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# Development of 3D Scroll Compressor and Its Application

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## ABSTRACT

Scroll compressor has been employed in various applications due to its advantages such as high efficiency and low vibration. For the purpose of further performance improvement in scroll compressor, the authors have developed a new conceptual three-dimensional compression mechanism (3D scroll) by adding an axial compression to the conventional radial compression. By realizing three-dimensional compression, which has been impossible for the conventional scroll, higher efficiency, higher reliability, and smaller size are achieved. Authors have taken advantages of these characteristics and developed 3D scroll compressors for commercial air-conditioner, heat pump water heater, gas engine heat pump, reefer truck refrigeration unit and automotive air-conditioner. The developed 3D scroll compressors archived substantial efficiency improvement and downsizing compared with the conventional compressor.

## 1. INTRODUCTION

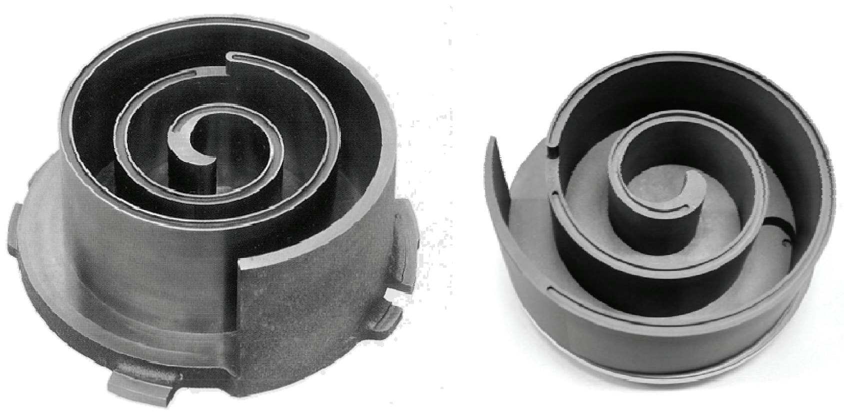
A demand for saving energy has been further increasing from the viewpoint of environmental conservation against global warming. Since most energy in refrigerating and air-conditioning systems is consumed by the compressor, the efficiency improvement in the compressor is indispensable for saving energy. Meanwhile, since the installation space of refrigeration and air-conditioning systems is often restricted, downsizing of each component including the compressor is required to enhance the flexibility of installation and construction.

Scroll compressor, which has advantages such as high efficiency and low vibration, has been used for various applications to meet the demand for saving energy and its use is expected to spread increasingly. For the purpose of further performance improvement in scroll compressor, authors have developed a new conceptual three-dimensional compression mechanism (3D scroll) that adds an axial compression to the conventional radial compression, and have adopted the 3D scroll for wide range of applications.

This paper describes the efficiency improvement and downsizing technology of the 3D scroll compressor and its application to various refrigeration and air-conditioning systems.

## 2. FEATURES OF THE 3D SCROLL

Figure 1 shows a schematic diagram of the sectional view of the conventional and the 3D scroll, and Figure 2 shows photographs of the orbiting scroll of the 3D scroll compressor for commercial and automotive air-conditioner. The wrap height of the conventional scroll is constant throughout the compression process, and the refrigerant is compressed two-dimensionally from the outer side to the inner side by the orbiting motion of the orbiting scroll. For



