2021

Development of 3-Cylinder Rotary Compressor for Large Capacity

Tomohide Shishimoto
Toshiba Carrier, Japan

Toshimasa Aoki

Koji Hirano
koji.hirano@toshiba.co.jp

Shogo Shida

Takuya Hirayama

Development of 3-Cylinder Rotary Compressor for Large Capacity

Tomohide Shishimoto [1]*, Toshimasa Aoki[1], Koji Hirano[1],
Shogo Shida[1], Takuya Hirayama[2]

[1]Toshiba Carrier Corporation, Compressor Design Department,
Tadehara 336, Fuji City, Shizuoka Prefecture, Japan 416-8521

[2] Toshiba Carrier Corporation, Core Technology Center,
Tadehara 336, Fuji City, Shizuoka Prefecture, Japan 416-8521

* Tomohide Shishimoto (tomohide1.shishimoto@glb.toshiba.co.jp)

ABSTRACT

The authors have developed a large capacity rotary compressor with compact size and low vibration. Recently, we have strong requirements for larger capacity without changing the compressor shell diameter. Considering for larger capacity in conventional 2-cylinder rotary compressor inverter type, there are issues such as high vibration, big sound. As the solution for these problems, we have developed 3-cylinder rotary compressor inverter type which have different compression process of 120 ° phase per revolution for each cylinder. The developed compressor achieves a capacity target, proves one-quarter vibration level comparing with 2-cylinder rotary compressor and ensure the improvement of reliability result. We have been manufacturing the world largest capacity of new rotary compressor and have been launching into the market since September 2020. This new model has successfully attained more large capacity with same shell diameter as our previous large capacity of 2-cylinder rotary compressor inverter type. This new model adopt some new technologies such as the 3-cylinder design for balancing rotation torque, the multi discharge valve structure, the integrated bearing with partition plate and the new wide-range motor. By these technologies, the outdoor units of multiple air conditioner for buildings (Variable Refrigerant Flow-VRF) can achieve a large capacity 20 HP (56kW) with applying one compressor unit only.

1. INTRODUCTION

From global environmental protection point of view, energy saving, resource saving and down-sizing of refrigeration air conditioning system become important issues. Moreover, refrigeration air conditioning system have a tendency to increase the capacity in recent years. However in compressor design, it need to encounter the contradiction between increasing a capacity and its compactness.

In case of adapting the same long-experienced shell with having high pressure resistance safety and economically in design, 2-cylinder rotary compressor within two compression process as known as Twin Rotary Compressor will have an excessive shaft load, low reliability result, high sound and more big vibration when try to enlarge its capacity over than our conventional larger model 100cc. As a solution of those problems, we developed a 3-cylinder rotary compressor inverter type with three compression process inside that is called Triplet Rotary Compressor. This compressor achieve more large capacity and reduce its high vibration. And also, magnifying 20% of its displacement volume from 100cc to 120cc make it as the world's largest one (*) in rotary compressor types. Furthermore, the vibration of developed 3-cylinder compressor reduce to one-third comparing to the 100cc capacity of conventional 2-cylinder rotary compressor type (*According to TCC internal investigation, July 2020)

This developed model has been installing in outdoor units of multiple air conditioner for buildings "SMMS-u" with R410A refrigerant and has been launching into market since September 2020. In this paper, we introduce 3-cylinder design, the multi discharge valve structure design and new wide range motor.

2. THE ELEMENTAL TECHNOLOGIES FOR LARGE CAPACITY

2.1 3-cylinder design

In the large capacity of rotary compressor, from the viewpoint of partial load performance, vibration, and sound, currently the mainstream is a 2-cylinder rotary structure. Generally in conventional 2-cylinder rotary compressor, the eccentric crankshaft arrange 180 ° in opposite to each other so suction and compression are repeated alternately. In the case of increasing capacity, if cylinder height is increased the compression load fluctuation ratio is same but the reliability become worse due to load increasing at bearing. In addition, operating vibration including an increased swing due to increasing moment refer to the shaft rigidity, there is a concern about noise deterioration according to an increasing of pressure pulsation. On the other hand, the torque fluctuation ratio can be reduced by arranging the eccentric of crankshaft at an equal distribution of 120 ° in the developed 3-cylinder rotary compressor.

