Deformation Control of Scroll Compressor for CO2 Refrigerant

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DEFORMATION CONTROL OF SCROLL COMPRESSOR FOR CO_2 REFRIGERANT

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ABSTRACT

The compressors for CO_2 refrigerant have a lot of difficulties to achieve its high efficiency and reliability, because of its very high operating pressure. For the fixed scroll, we decreased the deformation under operation by conducting an adequate initial deformation control in order to cancel the pressure deformation. For the orbiting scroll, we made a slope shape on the tip and bottom of the wrap to decrease the losses due to friction and leakage.

1. INTRODUCTION

From the viewpoint of ozone-layer protection, production of fluorocarbon that contains chlorine is to be phased out by 2020. In addition, HFC refrigerant that is now popularly substituted as alternative refrigerant has been designated as an excretion control gas in COP3 held in the end of 1997 due to its high global warming potential. Thereupon, movements have occurred to review the natural substances as refrigerants for heat pumps, and recently research and development of heat pump systems, using natural refrigerants is being actively promoted. In particular, carbon dioxide (hereinafter called CO_2), with its advantageous non-flammable and non-toxic properties, is becoming a focus of attention from the viewpoint of low global warming potential, and aggressive works are being made to apply CO_2 to the heat pump water heater systems, which have already been commercialized in Japanese markets.
However, compressors for CO_2 heat-pump systems have many problems to be solved in improving performance and securing reliability because of smaller displacement volume per unit capacity and extremely high operating pressure, etc. as compared with conventional air-conditioner compressors. Therefore, with respect to the fixed scroll, examinations were carried out to analytically grasp characteristics of pressure deformation and thermal deformation during operation, as well as to analytically and experimentally grasp welding deformation and bolt tightening deformation. From those examinations, the deformation control is adopted to minimize the deformation during operation. With respect to the orbiting scroll, a slope shape is adopted to compensate leakage pressure deformation and thermal deformation during operation. The slope shape realizes the high efficiency by reducing both the wrap contact friction and the leakage across the tip of the wrap.

2. DEFORMATION OF FIXED SCROLL

Deformations of the fixed scroll during operation fall into the following four categories: (1) pressure deformation due to pressure differences; (2) thermal deformation due to temperature difference; (3) deformation caused by welding for fixing the frame to the shell; and (4) bolt tightening deformation of the compression mechanism. In this study, in order to minimize deformations during operation, deformations (1) and (2) are grasped by numerical calculations in detail, and deformations (3) and (4) are controlled to cancel the deformations (1) and (2) by adjusting the stiffness of fixed scroll.

2.1 Deformation by Pressure Difference

Figure 1 shows the cross-sectional view of our CO_2 scroll compressor that adopts a high-pressure shell. The fixed and orbiting scrolls are mated to form a multiple number of compression chambers. With the orbiting motion, these compression chambers move towards the center while reducing their volume to compress the refrigerant. The orbiting scroll is connected to the crankshaft driven by the motor. The Oldham's ring plays the role of preventing the orbiting scroll from self-rotation. The seal ring is attached between the orbiting scroll and the frame to divide the high-pressure section inside the seal ring and the intermediate pressure section outside the seal ring. By pressing the orbiting scroll against a fixed scroll by that intermediate pressure section, the clearances between the tips of the wrap are reduced to prevent refrigerant leakage in the compression process.

