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Development of an Evolutionary Three-Dimensional Scroll Compressor

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ABSTRACT

A novel three-dimensional scroll compressor was developed. The authors have produced 3D scroll compressor since 2006. The 3D scroll is able to compress refrigerant in axial direction as well as in existing radial direction by employing steps at the bottom and the tip of the scroll which change the height of compression chamber on the middle of the compression process. For the purpose of further performance improvement, the authors developed an evolutionary three-dimensional compression mechanism, named "e-3D scroll". The e-3D scroll is equipped with a sloped tip and a sloped end plate in each scroll instead of steps in the conventional 3D scroll. The height of compression chamber decreases continuously with progression of compression by the sloped shape. The e-3D scroll has advantages of high efficiency, high compression ratio, large capacity and high strength compared to the conventional two-dimensional or three-dimensional scrolls. Performance tests showed that there exists an optimum range of slope angle in order to maintain high efficiency and the developed e-3D scroll compressor for heat pump modular chiller and VRF application achieved up to 4.8% improvement in efficiency compared to the conventional 3D scroll compressor.

1. INTRODUCTION

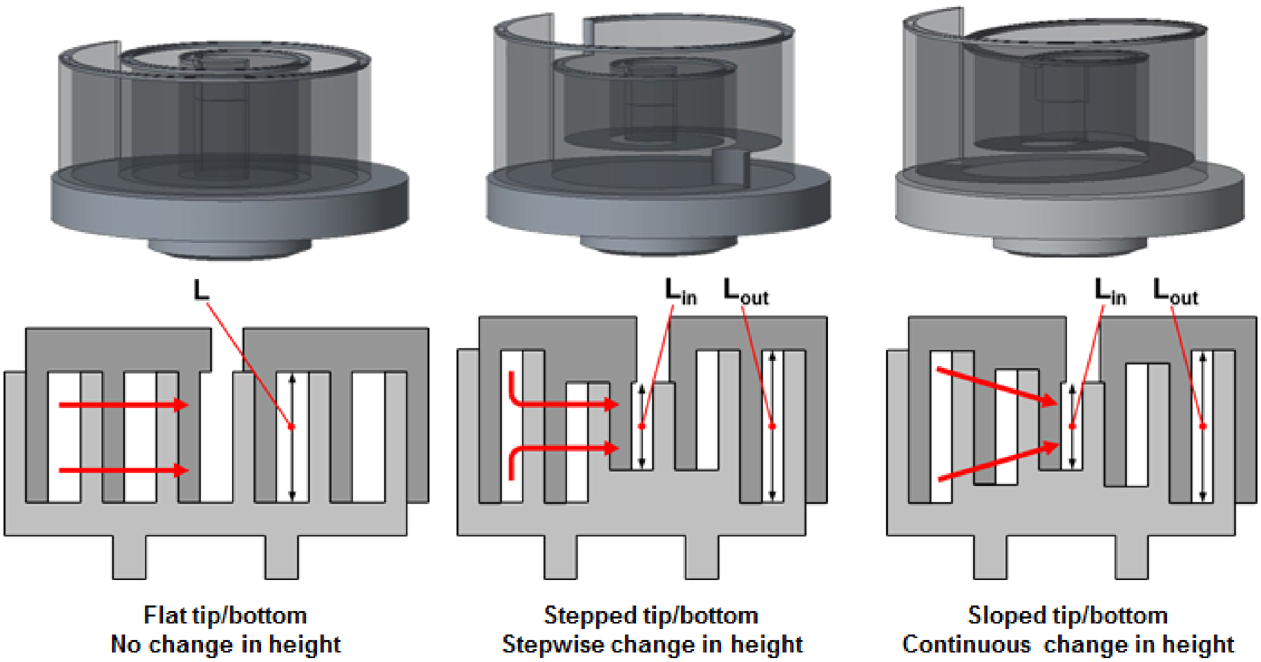
A scroll compressor is characterized by high efficiency and low vibration arising from its unique compression mechanism. It has been used for decades in various fields of air-conditioning and refrigeration systems. The authors have produced three-dimensional scroll compressor (Sato *et al*., 2008) since 2006. The 3D scroll is able to compress refrigerant in axial direction as well as in existing radial direction by employing steps at bottom and tip of the scroll which change the height of compression chamber on the middle of compression process. This structure provided us with higher compression ratio, larger capacity and smaller size of the compressor and has been employed on various air-conditioning and refrigeration systems in the past ten years. Meanwhile, the 3D scroll has additional leakage clearances formed by an engagement of the tip step and the bottom step. It is required for further performance improvement to eliminate leakage losses in the step clearances.

