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ABSTRACT

In recent years, annual power consumption has been receiving global attention because of greenhouse gas emission. Improvement in compressor performance at part load condition is a key factor in reducing annual power consumption. To achieve such improvement, a reduction in dysprosium (Dy) consumption is important. In addition, using less Dy could save precious resources such as rare material.

We have developed a new swing type compressor that offers inherently less leakage loss at low speed. The new high efficiency Interior Permanent Magnet Synchronous Motor (IPMSM) with 60% less Dy magnet is used in this new swing type compressor. The annual power consumption of this newly developed swing type compressor has been reduced 1.5% compared to conventional compressors by using a high efficiency motor and increasing the range of minimum load. As a result, it is now possible to provide a more environmentally friendly compressor for HVAC applications.

1. INTRODUCTION

Compressors play a key role in energy-saving refrigeration & air conditioning and we have been working hard on increasing compressor efficiency to meet the needs of global warming prevention. Furthermore, from a resource-saving perspective, decreasing the consumption of Dy, which is a Heavy Rare Earth (HRE) element contained in rare earth sintered magnets used in high efficiency motors, will be an important technology factor not only in Japan, but also around the world.

We have successfully developed a high efficiency swing type compressor with a new fixation motor method. The Nd-Fe-B sintered magnet with the industry's first HRE grain boundary diffusion process was used in the newly developed IPMSM.

This report discusses the characteristics of the fixation method, magnetic steel sheet thickness, as well as the positioning of magnets to achieve high efficiency IPMSM using HRE grain boundary diffusion magnets. Moreover, evaluation results of the newly developed high efficiency swing type compressor are also discussed in this report.

2. OVERVIEW OF SWING TYPE COMPRESSOR

Figure 1 shows the mechanisms of both a rotary compressor and swing type compressor. Swing type compressors can be distinguished by a unified vane and roller that achieve higher reliability and efficiency compared to conventional rotary compressors. Figure 2 shows the cross sectional view of a swing type compressor.