(a) For commercial air-conditioner (b) For automotive air-conditioner

Figure 1: Orbiting scrolls of the 3D scroll compressor

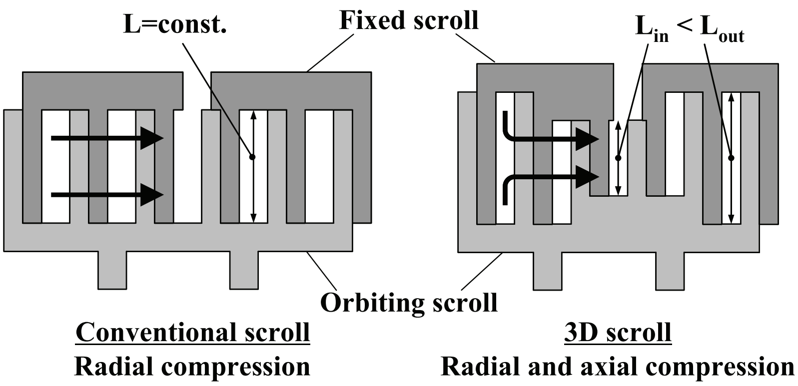



Figure 2: Sectional view of the conventional and the 3D scroll

the 3D scroll, in contrast, the outer wrap is higher than the inner one by installing steps in the scroll tip and the end plate. Therefore, three dimensional volume change, radial and axial direction, becomes possible.

The 3D scroll has the following features.

- Higher compression ratio is obtained by adding axial compression to the existing radial compression.
- The strength of scroll wrap is improved and higher reliability is obtained by decreasing the height of inner wrap which receives a heavy load.
- Larger capacity is obtained without extension of the outer diameter of scroll by increasing the height of outer wrap, and thus the 3D scroll is suitable for downsizing.

These features satisfy the required performances on wide variety of refrigeration and air-conditioning products with different usage and operating condition. Table 1 shows an aptitude of the 3D scroll for each product. The

Table 1: Aptitude of the 3D scroll for each product

| | Higher compression ratio | Higher strength of scroll | Larger capacity | Smaller size and lighter weight |
|---|---|---|---|---|
| Commercial air-conditioner | + | + + | + + | + |
| Heat pump water heater | + + | + + | + + | + |
| Refrigeration unit | + + | + + | + + | + |
| Automotive air conditioner | + + | + + | + | + + |
| Reefer truck refrigeration unit | + + | + + | + | + + |

introduction of 3D scroll satisfies various requirements specific to each product such as larger capacity in commercial air-conditioners, higher compression ratio in refrigeration unit and downsizing in automotive air-conditioner.

The compression mechanism of the 3D scroll is shown in Figure 3. The 3D scroll has steps in the scroll tip (tip step) and the end plate (bottom step). When these steps are not engaged ((b), (d)), compression chambers across the step have the same pressure. In this range, the compression proceeds as if both chambers are one combined chamber. On the other hand, when the steps are engaged ((a), (c)), seal lines are formed by the engagement of both steps.

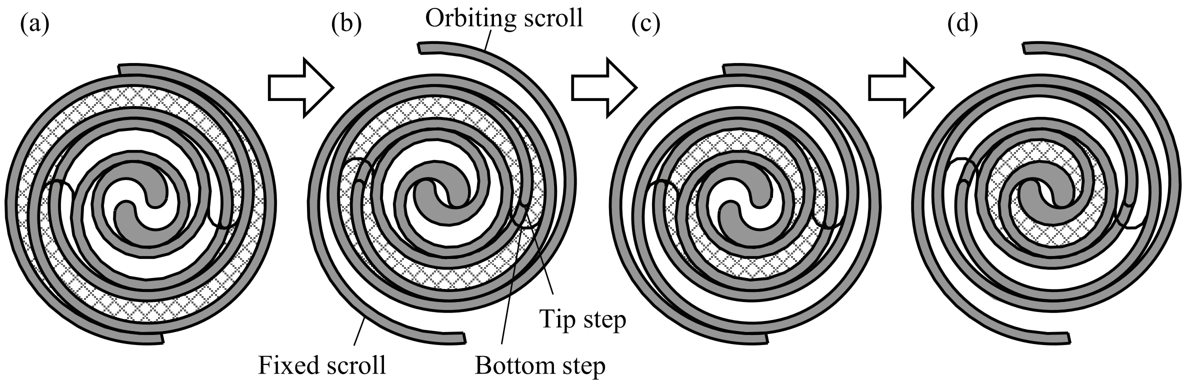



Figure 3: Compression mechanism of the 3D scroll

## 3. EFFICIENCY INPROVEMENT OF THE 3D SCROLL

Since the 3D scroll has the seal lines composed of the tip step and the bottom step, additional leakage clearances appears in the steps which the conventional scroll does not have. Therefore, the key point of efficiency improvement in the 3D scroll is to minimize the gas leakage in the steps. Authors focused on the fact that gas leakage decreases due to the sealing effect of the lubricant oil contained in refrigerant gas and studied the leakage characteristics of the step clearances using a visualization experiment in the step section.