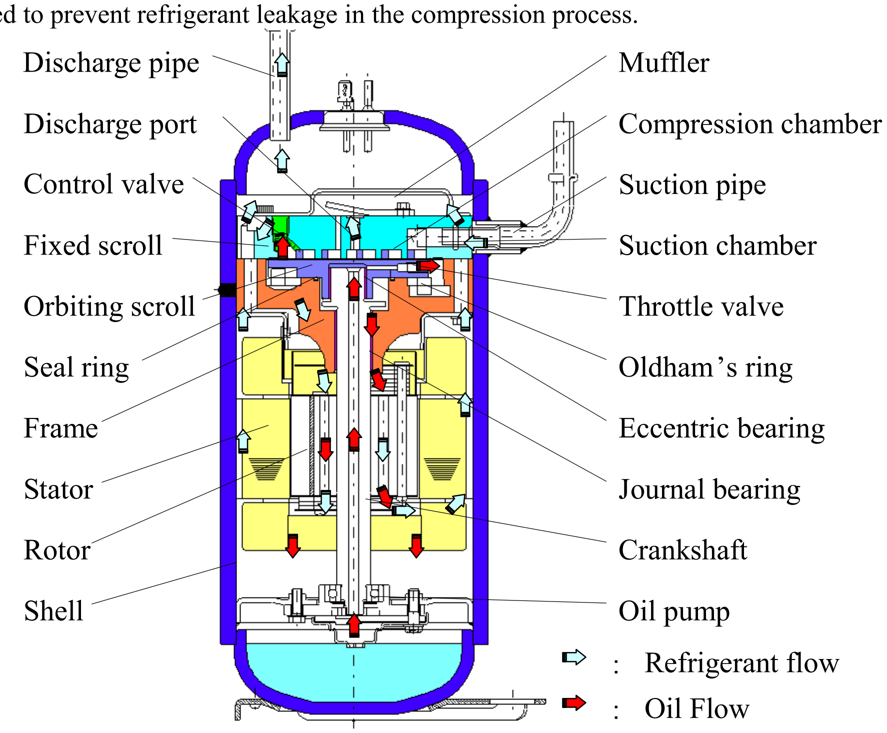


Fig.1 Cross section of the CO_2 scroll compressor

Under the rated operating conditions of CO_2 heat-pump water heater (outdoor air temperature: 16°C; entry water temperature: 17°C; heating up temperature: 65°C), the FEM analysis was carried out on the fixed scroll and the frame. In this analysis, the fixed scroll was approximated as a disk that has equivalent stiffness. Figure 2 shows the analysis results, where the fixed scroll is pressed down by pressure difference (to be concave). We found that the maximum deformation is -11.6 μm with the compressor upward direction designated to be positive.

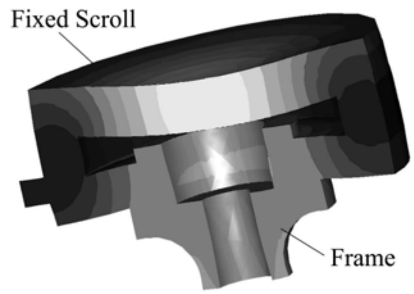
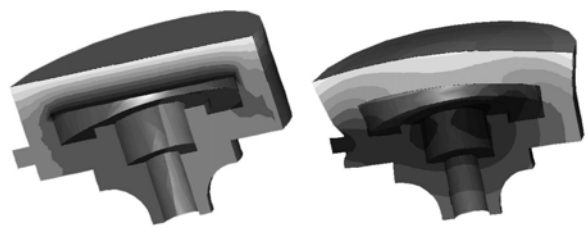


Fig.2 FEM result of pressure deformation of fixed scroll and bearing

2.2 Deformation by Temperature Difference

Under rated operating conditions of the CO_2 heat-pump water heater, we conducted an experiment, where there is about 15°C temperature difference between the surface temperature of the fixed scroll near the suction chamber and the surface temperature of the fixed scroll on the counter-compression chamber side. Figure 3 shows the FEM analysis result with the temperature distribution given as the boundary conditions based on the experimental result. The fixed scroll is pressed up by temperature difference (to be convex). We found that the maximum deformation is 6.9 μm with the compressor upward direction designated to be positive.



(a) (b)

Fig.3 (a) Thermal boundary condition and (b) FEM result of thermal deformation of fixed scroll and frame

3. DEFORMATION CONTROL OF FIXED SCROLL

In a conventional air-conditioner refrigerant compressor, approaches to prevent the welding deformation have been made as adopting flexible structure of welded parts, using separate parts, etc. However, as compared with air-conditioner compressors, CO_2 refrigerant compressors provide remarkably high operating pressure that causes the more deformation during operation. We investigate the characteristics of the welding and bolt tightening deformations. From these results, we determine the initial deformation of the fixed scroll to cancel the pressure and temperature deformations during operation.

3.1 Deformation by Welding - Modeling of Welding Analysis

For welding analysis, the deformation of the fixed scroll at room temperature after welded is found by tracing deformations caused by thermal expansion and contraction in the welding process using heat-stress coupled non-linear analysis. Figure 4 shows the numerical analysis model used for welding. For the fixed scroll, it was also approximated as a disk of equivalent stiffness. In addition, since our CO_2 scroll compressor has the three welding spots to fix the frame to the shell, the analysis was carried out with the welding spots designated as a 120° equally divided 1/6 symmetrical model.

For the thermal boundary conditions given to the welding spots, the time history of temperature shown in Fig.5 measured by a thermo-viewer was used. In this study, because before welded, the welding spot was a space where no material existed, the maximum temperature was substituted for the mechanical property of the welding part until the outer edge of the welding part reached the maximum temperature, and in the cooling process, the mechanical property that had the temperature dependency was substituted.