The authors developed an evolutionary three-dimensional compression mechanism, named "e-3D scroll". This article describes structure and compression mechanism of the e-3D scroll and development of a large capacity e-3D scroll compressor which attained drastic efficiency improvement.

2. STRUCTURE OF THE e-3D SCROLL

2.1 Features of the e-3D scroll

Figure 1 shows a cross-sectional diagram of the conventional two-dimensional (2D) scroll, three-dimensional (3D) scroll and the developed e-3D scroll. The wrap height of the 2D scroll is constant throughout the compression



(a) Conventional 2D scroll (b) Conventional 3D scroll (c) Developed e-3D scroll

Figure 1: Cross-sectional diagram of the conventional 2D/3D and the developed e-3D scroll

process, and the refrigerant is compressed two-dimensionally from the outer side to the inner side. On the other hand, the 3D scroll has two different wrap heights. The outer wrap is higher than the inner one by installing steps in scroll tip and end plate.

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 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.

Introduction of the 3D scroll satisfies various requirements specific to each product such as larger capacity in commercial air-conditioners, high compression ratio in refrigeration systems and downsizing in automotive air-conditioners.

Meanwhile, the 3D scroll has additional leakage clearances formed by an engagement of the tip step and the bottom step. Figure 2 shows a schematic diagram of step clearances and Figure 3 shows a photograph of leakage flow in the step clearance obtained from a visualization test using a high speed video camera. In Figure 3, 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. A leakage flow from the right chamber to the left chamber along with the bottom step can be observed. Although it is known that the leakage loss in the step can be minimized by optimizing an oil circulation ratio as well as the magnitude of clearances, it is required for efficiency improvement of the 3D scroll to eliminate leakage losses in the step clearances.

For the purpose of further performance improvement, the authors developed an evolutionary three-dimensional compression mechanism, named "e-3D scroll". As shown in Figure 1(c), the e-3D scroll is equipped with a sloped tip and a sloped end plate in each scroll instead of the steps in the conventional 3D scroll. The height of compression chamber decreases continuously along with compression process by the sloped shape.