The prototype compressor for visualization equips a sight glass in the end plate of the fixed scroll, and the orbiting motion of the orbiting scroll and the behavior of leakage flow in the steps were visualized with a high speed video camera. Figure 4 shows an example of test result. The bottom step of the fixed scroll is shown as a semi-circular portion in the upper area and the tip step of the orbiting scroll is shown in the middle area, and the right side of the wrap is higher pressure chamber, and the left side is lower pressure chamber in each photograph. Figure 4(a) shows the condition just after engagement between the tip step of the orbiting scroll and the bottom step of the fixed scroll. This engagement continues until Figure 4(d), and then the tip and the bottom step separates and the compression chambers on both sides of the steps have the same pressure. The tip step comes again the position in Figure 4(a) with the orbiting motion proceeding.

Figure 5 shows the comparison with the oil circulation ratio (OCR). Focusing on the step clearance marked with circles, it is found that there is no oil in the clearance when the OCR is small (Figure 5(a)). In this case, the occurrence of gas leakage is considered. On the other hand, when the OCR increases as shown in Figure 5(b), the clearance is filled with oil and oil flow along the bottom step is also observed. Figure 6 shows the comparison with the magnitude of clearance setting the OCR at a constant value. The clearance is filled with oil when it is small as in Figure 6(a). However, when the clearance is large as in Figure 6(b), it is no longer filled with oil and the gas leakage occurs. This indicates the required OCR to seal the step clearance depends on the magnitude of clearance, and it can be also important to set the oil content in the cylinder at a proper value.

By the above-mentioned visualization tests as well as performance analyses, the proper clearance range in order to keep high efficiency is determined.

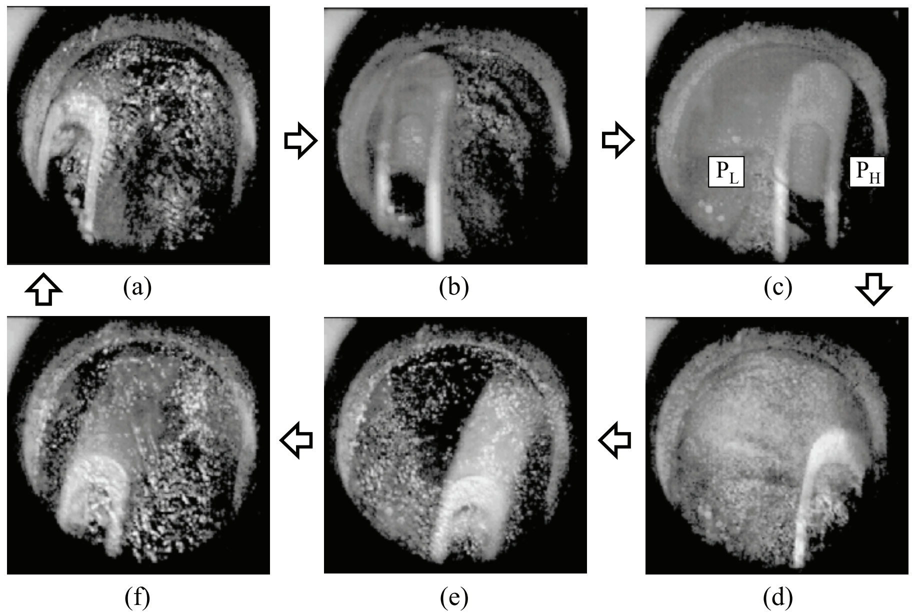
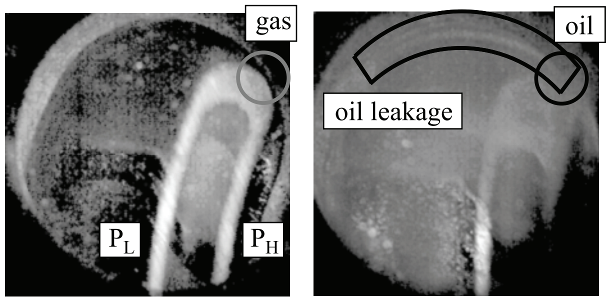
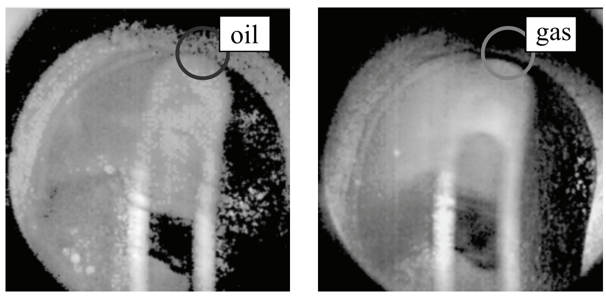