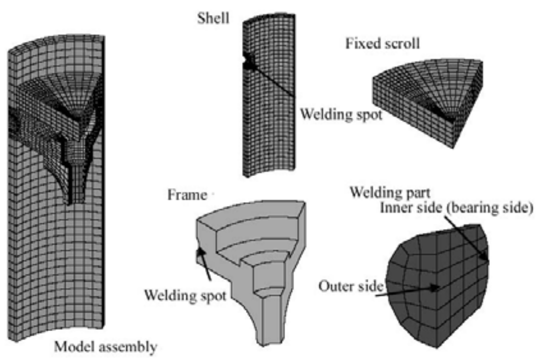


Fig.4 Analysis model for 3 spots welding

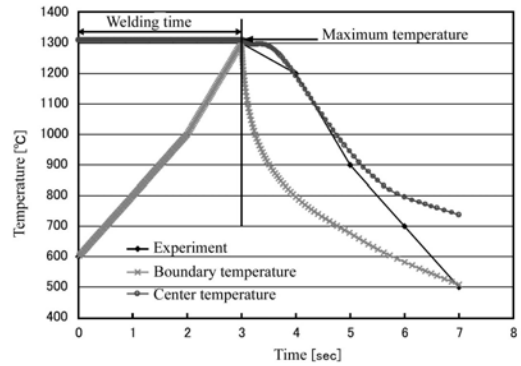


Fig.5 Time history of temperature under the welding process

3.2 Deformation by Welding - Welding Analysis Results

Figure 6 represents the maximum deformation of the fixed scroll in contour when the maximum temperature is varied to 1300, 1650, and 2000°C and heating-up time to 1, 2, 3, and 5 seconds.

As shown in Fig. 6, the analysis results indicate that the higher the maximum temperature and the longer the heating-up time, the more the fixed scroll is deformed to be convex upward.

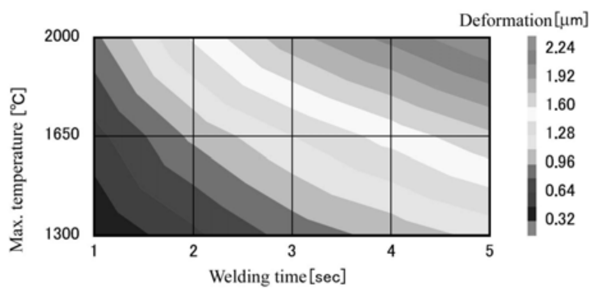


Fig.6 Deformation characteristics for welding condition

3.3 Deformation by Welding - Welding Experimental Results

The welding time was varied to 2, 3, and 5 seconds. In addition, the maximum temperature was measured by a thermo-viewer to be 1300°C. Table 1 shows the welding time and maximum deformation of the fixed scroll.

As shown in Table 1, the welding causes to deform the fixed scroll by about 2.0 μm in upward convexity. However, even when the welding time was varied in the range more than 2 seconds, no significant change was observed in the maximum deformation of the fixed scroll. We also found the distortion of the formation of the welding spot at 3 and 5 seconds welding time. The distortion of the formation has the great influence on the heat transfer in the welding process. That is the reason why the tendency of the analysis results is in discord with that of the experimental results in this welding process.

Table 1 Experimental results of the relationship between deformation and welding time

Welding time	Amount of deformation [μm]
2[sec]	2.3
3[sec]	2.0
5[sec]	2.1

3.4 Deformation by Bolt Tightening

The fixed scroll is tightened to the frame by 8-evenly distributed bolts in the peripheral direction. It was experimentally verified that before and after bolt tightened, the fixed scroll deforms by 5.0 μm in upward convexity. Based on this result, the FEM analysis was conducted to get the bolt tightening force and friction coefficient, which were used for the study of the deformation control.

3.5 Deformation Control - Effects of Stiffness of the Fixed Scroll

Calculations and experiments were carried out on (1) pressure deformation by pressure difference; (2) thermal deformation by temperature difference; (3) deformation by welding for fixing the frame to the shell; and (4) deformation of bolt tightening, respectively, and the characteristics of the deformation were grasped. When the thickness of the fixed scroll is increased, now we can calculate the pressure, thermal, welding and bolt tightening deformations respectively from the characteristics of our study, as shown in Fig.7.

Figure 7 indicates that as the thickness of the fixed scroll increases, the deformation during operation increases. As the stiffness increases with changing the thickness of the fixed scroll, the pressure deformation, welding deformation and tightening deformation decrease, while the amount of thermal deformation increases. In order to keep the deformation during operation to its minimum, the fixed scroll thickness must be properly chosen in such a manner that the total of deformations should be minimized. Table 2 shows the components of the fixed scroll deformation when the thickness of the fixed scroll is chosen to minimize the fixed scroll deformation under the rated operating conditions of the CO_2 heat pump water heater. Table 2 clearly indicates that examination of stiffness and proper initial deformation can minimize its total amount of deformation during operation.