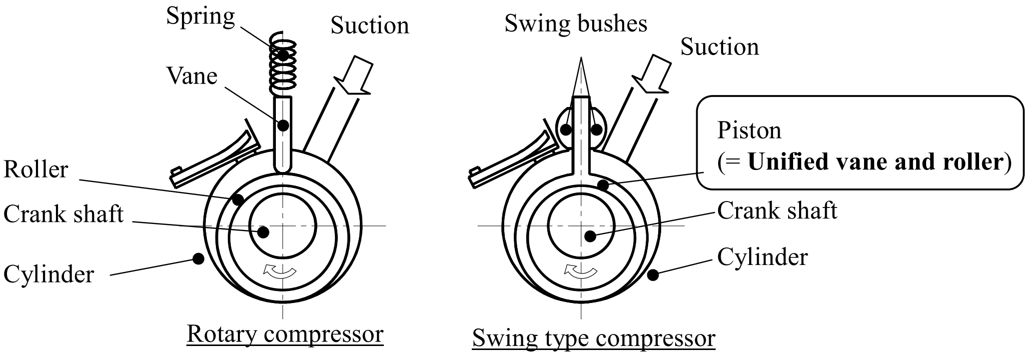


Figure 1 – **Mechanism of rotary and swing type compressor**

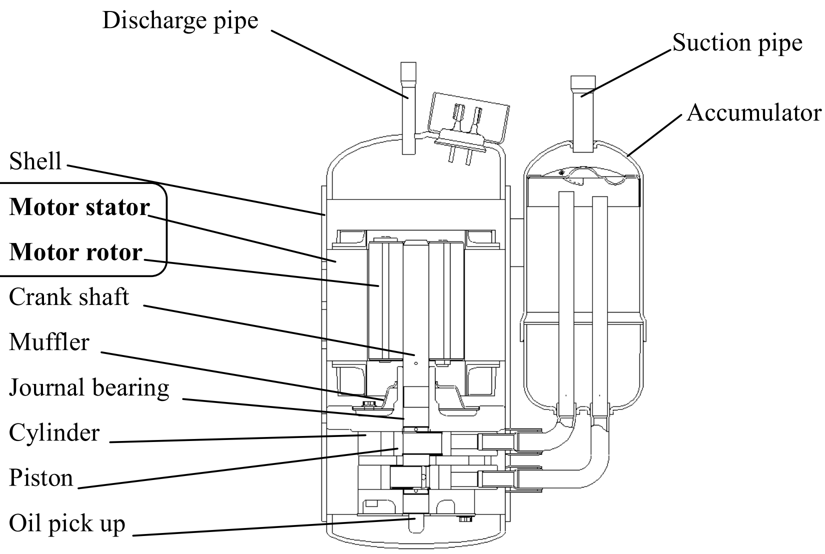


Figure 2 – **Cross sectional view of swing type compressor**

3. THE CHARACTERISTICS OF HIGH EFFICIENCY SWING TYPE COMPRESSOR USING NEW IPMSM

Table 1 – **Comparison of conventional and newly developed motor**

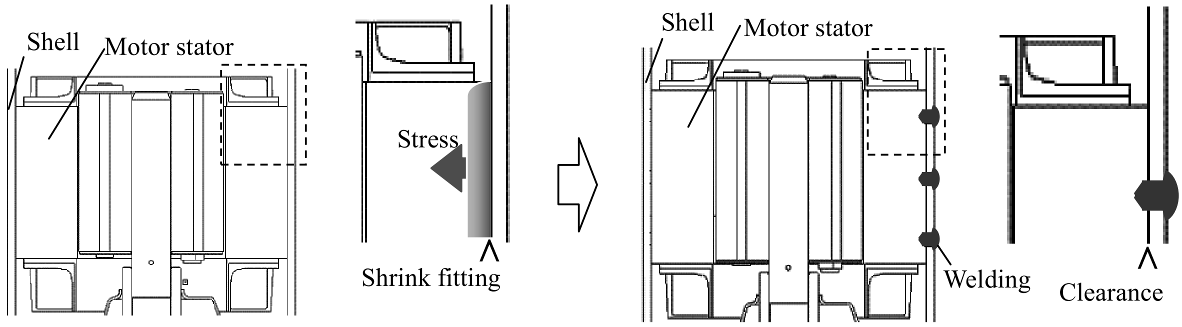
	Conventional IPMSM	Developed IPMSM
Motor type	Concentrated winding motor	Concentrated winding motor
Motor stator fixation method	Shrink fitting	Welding
Magnet steel sheet thickness	t0.35 mm	t0.30 mm
Magnet positioning	Straight type positioning	V type positioning
Magnet	Nd-Fe-B sintered magnets with conventional binary alloy process	Nd-Fe-B sintered magnets with HRE grain boundary diffusion process

3.1 Motor Stator Fixation Method

Figure 3 shows the cross sectional view of a compressor. Figure 3(a) shows the stator fixation by shrink fitting method, and Figure 3(b) shows the stator fixation by welding method.

The shrink fitting method has been widely used for stator fixation in hermetic compressors. As shown in Figure 3(a), a higher compressive stress is applied around the stator if the fixation is conducted by this method. The compressive stress to the stator by shrinkage fitting method is estimated to be 50 ~ 100MPa for conventional hermetic compressors.

On the other hand, as shown in Figure 3(b), it is possible to maintain clearance between the shell and stator by using the welding fixation method, which results in nearly zero compressive stress.



(a) Conventional motor stator fixation method
shrink fitting

(b) Developed motor stator fixation method
welding

Figure 3 – Cross sectional view of motor of swing type compressor

Yamamoto et al. (1998) stated that the compressive stress applied to the stator increases iron loss, which results in a decrease of motor efficiency. Figure 4 shows the relation of iron loss with regards to stress. The horizontal axis represents stress to the stator and the vertical axis represents motor iron loss. Results show that the compressive stress to the stator via the shrinkage fitting method causes 2.2 ~ 2.5 times the iron loss compared to the welding fitting method.

In order to develop a high efficiency motor, the stator fixation by the shrinkage fixation method needs to be carried out without any compressive stress. A recent study revealed that it is difficult to completely remove (to near zero) the compressive stress by conventional fixation method. Therefore, we have developed a welding method that does not cause any compressive stress.

Figure 5 shows the comparison of motor iron loss without fixation, motor iron loss by shrinkage fitting and motor iron loss by welding fixation method. Results show that motor iron loss, as a result of welding, is nearly the same as motor iron loss without any fixation. It is possible to decrease iron loss by about 20% in a nominal running area by using the welding fixation method compared to the shrinkage fitting method.