Figure 4: Visualization of the step




(a) OCR = small (c) OCR = large

Figure 5: Leakage flow variation with the OCR




(a) Clearance = small (b) Clearance = large

Figure 6: Leakage flow variation with the magnitude of step clearance

## 4. IMPROVEMENT OF COMPRESSOR RELIABILITY

One of the reliability issues of compressors is related to their strength when liquid compression occurs. When the compression chambers suck incompressible liquid refrigerant during operation, a rapid pressure increase occurs as shown in Figure 7. If the compressor is driven by an inverter such as a residential air-conditioner, liquid compression can be avoided by controlling the compressor rotation speed using the inside/outside temperature information. However, when a compressor is driven by an engine, as in the case of a reefer truck refrigeration system, the compressor rotation speed is independent of the refrigeration cycle. Therefore, liquid compression may occur depending on the operating condition. Since the ratio of volume change in the 3D scroll is larger than the conventional scroll due to the three dimensional compression, it is more important for the 3D scroll to prevent pressure increase when liquid refrigerant enters the compression chamber.

This problem has been solved by improvement of relief port. Figure 8 shows the port layout in conventional and improved 3D scroll compressor for reefer truck refrigeration system. By improvement of the port layout, the relief function was enhanced over the entire compression process. Figure 9 shows the maximum pressure that occurs at startup when the compressor is filled with liquid refrigerant. The improved relief ports are able to prevent occurrence of abnormally high pressure in all rotation speeds.

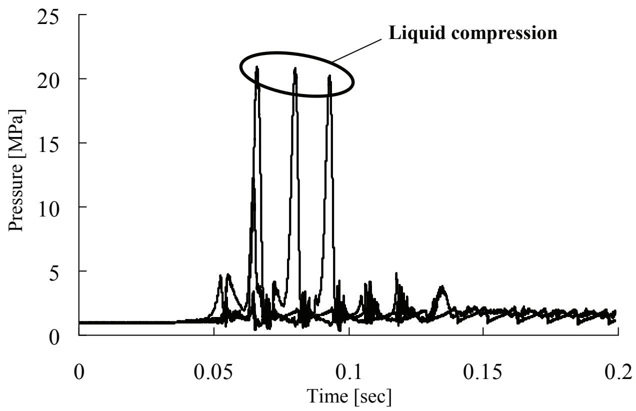
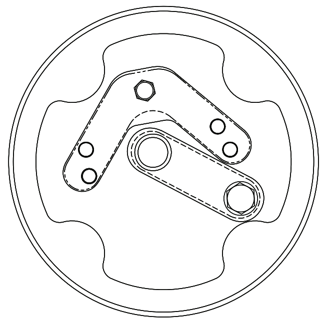
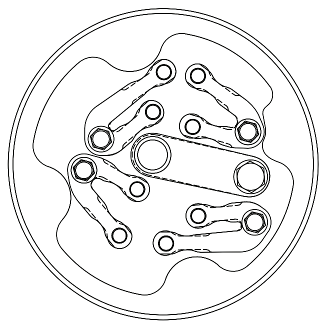



