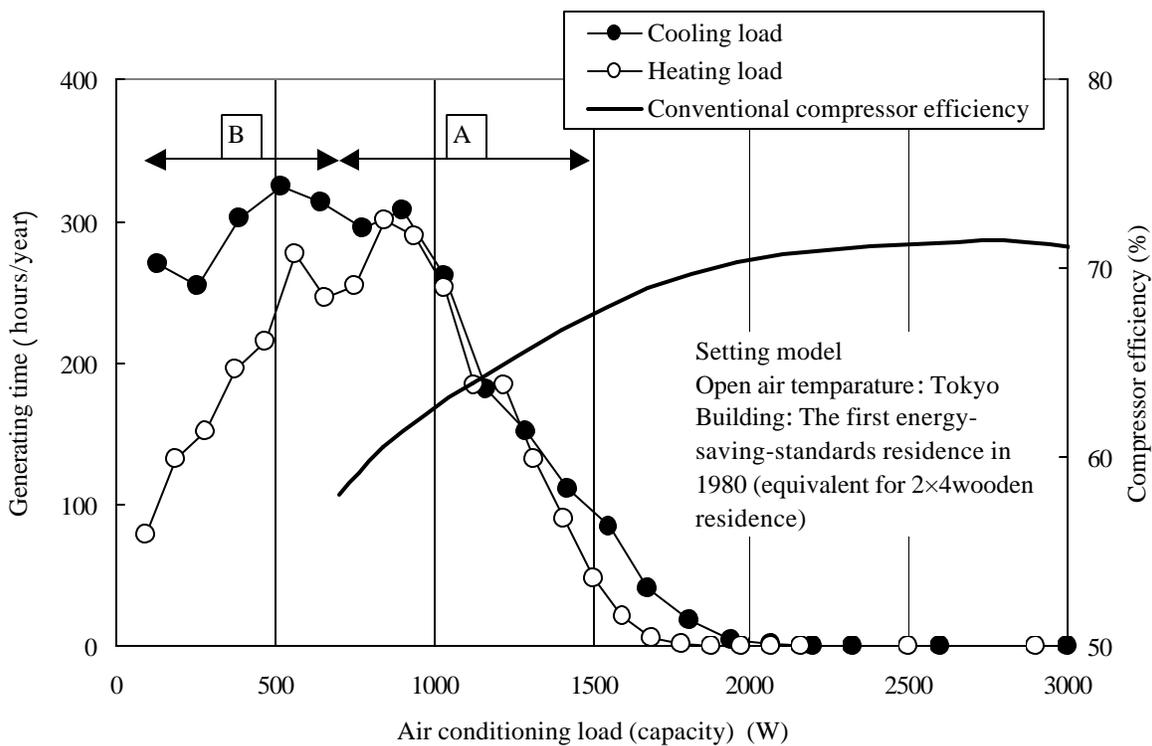


Fig. 1 Distribution of annual air-conditioning load and conventional compressor efficiency