The eccentric crankshaft at an equal distribution of conventional 2-cylinder rotary structure and developed 3 cylinder rotary structure are shown in figure 1 and 2. Comparison of the torque fluctuation ratios of both model is shown in figure 3 in the rated cooling condition.

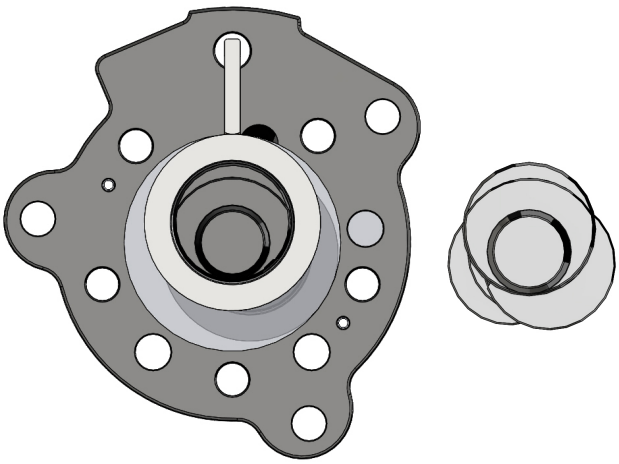

Figure 1 : The eccentric crankshaft at an equal distribution of 120° (Developed 3-cylinder rotary structure)

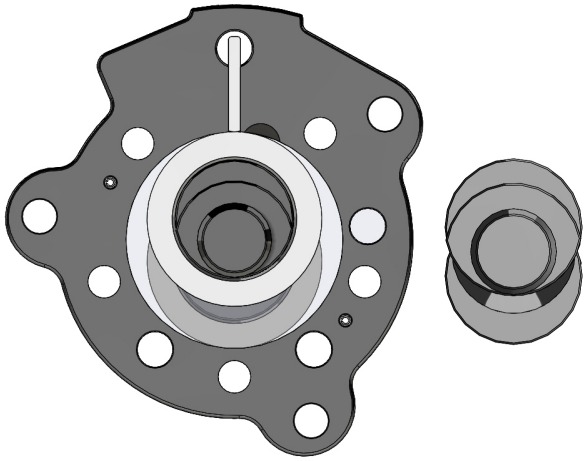

Figure 2 : The eccentric crankshaft at an equal distribution of 180° (Conventional 2-cylinder rotary structure)

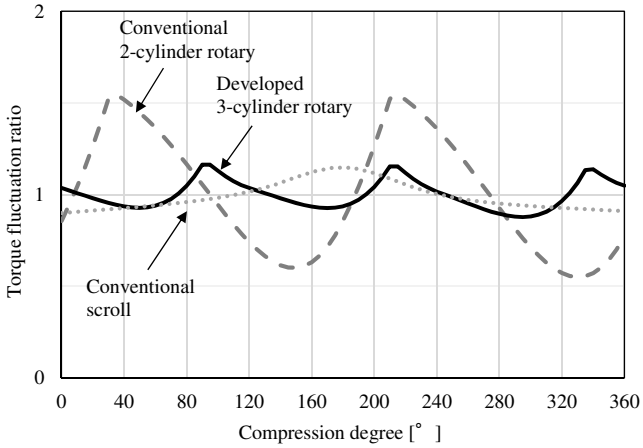

Figure 3 : Torque fluctuation ratio

Compared to the conventional 2 cylinder rotary structure 100cc, developed 3 cylinder rotary structure 120cc has increased the eccentric weight and extend the distance length between the compression chambers, therefore, it is becomes necessary to increase the balancer weight to balance the moments. On the other hand, increasing the balancer

weight lead to more crankshaft deflection, and worsen the reliability of the main bearing particularly. Hence, the deflection of crankshaft is reduced by rotor with lower gravity center and also counter bore at lower side of rotor. In addition of reducing torque fluctuations, a new structure has been adopted to new balancer which is attached at top of rotor and at sub bearing side as maximum as possible to perform a low vibration. Comparison of the vibration ratios of both model is shown in figure 4.The developed model 120cc achieve 78% more low vibration comparing with the conventional 100cc.