Figure 7: Pressure waveform in a liquid compression



(a) conventional relief ports



(b) improved relief ports

Figure 8: Relief port layout

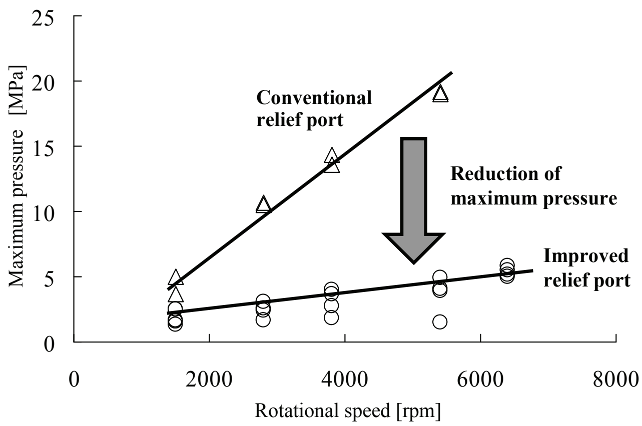
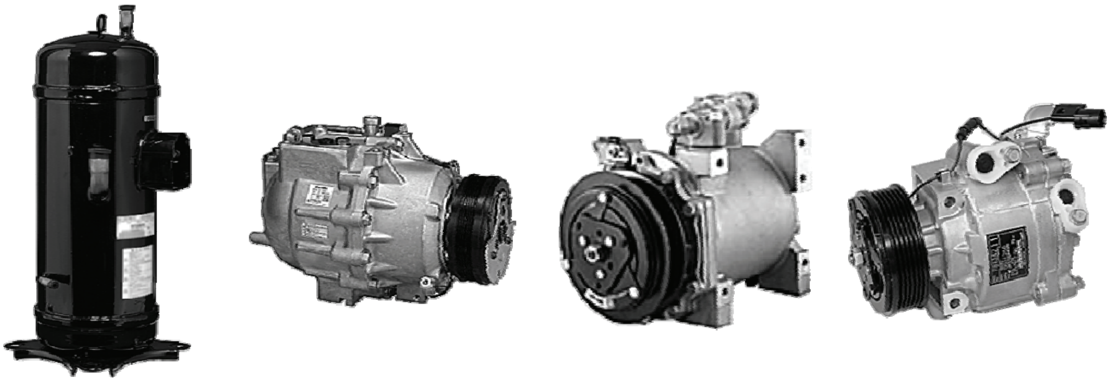



Figure 9: Pressure reduction by relief port improvement

## 5. APPLICATION OF THE 3D SCROLL COMPRESSOR

As described above, 3D scroll has the characteristics such as higher compression ratio, higher strength of the scroll and smaller size. Authors have taken advantages of these characteristics and developed 3D scroll compressors for commercial air-conditioner, heat pump water heater (Sato *et al*. 2008), gas engine heat pump (Miyamoto *et al*. 2004), reefer truck refrigeration unit (Fujitani *et al*. 2007) and automotive air-conditioner (Takeuchi *et al*. 2008) as shown in Figure 10. This section describes the application of the 3D scroll compressor to refrigeration and air-conditioning systems.



**For commercial air-conditioner/heat pump** | **For gas engine heat pump** | **For reefer truck refrigeration unit** | **For automotive Air-conditioner**

Figure 10: 3D Scroll Compressors

## 5.1 Efficiency Improvement

Figure 11 shows the efficiency variation against the operating pressure ratio in the conventional scroll and the developed 3D scroll compressor for commercial air-conditioner. In this figure, the efficiency is normalized by the representing value (Pd/Ps = 3.4) of the conventional scroll. Since the 3D scroll achieves a high compression ratio by both radial and axial compression, an indicative loss due to a lack of compression ratio (re-compression loss) is reduced. Therefore, the efficiency on high pressure ratio condition is substantially improved compared with the conventional scroll compressor. This indicates that the 3D scroll has a special advantage for applications operating under high compression ratio such as heat pump for cold area and refrigeration. For low pressure ratio condition, the efficiency is also kept high by introducing bypass mechanism which releases the refrigerant gas in the compression process to the discharge chamber to prevent excessive compression. By the combination of the three dimensional compression and the bypass mechanism, the efficiency improvement over a wide range of operating conditions was archived.