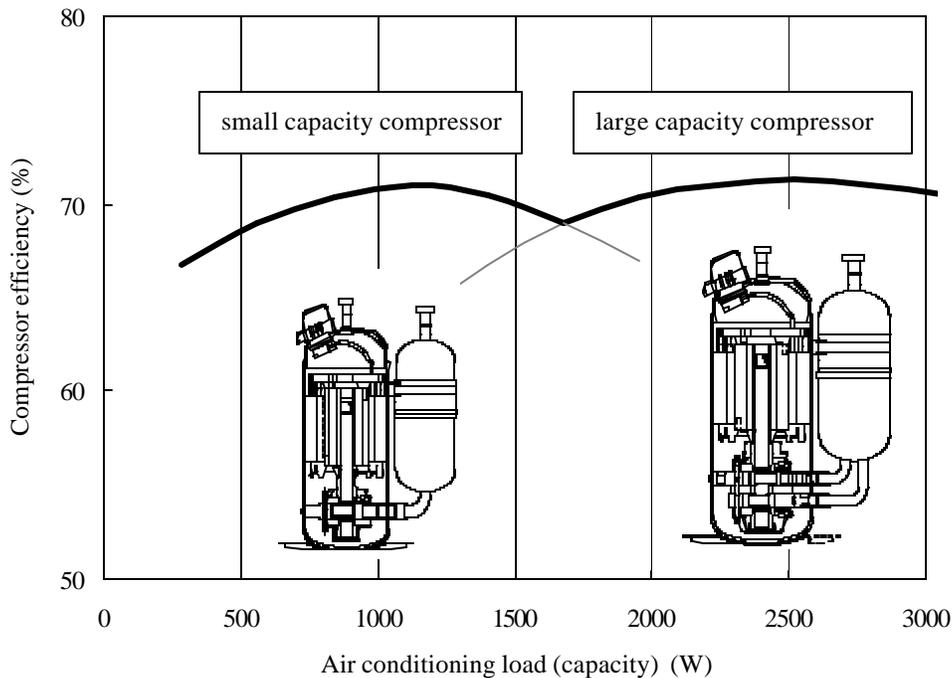


Fig. 2 Ideal compressor system for energy saving

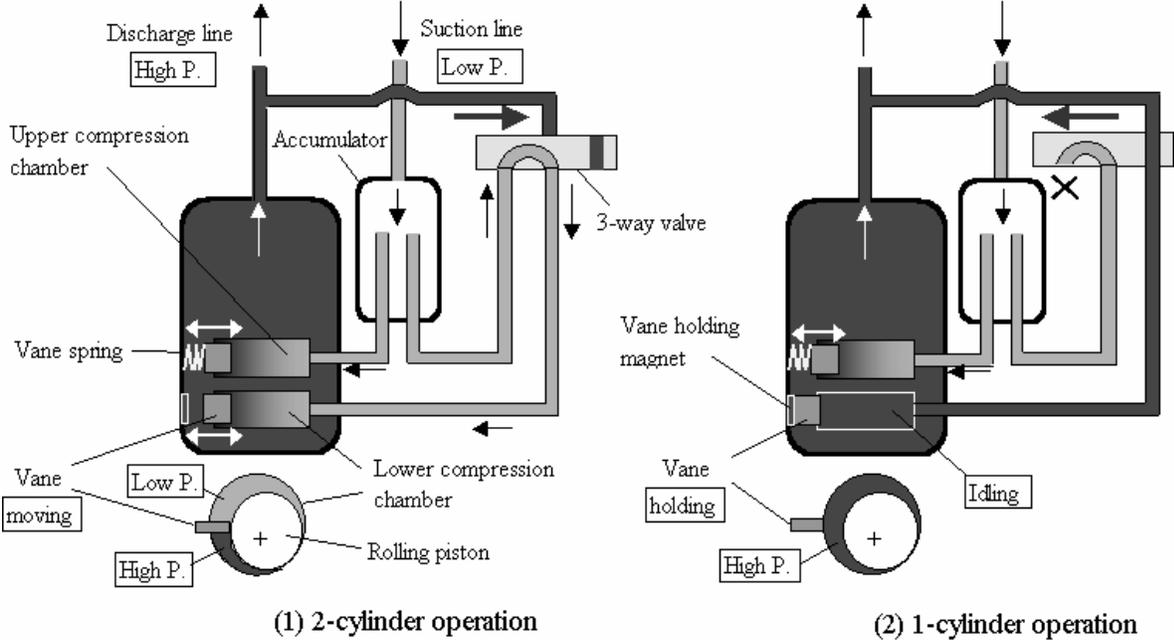


Fig. 3 Circuit diagram of Dual-Stage Compressor modulation mechanism

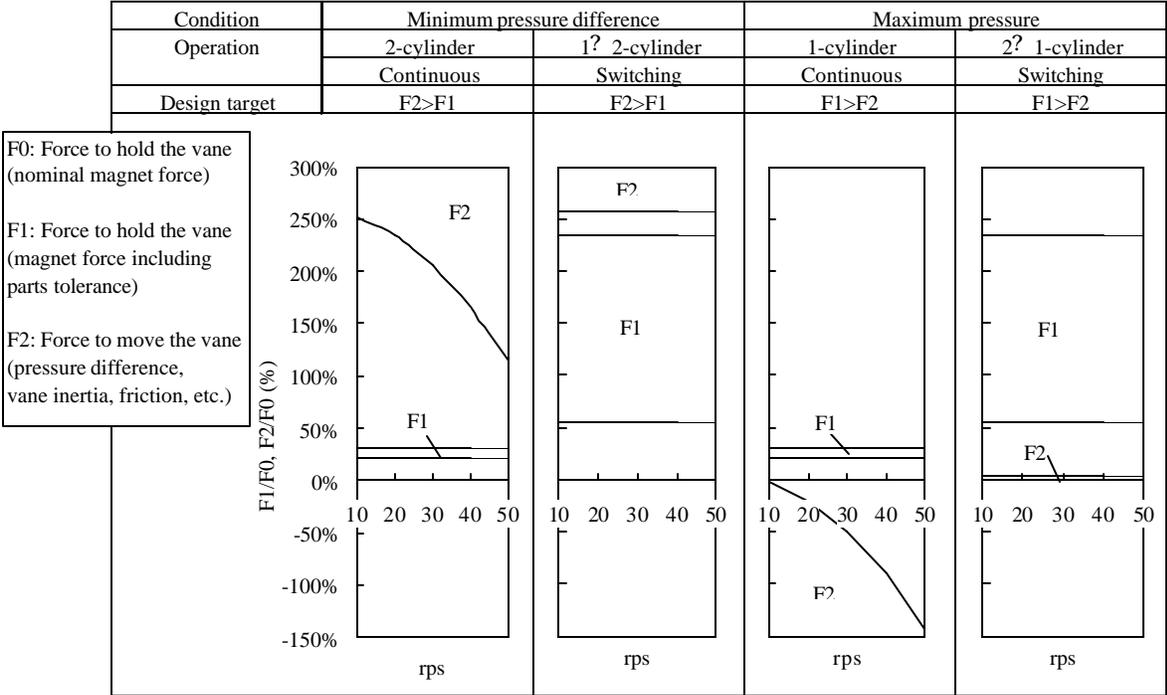


Fig. 4 Comparison of the force to hold the vane and to move it in four operation modes