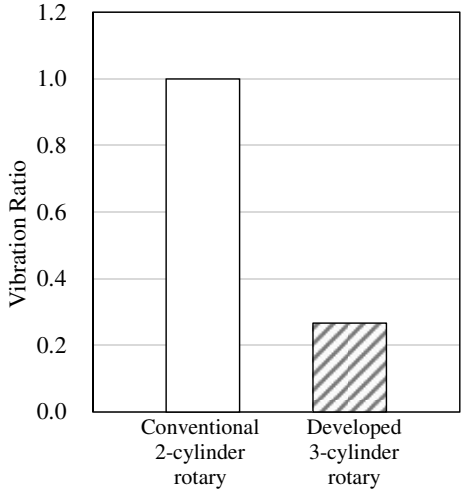

Figure 4 : Vibration ratio

On the other hand, compared to 2-cylinder rotary structure, 3-cylinder rotary structure increases the compression load and the bearing load due to longer distance between main bearing and sub bearing. Therefore, new third bearing is installed, in addition to conventional technology such as providing tapered shape on the upper end of main bearing and counter bore for the center of gravity of the rotor is lowered and installing a ring groove on each bearing's end face. New third bearing which has both the functions of partitioning between each chambers and bearings, is installed to get good reliability and keep the shaft diameter unchanged.

Figure 5 shows the compressor structure of conventional 2-cylinder rotary and developed 3-cylinder rotary.

Bearing reliability index is in figure 6 shows bearing load ratio of cooling load capacity condition for refrigeration 410A environment. Comparing to capacity enlargement 20% of 3 cylinder without new third bearing, bearing load of main bearing and sub bearing with new third bearing of 3 cylinder rotary has improved about half.

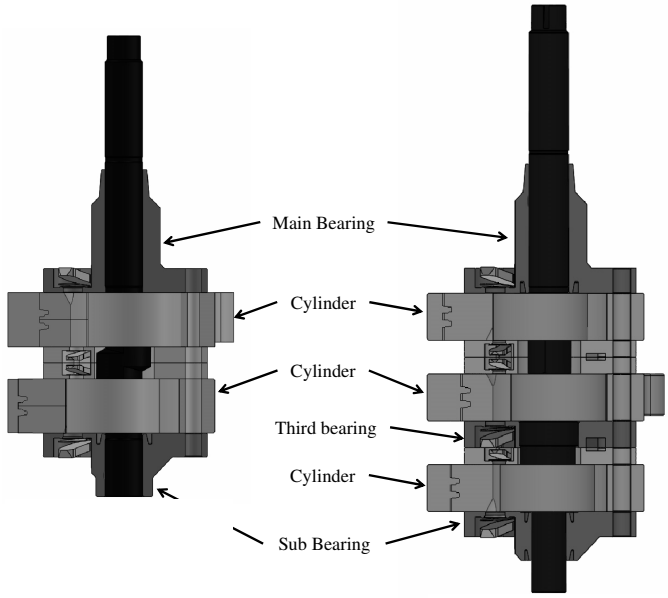

Figure 5 : The compressor structure of the 2-cylinder and 3-cylinder rotary

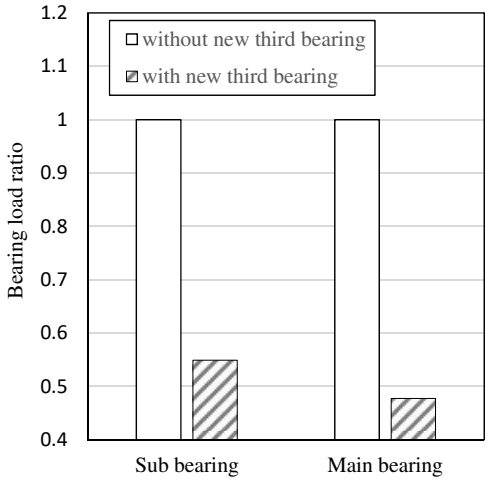

Figure 6 : the ratio of the bearing load under the cooling overload condition with R410A refrigerant

2.2 The multi discharge valve structure design

It is necessary to reduce the flow path loss due to increasing the refrigerant flow rate for maximum performance of larger capacity compressor. The discharge structure of 3-cylinder rotary compressor uses a reed valve structure. In order to suppress the flow path loss by the reed valve structure, it is necessary to increase the cross-sectional area of the discharge port, but it is difficult due to radial restrictions. Therefore, 2 discharge ports are installed in upper and lower side of each compression chamber, and it is tried that the discharge flow loss is reduced.