Figure 12 compares the efficiency of the developed 3D scroll compressors with the conventional compressors for commercial air-conditioner, automotive air-conditioner, reefer truck refrigeration unit and gas engine heat pump. The developed 3D scroll compressors resulted in a 6% efficiency improvement compared to conventional scroll compressors and a 15% improvement to conventional reciprocating compressors.

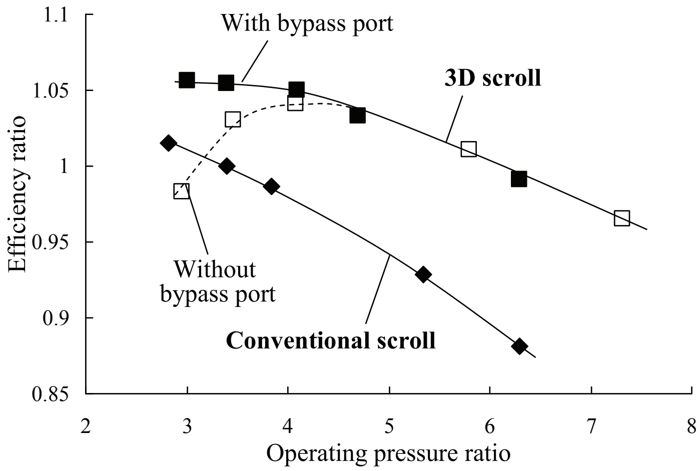



Figure 11: Efficiency variation against operating pressure ratio

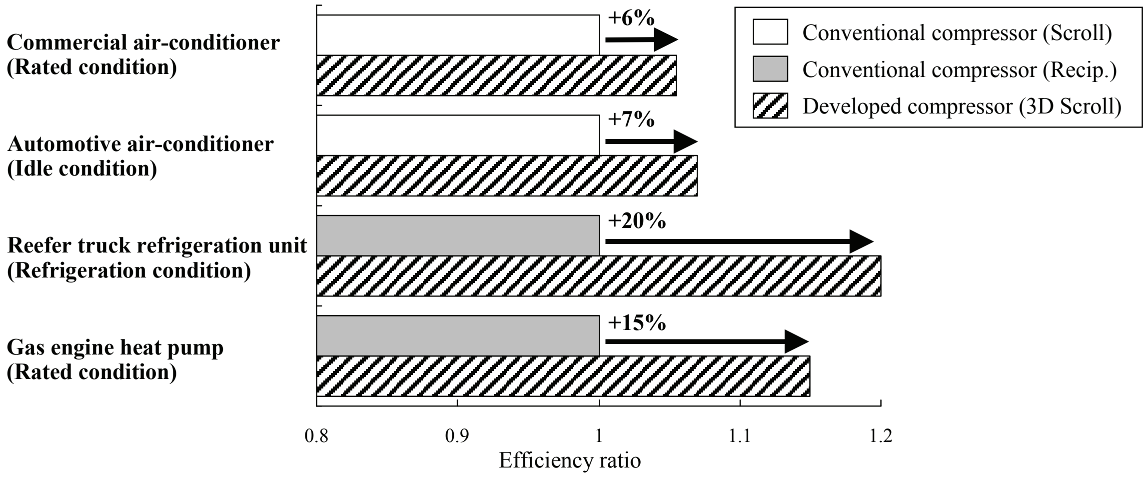



Figure 12: Efficiency improvement of the developed 3D scroll compressor

## 5.2 Downsizing

The displacement volume of scroll compressor is determined mainly by the scroll diameter and the wrap height. In order to increase the displacement, the scroll diameter must be increased because there is a limitation of wrap height due to the strength of scroll. However, the introduction of the 3D scroll made it possible to increase the outside wrap height which determines the displacement without increasing the inner wrap height and thus a substantial downsizing is realized. Figure 13 shows the outside dimensions of the conventional and the developed 3D scroll compressors. The compressor size and weight are significantly reduced compared to conventional one in each product, resulting in improvement of installation flexibility.