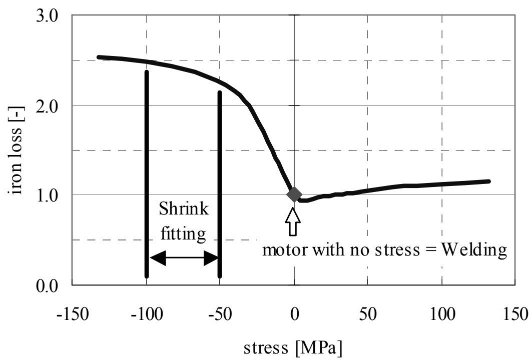


Figure 4 – Relationship between stress and iron loss of magnetic steel

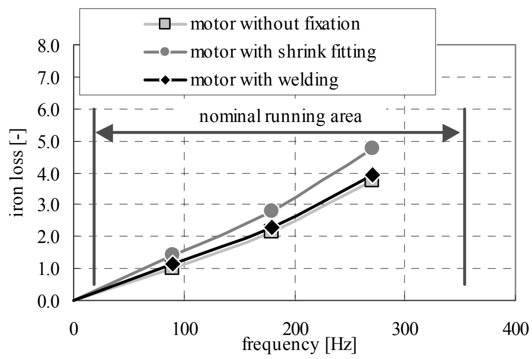


Figure 5 – Iron loss of motor stator fixation method

Figure 6 shows the structure of welding fixation of the stator in a swing type compressor. This study revealed that three sections of welding is suitable in consideration of achieving better reliability, lower compressor noise, and vibration.

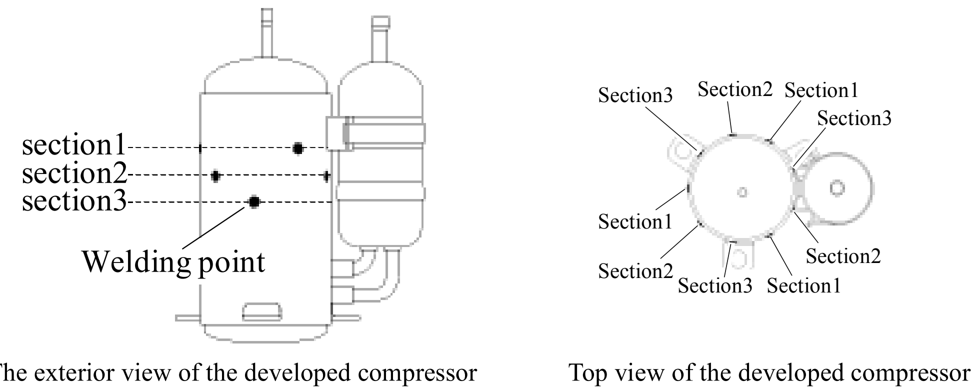


Figure 6 – Structure of three sections welding

3.2 Magnetic Steel Sheet Thickness

There are two types of iron loss: hysteresis loss and eddy current loss. Figure 7 shows hysteresis loss and eddy current loss of magnetic steel with regards to frequency. Results show that the eddy current loss is very high relative to hysteresis loss at high frequencies. Therefore, eddy current loss should be decreased to realize a high efficiency motor.

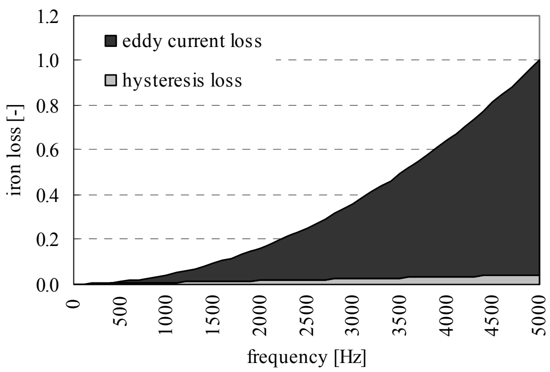


Figure 7 – Ratio of eddy current loss and hysteresis loss at different frequencies.

The eddy current loss can be represented by using Equation (1). As shown in Equation (1), eddy current loss is proportional to the square of magnetic steel sheet thickness.

$$We = 0.1645\frac{t^2 f^2 Bm^2}{\rho D} \tag{1}$$

We	eddy current loss	[W]
t	magnetic steel sheet thickness	[m]
f	frequency	[Hz]
Bm	magnetic flux density	[T]
ρ	resistivity	[Ωm]
D	density	[kg/m^3]

According to the above equation, a decrease of magnetic steel sheet thickness is an essential factor for decreasing motor iron loss.

However, the thinner the stator magnetic steel sheet, the lower the stator rigidity, which results in a higher deflection of the stator by compressive stress. Therefore, it is difficult to maintain an equal gap between the rotor and stator. As a result, the noise of the compressor increases and the compressor efficiency decreases. Combining the welding fixation method (that doesn't create compressive stress) with the application of a thin magnetic steel sheet successfully improves efficiency without increasing noise.