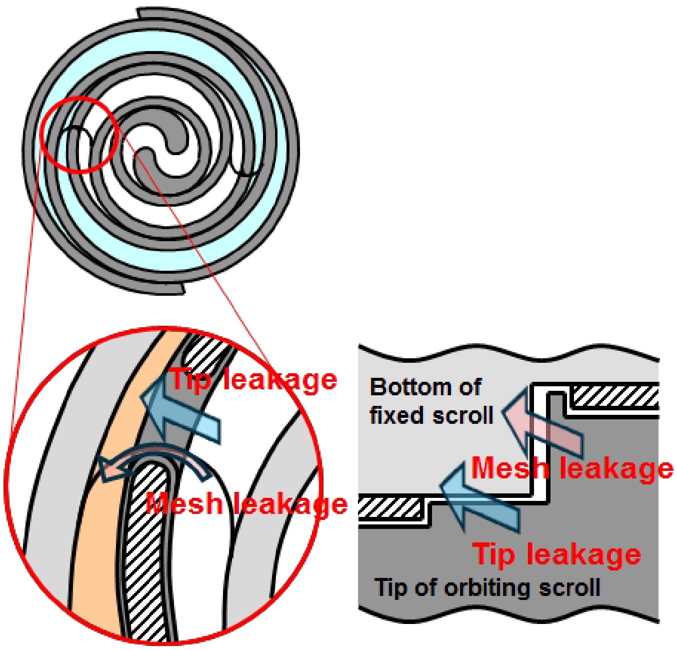


Figure 2: Step clearances in the 3D scroll

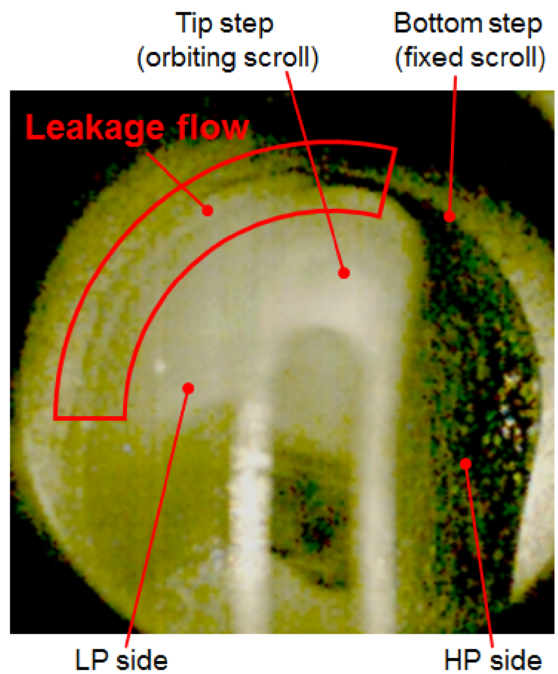


Figure 3: Visualization of leakage flow

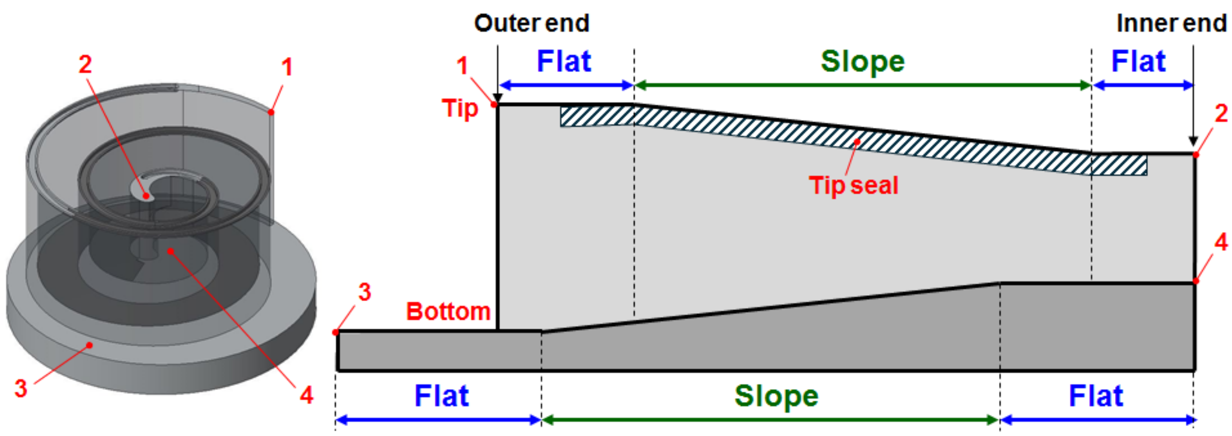


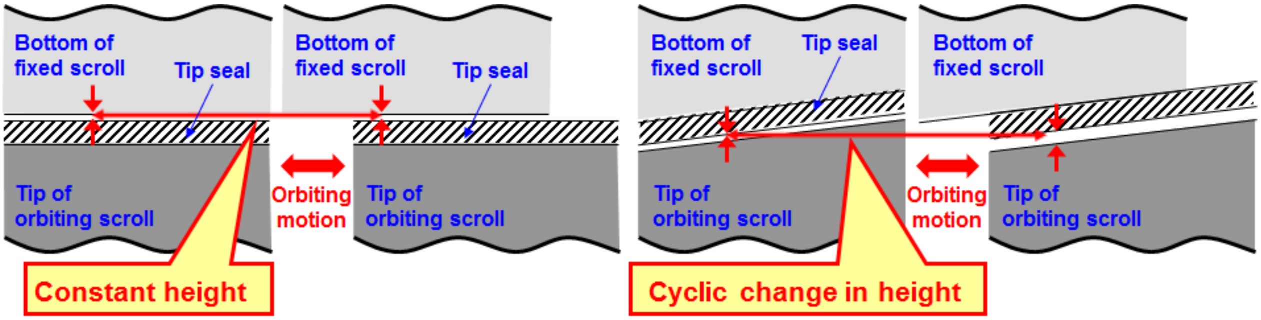
Figure 4: Developed view of scroll wrap in the e-3D scroll

The e-3D scroll has the following features compared with the conventional 3D scroll.

- There are no steps in the scroll tip and end plate. This leads to reduction of leakage loss and improvement in efficiency.
- Advantages of the current 3D scroll, higher compression ratio, higher strength of the scroll, larger capacity and smaller size, are inherited.

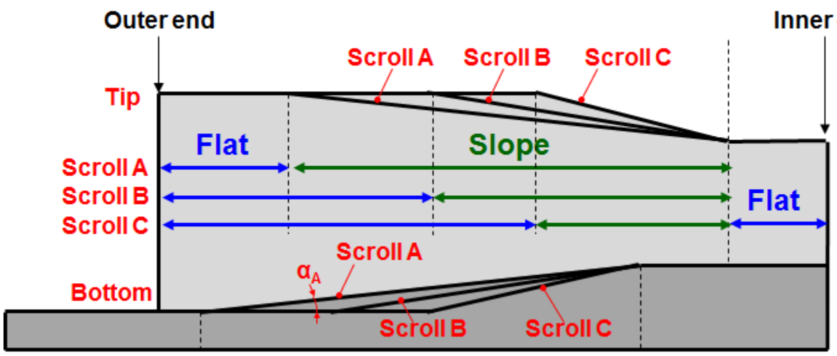
2.2 Compression mechanism of the e-3D scroll

Figure 4 shows a developed view of scroll wrap in the e-3D scroll. The e-3D scroll has sloped tip and end plates so that the height of scroll wrap gradually get smaller from the outer end to the center. In a couple of scrolls, the angle of sloped tip in one scroll is equal to that of sloped end plate in the other one in each position of scroll wrap. However, in the outer end and the center part in each scroll, the shape of tip and plate remains flat in order to be easy to assemble the scroll components.



(a) Conventional 2D/3D scroll (b) e-3D scroll

Figure 5: Behavior of the tip clearance associated with orbiting motion



	Slope range	Flat range	Slope angle
Scroll A	Large	Small	α_A
Scroll B	Medium	Medium	$1.3\alpha_A$
Scroll C	Small	Large	$1.9\alpha_A$

Figure 6: Developed view of prototype e-3D scrolls which have different slope angles

The most important characteristics in the e-3D scroll is that the height of tip clearance changes periodically with orbiting motion of the orbiting scroll due to its sloped tip and end plate. Figure 5 shows behavior of tip clearance associated with orbiting motion in the conventional 2D/3D scroll and the developed e-3D scroll. The conventional 2D/3D scroll has constant height of tip clearance over the rotation of the orbiting scroll because the tip and the end plate of both scrolls are parallel to moving direction of the orbiting scroll. On the other hand, the clearance in the e-3D scroll changes periodically in association with the rotation of the orbiting scroll. Maximum height of the tip clearance per revolution is determined by the slope angle and the orbiting radius, and the minimum value of the tip clearance should be determined in order not to make contact with both scrolls in every operating condition.