In addition to the reliability of the valve, the multi discharge valve structure is examined along following 3 focused items. In a general rotary compressor, the discharge port on the bearing side can obtain a sufficient muffler volume for suppressing the pressure pulsation of the discharge gas. While, if the discharge port on the partition plate side between the compression chambers has the same muffler volume, the distance between the eccentric of crankshaft is long and the crankshaft reliability is worse. In the 3-cylinder rotary structure, the eccentric crank shaft are arranged at an equal distribution of 120 °, so the ability to respond of the reed valves and the interference between the reed valves affect the compressor performance compared to the 2-cylinder rotary structure with a 180 ° phase. Therefore, there is a possibility to affect a performance by the discharge gas flow path loss and flow confluence loss from each compression chamber.

In consideration of these, the multi valve structure having a plurality of discharge valve and a muffler structure in one compression chamber is examined. The multi valve structure has a discharge valve on the partition plate side in addition to the bearing side. In order to suppress the pressure pulsation of the discharge gas, the discharge port diameter on the bearing side, which can secure a sufficient muffler volume, is large, and the discharge port diameter on the partition plate side, which limits the space volume of the muffler, is small. The required total cross-sectional area was secured by arranging two discharge ports in one compression chamber.

By the discharge valve and the discharge gas path in the upper and lower compression chambers are symmetrically located in the partition plate side, it is aimed to secure the muffler volume and suppress pressure pulsation and passage loss.

In addition, the discharge valve is designed with a spring constant suitable for each discharge port diameter, and high performance is achieved by effectively opening and closing each valve in the operating range of low rotation to high rotation (low load to high load).

Figure 7 shows the arrangement of multi discharge valve structure, figure 8 and 9 show discharge gas flow path of the discharge valve on bearing and on partition plate side, and figure 10 shows the performance results. As shown in figure 10, the 3-cylinder rotary compressor has achieved a large capacity of over 20HP (56kW), and in the comparison of 56kW efficiency, the efficiency of 3-cylinder rotary compressor is 3.5% higher than 2-cylinder rotary compressor equipped with VRF products of current model.