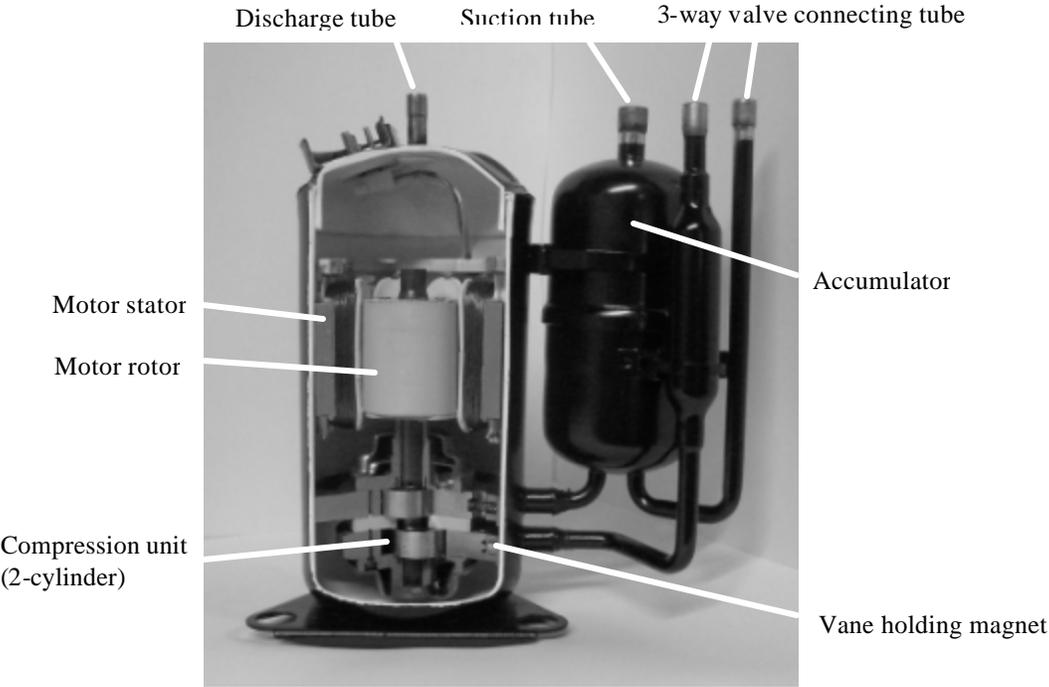


Fig. 5 Cross-section of Dual-Stage Compressor