Although the tip clearance expands periodically in every rotation, leakage across the tip clearance can be prevented by a tip seal. Since the tip seal is placed continuously over the entire wrap from the center to the outer end in each scroll, there is no leakage in the opening of tip seal which exists in the conventional 3D scroll. The tip seal is made of an elastic material in order to follow the cyclic change in height of tip clearance.

3. IMPACT OF THE SLOPE ANGLE ON EFFICIENCY

As mentioned before, the sloped tip and end plate is placed over the length of scroll wrap except for the outer end and the center part. The slope angle is determined by the height of slope, which is defined as a difference of wrap height between the inner end and the outer end, and the length of slope in a longitudinal direction of scroll wrap. In the slope region, the height of the tip clearance changes periodically with orbiting motion of the orbiting scroll. Although leakage across the tip clearance supposed to be prevented by a tip seal, the slope angle may have an influence on compressor efficiency.

The authors made three pairs of prototype e-3D scrolls which have different slope angle as shown in Figure 6. The slope angles are controlled by changing the length of sloped region. Scroll A has the smallest slope angle. Slope angles in Scroll B and C are 30% and 90% larger than Scroll A respectively by extending the flat region of outer end.

Table 1: Operating conditions

	CT/ET [degC]	Rotating Speed [rps]
Cond. 1	46 / 13	95
Cond. 2	44 / 20	37
Cond. 3	33 / 19	23

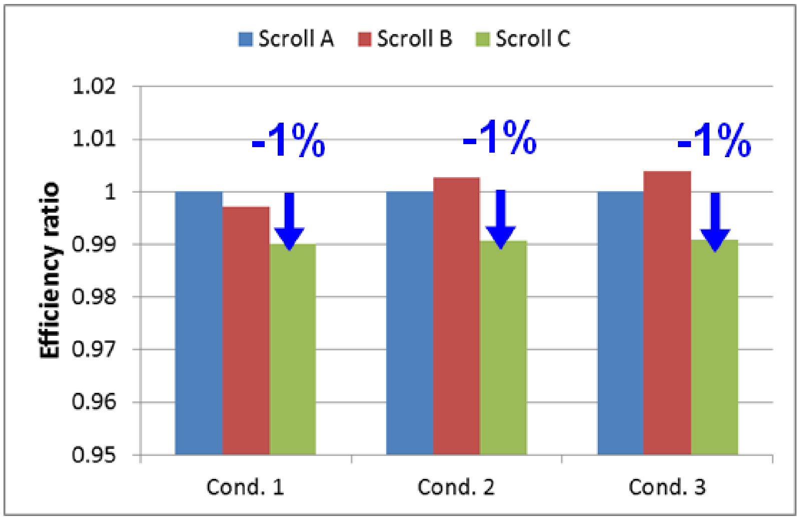


Figure 7: Relationship between slope angle and efficiency

On the other hand, the three scrolls have the same horizontal sectional shape, height of outer wrap and height of slope. Therefore they have almost the same built-in volume ratio and displacement volume.

Figure 7 shows the performance test results on three different operating conditions shown in Table 1. These tests were conducted with the use of one prototype compressor which can replace the fixed and orbiting scrolls to minimize errors from individual difference and clarify only the influence of the slope angle. In Figure 7, the vertical axis shows efficiency ratio normalized by the value of Scroll A. The efficiency of Scroll C was about 1% lower than Scroll A and B in all operating conditions, meanwhile Scroll A and B has almost the same efficiency. Although the difference of efficiency in the three scrolls is relatively small, these results suggest that there exists an optimum range of slope angle in order to maintain high efficiency. Scroll B is adopted as a developed compressor described in the next section.