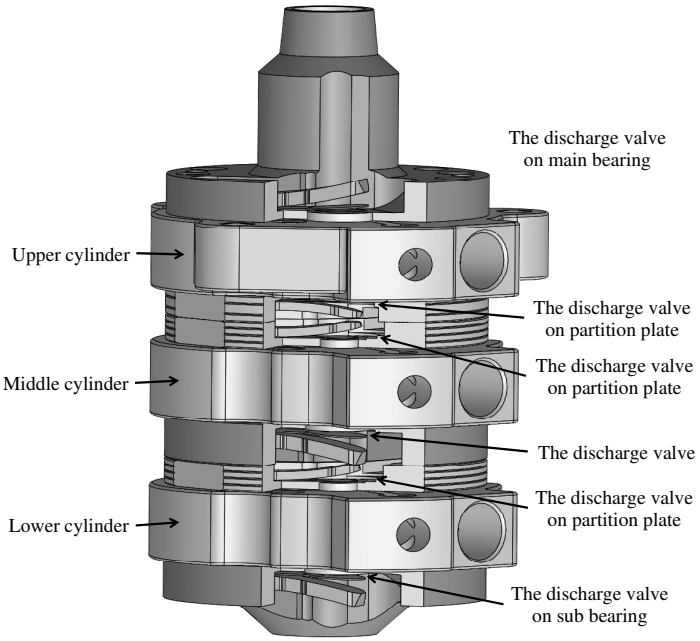

Figure 7 : The arrangement of multi discharge valve structure

Figure 8 : The discharge gas flow path of the discharge valve on bearing

Figure 9 : The discharge gas flow path of the discharge valve on partition plate

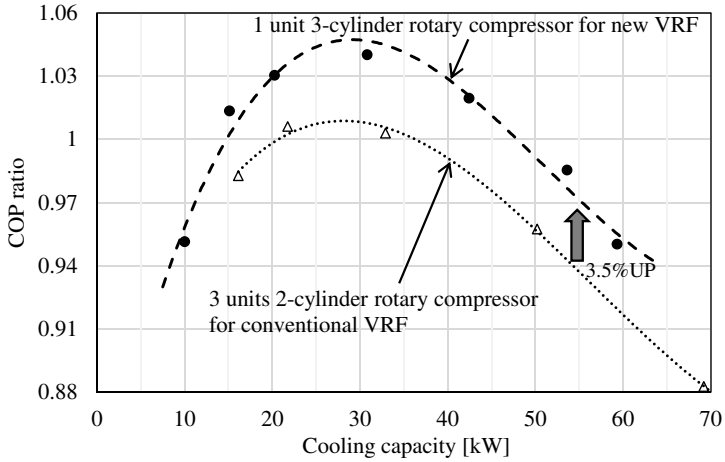

Figure 10 : The performance results between 2 and 3-cylinder rotary compressor

The behavior of the discharge valve (reed valve) installed in each compression chamber is measured by inductive displacement sensor installed in each discharge valve holder. The vertical line shows the maximum lift amount of each valve and the horizontal one the shaft rotating machine angle in figure 11.The operating condition is 90 [1/sec] equivalent to the rated cooling condition.

In each compression chamber discharge valve, the trend can be confirmed that the discharge valve on partition plate side starts to open first and then the discharge valve on bearing side starts to open. In addition, the discharge valve on partition plate side opens and closes twice while the discharge valve on bearing side opens and closes once.

This is designed to make the spring constant of the discharge valve on partition plate side smaller than that of the discharge valve on bearing side, making it easier to open for preventing over-compression and reducing the residual gas in the compression chamber, that is, reducing the re-expansion loss.

On the other hand, in the case of the operation of each the discharge valve on partition plate side is compared, the discharge valve on partition plate side operation of the lower compression chamber tends to be different from that of the middle and upper compression chambers. The reason is presumed that the pressure in the lower flow path is slightly higher than other flow paths due to the gas flow paths in the lower compression chamber is longer than the gas flow path in the middle and upper compression chambers. It can also be confirmed that the discharge valve on partition plate side with a small spring constant functions effectively for the interference of each valve and achieve highly responsive behavior without closing delay.

While, figure 12 shows the valve behavior results in 30[1/sec] condition in which the gas flow rate was reduced under the pressure condition equivalent to the rated cooling condition. In this case, the discharge valve on partition plate side functions as the main discharge flow path instead of the discharge valve on bearing side, and the discharge valve on partition plate side contributes to the performance improvement by suppressing over compression.

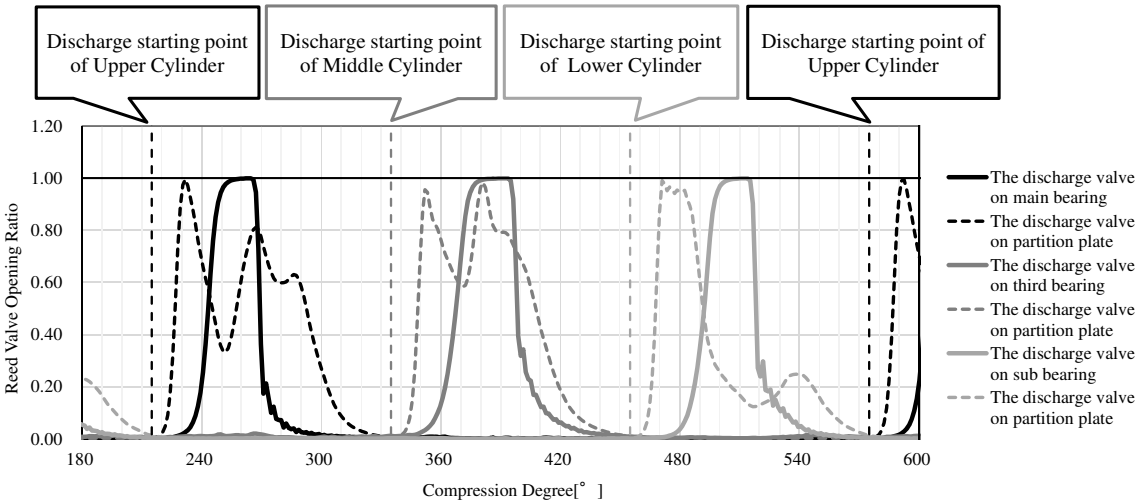

Figure 11 : The behavior of discharge valve in three compression chambers (at rotation speed 90[1/sec])