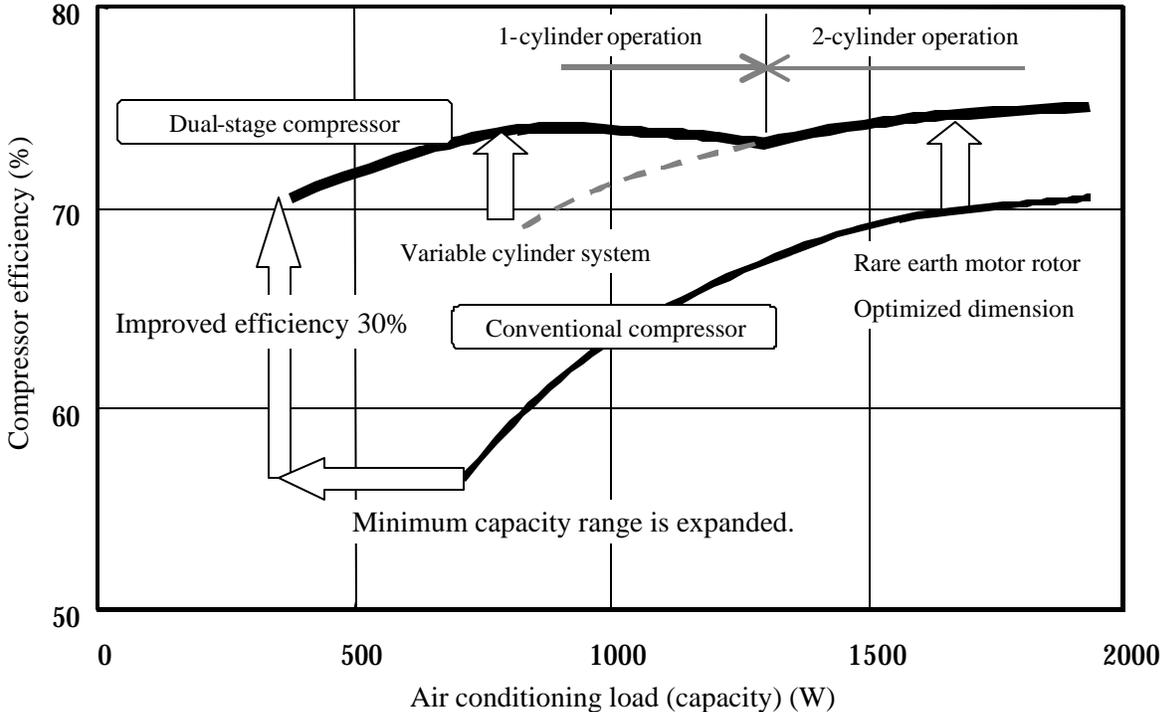
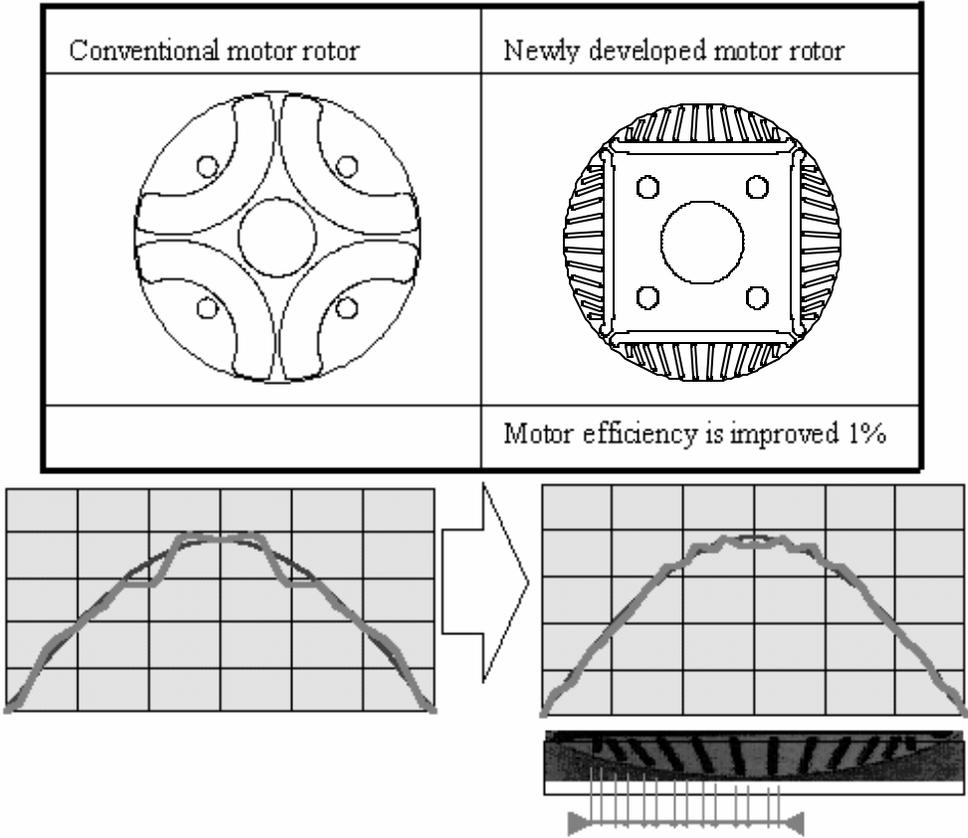