4. DEVELOPMENT OF A LARGE CAPACITY e-3D SCROLL COMPRESSOR

4.1 Outline of the developed e-3D scroll compressor

The authors developed a large capacity e-3D scroll compressor for heat pump modular chiller and VRF application. Figure 8 and Table 2 show a sectional view and a basic specification of the developed compressor respectively. The developed compressor attained large capacity and small size simultaneously by employing e-3D scroll. The compressor is driven by a concentrated winding blushless DC motor in the lower half of the compressor. A pair of scrolls, fixed scroll and orbiting scroll, is located above the motor. The inside of the compressor is separated into a suction chamber including mechanical parts and a discharge chamber by a partition cover located on the upper side of the fixed scroll. Refrigerant gas is introduced into the compressor through a suction pipe placed on the side of the housing. The refrigerant moves upward and flows into a compression chamber composed of the fixed and the orbiting scrolls. The refrigerant is compressed from the outer side to the inner side and discharged from a discharge port placed at the center of the fixed scroll.

The developed e-3D scroll compressor has the same sectional shape of scroll wrap, height of outer wrap, displacement volume and built-in volume ratio as the conventional 3D scroll. Therefore, the developed e-3D scroll can be employed on the existing model only by replacing the fixed and orbiting scrolls with the developed e-3D scrolls.

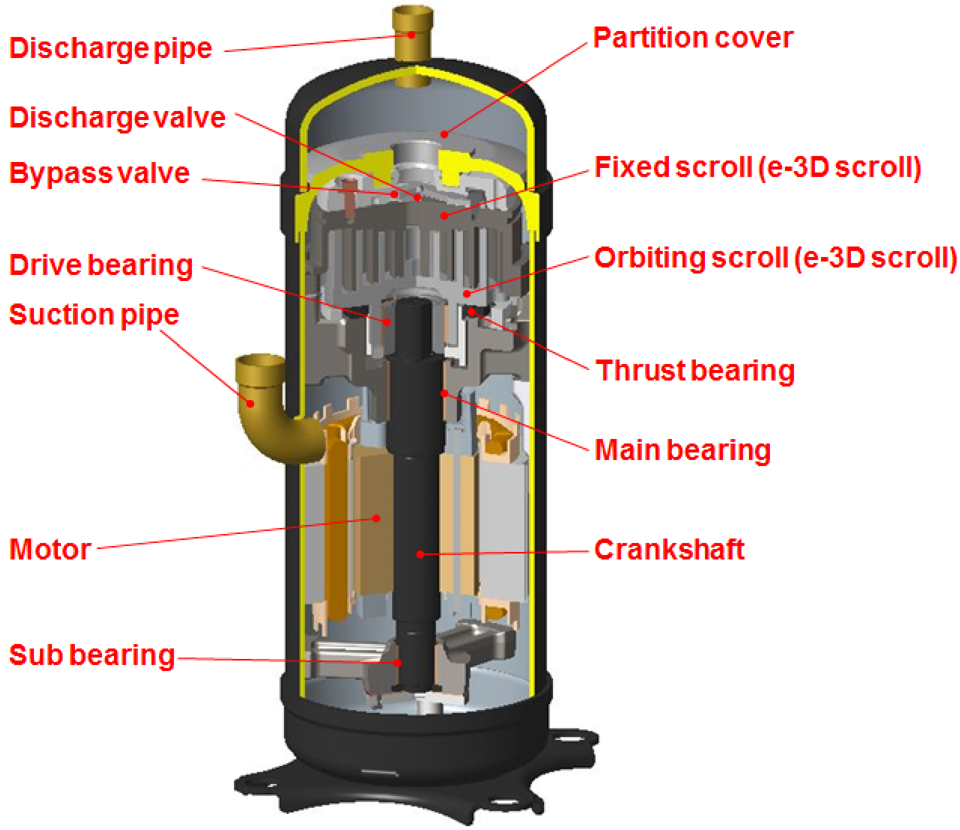


Figure 8: Sectional view of the developed e-3D scroll compressor

Table 2: Specification of the Sectional view of the developed compressor

Applicable products	Heat pump modular chiller, VRF
Refrigerant	R410A
Lubricant	POE
Displacement	$120cm^3/rev$
Scroll	e-3D scroll (Scroll B in Figure 6)
Motor	Concentrated winding BLDC
Outer diameter	183mm
Height	523mm