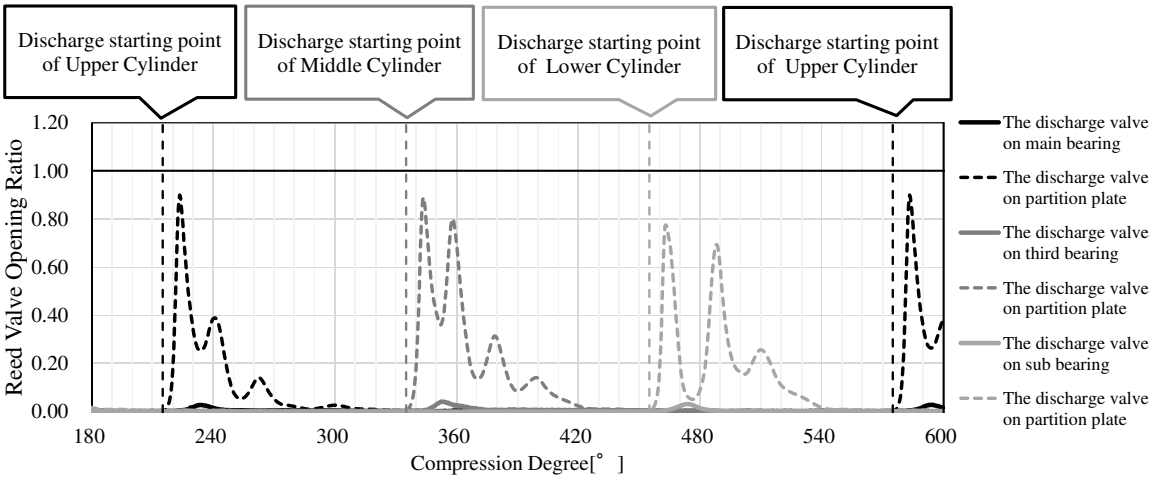

Figure 12 : The behavior of discharge valve in three compression chambers (at rotation speed 30[1/sec])

2.3 New wide range motor (Open winding motor)

In the actually operating air conditioner, the compressor has been operating under the low load operating region for a long time, and the performance improvement in the low load operating region leads to the reduction of the seasonal power consumption and the annual electricity bill. In a general DC inverter motor, the motor efficiency in the low load operating region is improved by reducing the wire diameter and increasing the number of the winding. In this method, the current increases in a high load operating region, so-called field weakening control is used to realize operation under the high speed rotation, but the motor efficiency decreases. Therefore, we have developed the world's first open winding motor (*) as a compressor for air conditioners. (* According to internal research as of July 2020)

Open winding motor is used with dual-state inverters that was developed at the same time as a drive controller.

In addition, open winding motor has a three-phase alternating current with the neutral points separated.

This system is operated with star winding motor drive during load operation below the middle level, and is operated by switching the open winding motor drive during high load operation.

In the case of operating with a star winding motor drive, the motor is driven by one inverter, and operating with an open winding motor drive, the winding is switched and the motor is driven by two inverters.

At the time of open connection, it is possible to apply a voltage about 1.7 times of a standard inverter, and it is possible to operate with a high winding motor at high load operation without decreasing efficiency. Figure 13 shows open winding motor, and figure 14 shows the applied voltage of the open winding motor.