A comparison of compressor noise power levels for conventional magnetic steel sheet using the shrink fitting method (conventional compressor), thinner magnetic steel sheet using the shrink fitting method and thinner magnetic steel sheet using the welding method (developed compressor) is shown in Figure 8. Measurement results show that the noise power level of thinner magnetic steel sheet using shrink fitting is higher than a conventional compressor. However, as shown in Figure 8, the noise power level of a developed compressor in which the thinner magnetic steel sheet was fixed by the welding method, is lower than a conventional compressor. Figure 9 shows the variation of iron loss with the variation of magnetic steel sheet thickness. Results are shown for 3 different torque conditions. As shown in Figure 9, by decreasing the steel sheet thickness from t0.35 to t0.30, the iron loss has been decreased by 10% regardless of torque conditions.

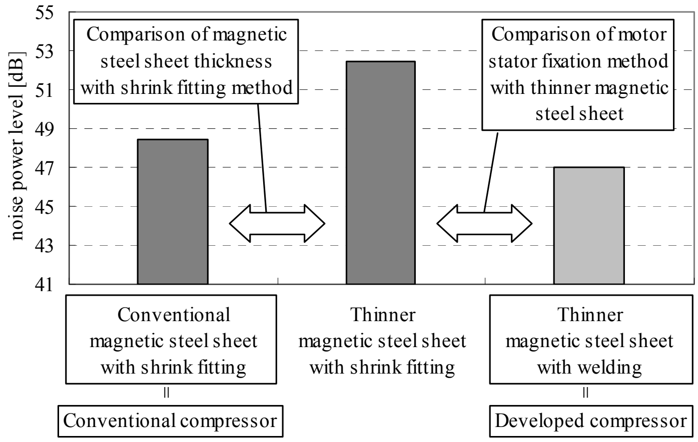


Figure 8 – **Compressor noise power level of magnetic steel sheet thickness and motor stator fixation method**

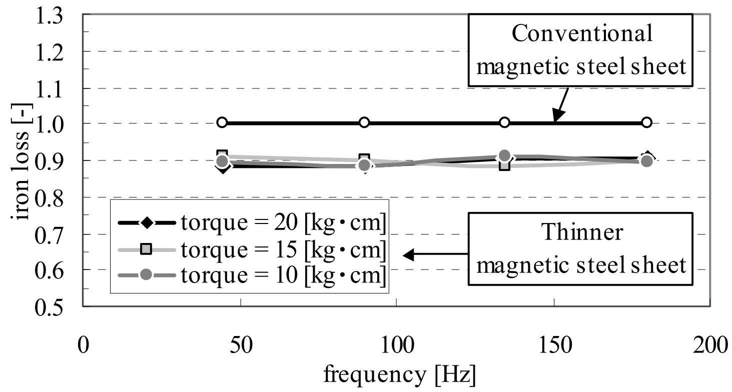


Figure 9 – **Iron loss of magnetic steel sheet thickness t0.30mm compared to t0.35mm**

3.3 Magnet Positioning

Annual power consumption can be decreased by applying higher magnetic flux to the motor. However, the iron loss at higher harmonic components increases due to excessive magnetic flux and conventional rotor shape. The formation of sinusoidal wave of the magnetic flux is possible by improving the magnetic structure of the rotor, which solves the iron loss problem.

However, because of the demand for high efficiency motors, larger surface and higher flux magnets are required.

Application of large surface magnets decreases the core area which restricts the design freedom of rotor and increases magnetic flux. Therefore, it is difficult to reduce the higher harmonic iron loss of a high flux magnet by conventional positioning of the magnet.

As shown in Figure 10, we have introduced a V-shaped positioning of magnets that reduces higher flux harmonic components. The new magnet positioning system enlarges the area of rotor core and creates a gradual distribution of magnetic flux components which protects the flux from saturation.

Figure 11 shows a comparison of conventional motor iron loss and a motor with a V-shaped positioning of magnets. Figure 11 also shows that the V-shaped positioning of magnets decreases the higher harmonic flux losses, which results in a reduction in iron loss of about 5%.