4.2 Improvement in efficiency

Figure 9 shows comparison of adiabatic efficiency between the conventional 3D scroll and the developed e-3D scroll compressor on the conditions shown in Table 1. The developed e-3D scroll compressor obtained a significant efficiency improvement especially in condition 2 and 3. On these conditions, a leakage loss occupies a large part of total losses because of low rotating speed, and the reduction of leakage loss by employing e-3D scroll leads to drastic increase in efficiency. These low speed conditions are used in partial load operation and make a large contribution to annual performance factor, APF or integrated part load value, IPLV. These efficiency improvements are supposed to contribute to further energy saving in various air-conditioning and refrigeration products.

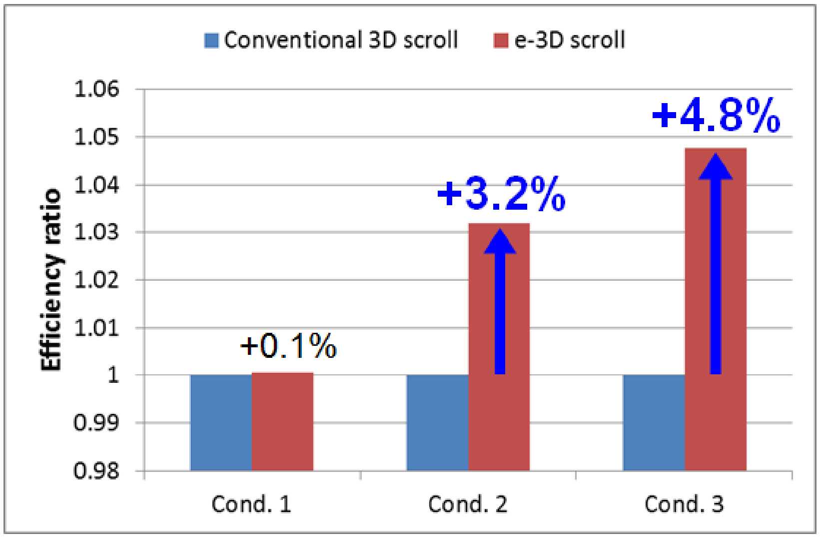


Figure 9: Comparison of adiabatic efficiency between the conventional 3D scroll and the developed e-3D scroll

5. APPLICATION OF THE e-3D SCROLL COMPRESSOR

The e-3D scroll is characterized by high efficiency, high compression ratio, large capacity and high strength compared with the conventional two dimensional or three dimensional scroll compressors. These advantages satisfy various requirements specific to each product such as large capacity in heat pump modular chillers, high efficiency in commercial air-conditioners, high compression ratio in refrigeration systems and small size in automotive air-conditioners. The authors have already developed the e-3D scroll compressor for heat pump modular chiller and continue to develop e-3D scroll compressors for other applications.

6. CONCLUSIONS

In this study, a newly developed evolutionary three-dimensional compression mechanism "e-3D scroll" is described and the following conclusions are obtained.

- The e-3D scroll is equipped with a sloped tip and a sloped end plate in each scroll. The height of compression chamber decreases continuously along with compression process by the sloped shape.
- The e-3D scroll has the advantage of smaller leakage loss compared to the conventional 3D scroll with inheriting the 3D scroll's advantages of higher compression ratio, higher strength of the scroll, larger capacity and smaller size.
- The height of tip clearance in the e-3D scroll changes periodically with orbiting motion of the orbiting scroll due to its sloped tip and end plate. Maximum height of the tip clearance per revolution is determined by the slope angle and orbiting radius. Gas leakage across the tip clearance can be prevented by a tip seal.
- There exists an optimum range of slope angle in order to maintain high efficiency.
- The developed e-3D scroll compressor achieved up to 4.8% improvement in efficiency compared to the conventional 3D scroll compressor.
- The strength of scroll wrap is also improved considerably by absence of steps in the conventional 3D scroll.

REFERENCES

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