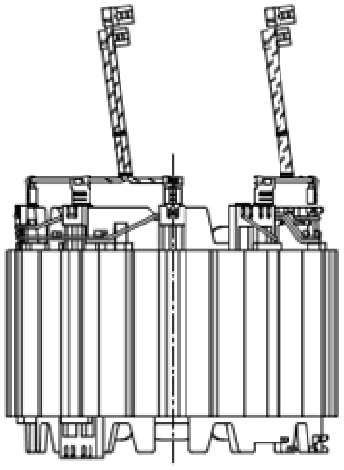

Figure 13 : New wide-range motor

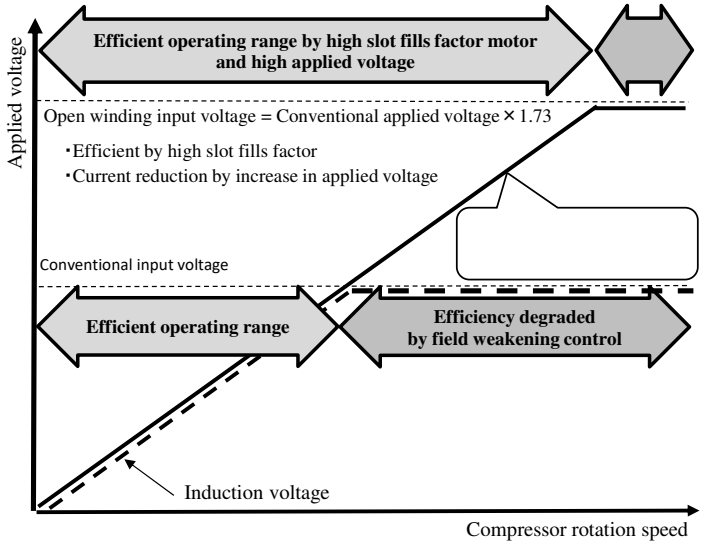

Figure 14 : Relationship between DC-voltage and rotation speed

As shown in figure 15, dual state inverter is composed of two inverters. In the case of the high load operation, the two inverters are used to operate the open winding motor drive. On the other hand, as shown in figure 16, in the case of the low load operation, the inverter loss is reduced and high-efficiency operation is maintained by driving one inverter and stopping the other inverter with star winding motor drive.

Figure 17 shows a performance comparison between open winding and star winding motor drive. Star winding motor drive is superior in the low load operation region, and open winding motor drive is superior in the 20HP (56kW) rated operation region. High-efficiency operation is realized in wide range operation region by selecting the optimal winding according to the operating conditions.