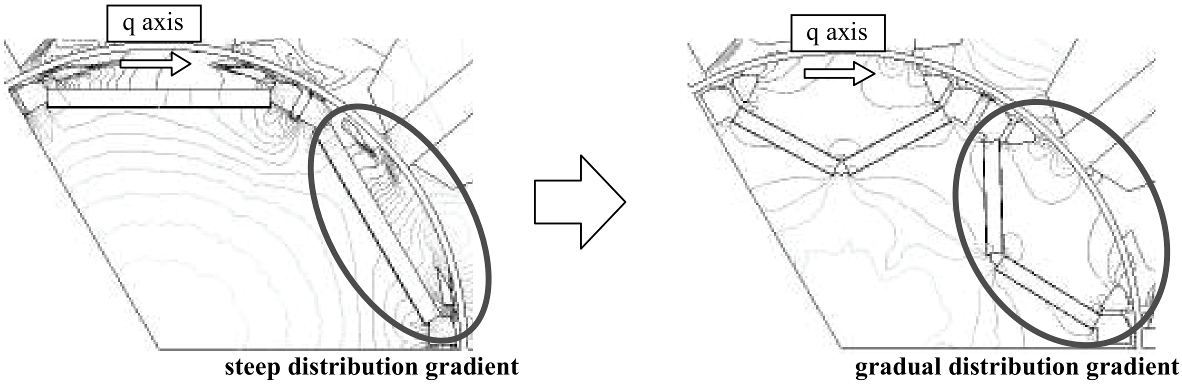


Figure 10 – Distribution of magnetic flux density

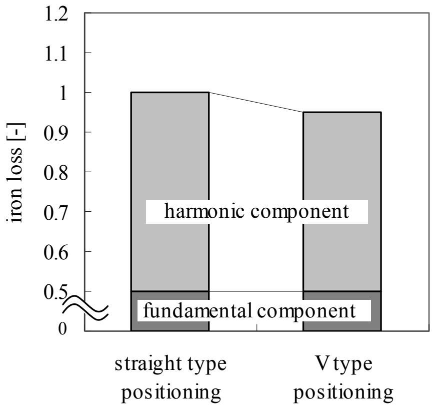


Figure 11 – Iron loss of magnet positioning

Furthermore, as shown in Figure 10, it is possible to enlarge the magnetic path of the q axis by positioning the magnets in a V-shaped formation. This enables the effective use of reluctance torque and decreases current by 5-7.4% for similar torque generation.

3.4 Magnet

The applications of Nd-Fe-B sintered magnets have been rising in various fields. Nd-Fe-B sintered magnets for the high efficiency motor raises the intrinsic coercivity (heat resistivity) by adding the HRE element. However, the distribution of HRE using the conventional binary alloy method lowers the remanent magnetization which affects motor efficiency. To solve this problem, the grain boundary diffusion process was recently invented for the distribution of HRE element.

Figure 12 shows the distribution of the Heavy Rare Earth (HRE) element of Nd-Fe-B sintered magnets. Figure 12(a) represents the distribution of HRE using the conventional process and Figure 12(b) represents the distribution of

HRE that applies the grain boundary diffusion process. By using the grain boundary diffusion process, HRE is enriched in an extremely thin portion around the grain boundary. Therefore, the amount of HRE, which causes the decrease of remanance, can be decreased for the same intrinsic coercivity.

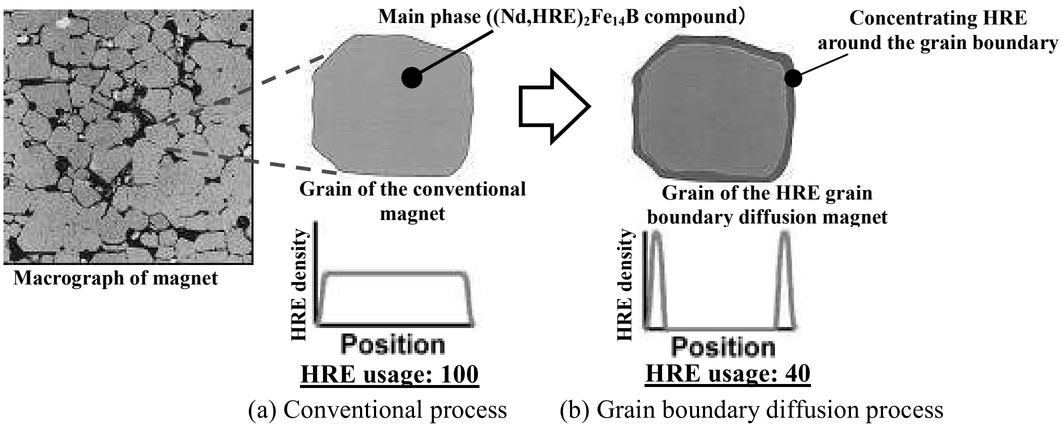


Figure 12 – **Distribution of HRE element**

The relationship between maximum energy product and intrinsic coercivity is represented in Figure 13. Maximum energy product is an index used to represent the performance as well as intrinsic coercivity of magnets. Results are shown for the conventional method and the grain boundary diffusion process. As shown in Figure 13, maximum energy product when using the grain boundary diffusion process is higher relative to the conventional process. The maximum energy product of magnet that has been applied in the newly developed motor is 20% higher relative to the conventional method for the same intrinsic coercivity.