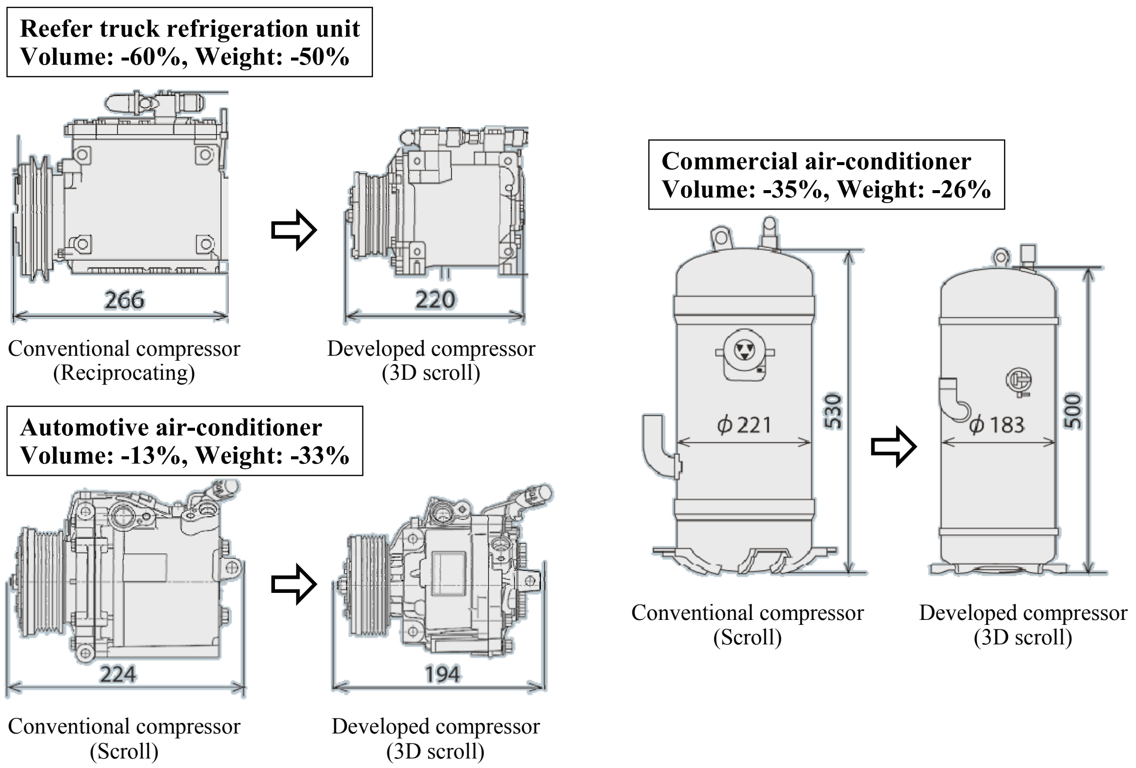



Figure 13: Outline of the conventional and the developed 3D scroll compressors

## 6. CONCLUSIONS

The 3D scroll has the features of high efficiency, high reliability, small size and lightweight that is the most desired quality to improve the performance of refrigeration and air-conditioning systems. These features were enhanced by the approaches of leakage reduction in the steps and suppression of liquid compression described in the paper.

Authors have taken advantages of these characteristics and developed 3D scroll compressors for commercial air-conditioner, heat pump water heater, gas engine heat pump, reefer truck refrigeration unit and automotive air-conditioner. In every developed 3D scroll compressor, substantial efficiency improvement and downsizing were archived compared with the conventional compressor.

The use of scroll compressor is expected to future expand due to its excellent basic properties. Authors are planning to develop 3D scroll compressors for wider range of applications.

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