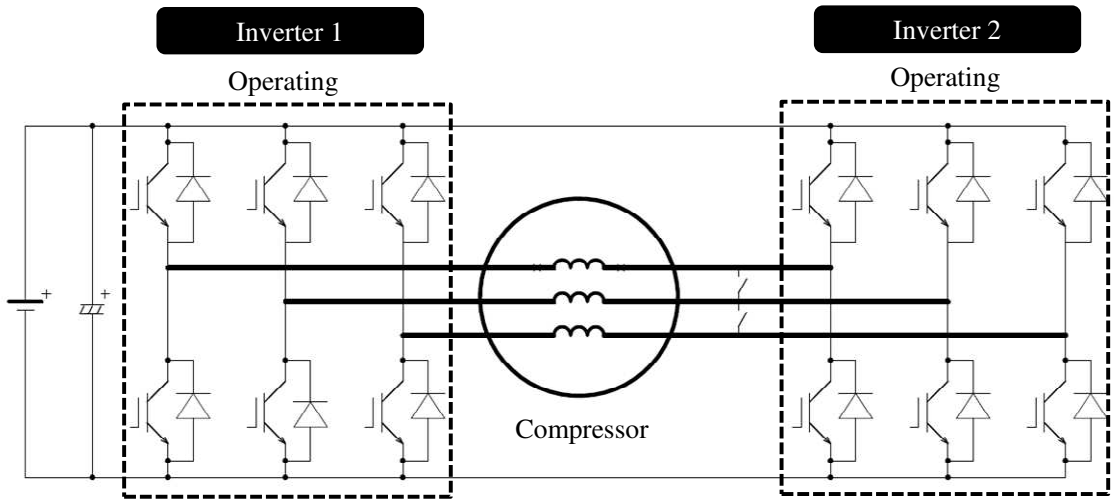

Figure 15 : Operating with open winding

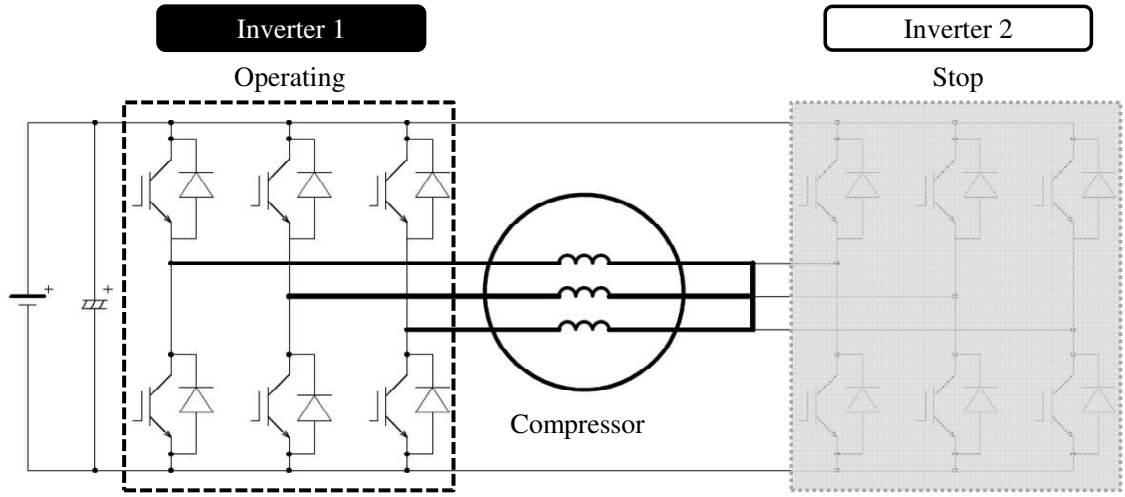

Figure 16 : Operating with star winding

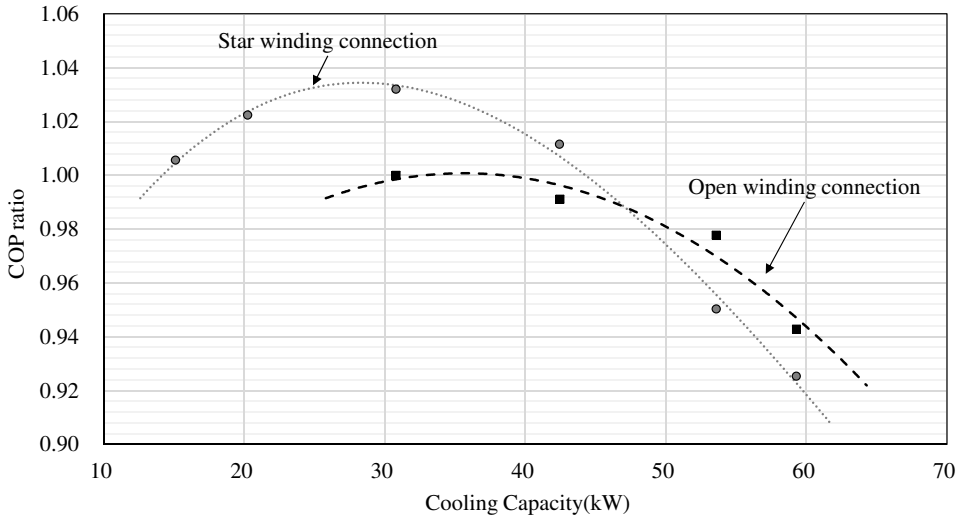

Figure 17 : Performance comparison between open winding and star winding.

3. CONCLUSION

This time, we achieved the development of 3-cylinder rotary compressor with 3 compression chambers and a shaft eccentric angle of 120 °. 3-cylinder rotary compressor is a compact compressor that can obtain a large capacity based on 2-cylinder rotary compressor. 3-cylinder rotary compressor not only has low vibration and small sound, but also realizes high efficiency and wide range of operation from low load to high load by open winding motor and a dual state inverter. In particular, the vibration of 3-cylinder rotary compressor achieve 78% lower comparing with 2-cylinder rotary compressor. For this reason, the large air-conditioning products that used multiple compressors can install one compressor. And, it can contribute to weight reduction, resource saving, and space saving of air-conditioning products.

In the future, using the 3-cylinder rotary compressor as a platform, we will make efforts to reduce the environmental footprint by promoting to lower GWP of the refrigerant and expanding it to various product applications.

REFERENCES

[1] Hirayama. T., Aoki. T., Shida. S., et al., (2017). Study on Large Capacity and High Efficiency of Rotary Compressor. *Trans. of the JASRAE, 34*(3), P261-271.

[2] Kimura. S., Hirayama. T., Aoki. T., et al., (2017). Development of High Efficiency and Large Capacity Rotary Compressor. Proceedings of 2017 JASRAE Annual Conference, Tokyo, B213, JASRAE.

[3] Shida. S., Shishimoto. T., Toda. H., (2020). Development of Large Capacity Rotary Compressor for VRF. *Toshiba Review.*

[4] Hirayama. T., "Rotary Compressor and Refrigeration Cycle Device" (in Japanese), 2011, Japanese Patent 6022247