As previously mentioned in section 3.3, the magnetic saturation of rotor core appears with an increase in magnetic flux which increases the motor iron loss. By combining V-shape magnet positioning and the grain boundary diffusion process of HRE elements, the high performance magnet has been applied to newly developed compressors without considerable increase in iron loss.

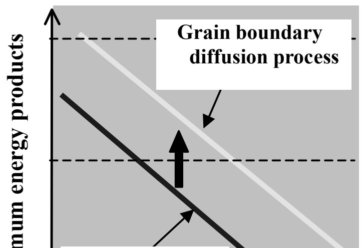


Figure 13 – **Relationship between maximum energy product and intrinsic coercivity of Nd-Fe-B sintered magnets**

Furthermore, the efficiency of the motor has increased and the use of heavy rare earth element (Dy) has been reduced by 60%.

4. DEVELOPED COMPRESSORE USING NEW IPMSM

Figure 14 shows the motor efficiency at four common running conditions of an air conditioner when using a built-in compressor. Results are shown for a conventional motor and the developed motor. By using the technology described above, it is possible to increase the motor efficiency by 1.4% - 1.7% depending on running conditions. Figure 15 represents the APF (annual performance factor) of the conventional compressor and the newly developed compressor. As shown in Figure 15, by using the new technologies, the compressor APF is successfully increased by 1.5%.

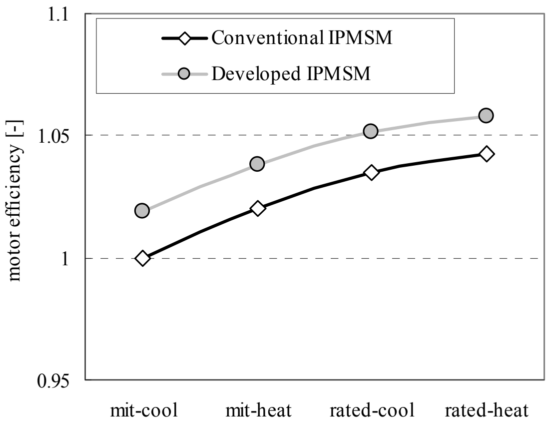


Figure 14 – **Comparison of conventional and newly developed motor efficiency**

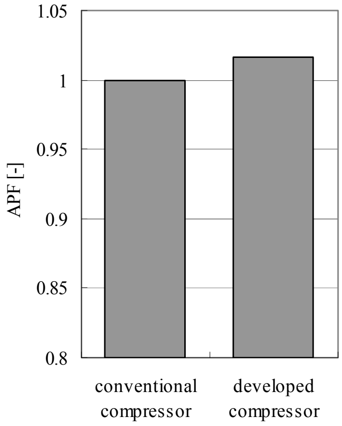


Figure 15 – **Comparison of conventional and newly developed compressor APF**

5. CONCLUSION

We have successfully developed a high efficiency swing type compressor by applying the new IPMSM. The new stator fixing method, thinner magnetic steel sheet, the V-shaped positioning of magnets, and the industry's first grain boundary diffusion process of Nd-Fe-B magnets with HRE have been applied to the newly developed IPMSM.

As a result, the following conclusions were obtained:

- The iron loss is decreased 20% by fixing the motor stator by welding.
- The magnetic steel sheet has been successfully made thinner by fixing the motor stator by welding.
- The iron loss is decreased 10 % by using the thinner magnetic steel sheet.
- The iron loss is decreased 5% by positioning the magnets in a V-shape formation.
- Grain boundary diffusion processed magnets are successfully applied by positioning magnets in a V-shape formation.
- The maximum energy product is 20% higher by using grain boundary diffusion processed magnets.
- The amount of Dy is reduced about 60% by keeping the same intrinsic coercivity.
- Finally, the motor efficiency is increased 1.4% - 1.7% and the annual performance factor (APF) of compressor is increased 1.5%.

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