Fig. 6 Efficiency comparison of Dual-Stage Compressor and conventional compressor



The slits make the induced voltage waveform close to the sine wave.

Fig. 7 Feature of newly developed motor rotor

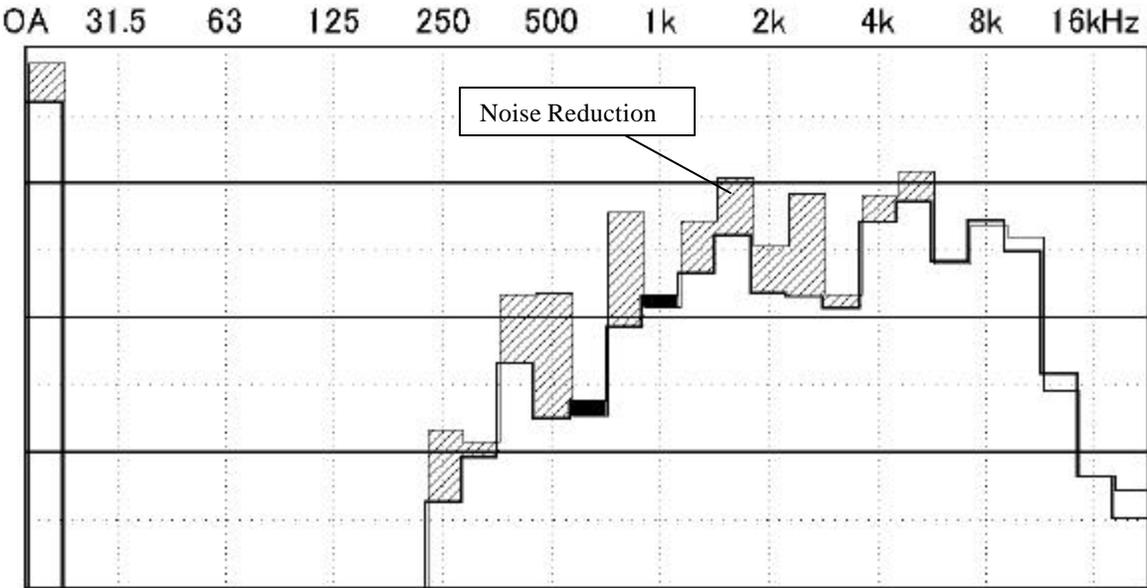


Fig. 8 Comparison of power level