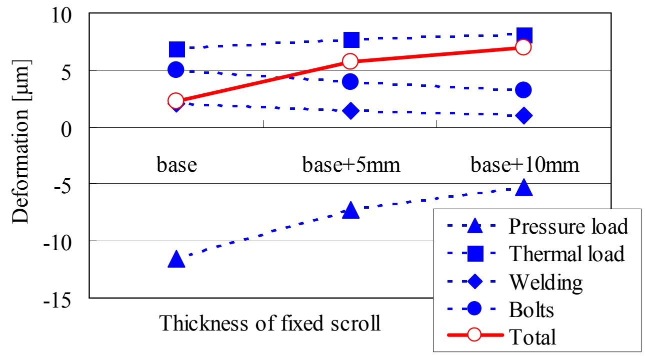


Fig.7 Influence of fixed scroll thickness on the total deformation

Table 2 Summarization of deformation factors

Factor	Amount of deformation [μm]
Pressure load	-11.6
Thermal load	6.9
Welding	2.0
Bolts	5.0
Total	2.3

4. DEFORMATION CONTROL OF ORBITING SCROLL

4.1 Pressure Deformation of the Orbiting Scroll During Operation

Figure 8 shows the pressure deformation of the orbiting scroll when it is supported by the outer peripheral part of the fixed scroll under the rated operating condition. In addition, Figure 9 and 10 shows deformation along the tip of the wrap when the orbiting scroll is rotated at every 90°. The pattern of the compression chamber varies in accord with the orbiting angles. As shown in Fig.9 and 10, we found that the orbiting scroll is deformed by pressure by 5-9 μm with the compressor upward direction designated to be positive.

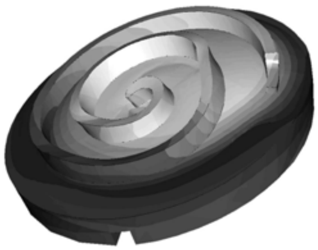


Fig.8 An example of FEM result of pressure deformation

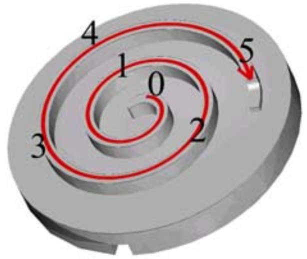


Fig.9 Reference position on the orbiting scroll

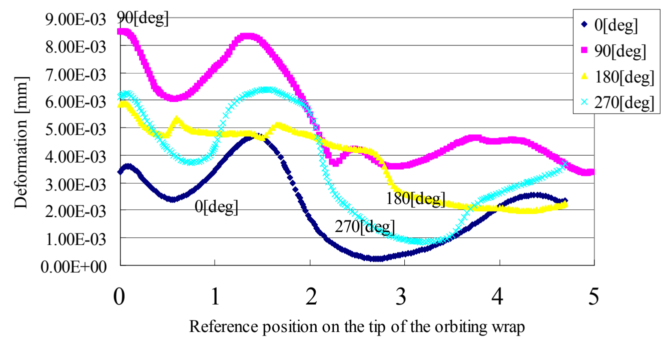


Fig.10 Deformation of the tip of the orbiting wrap

4.1 Optimum Slope Shape of the Orbiting Scroll

The pressure deformation of the orbiting scroll can be calculated, because the pattern of compression chamber also can be calculated by using CFD or other numerical analysis. But, the thermal deformation cannot be calculated, because we cannot measure the temperature distribution on the orbiting scroll, as same as for the case of the fixed scroll.

Moreover, the orbiting scroll is unable to be controlled by providing the initial deformation from the outside. Thereupon, in order to cancel the pressure and thermal deformation, a slope shape is adopted for both the tip of the wrap and the bottom of the wrap. The FEM analyses were made under the high load condition. Based on that analysis results, with respect to the tip of the wrap, we made the tip slope shape that the height of the wrap decreases, as the orbiting scroll wrap comes closer to the center. With respect to the bottom of the wrap, we made the bottom slope shape that the depth of the bottom becomes deeper from the outside than that in the outside.

Figure 11 shows the performance characteristics under the rated conditions by changing the amount of slope at the tip of the wrap, where the horizontal axis indicates the ratio of the amount of tip slope to that of bottom slope. The amount of slope at the bottom of the wrap was fixed to the maximum deformation calculated under the high load condition. As shown in Fig. 11, as the amount of slope at the tip of the wrap increases, the refrigeration capacity reduces, thus causing the increase of leakage from the tip of the wrap. With respect to the compressor input, the increase of input resulting from the increase of re-compression loss caused by leakage was observed. In the meantime, when the ratio of the amount of tip slope to that of bottom slope became 1.5 times or lower, severe contact occurred at the tip of the wrap under high load conditions. This result indicates that the wrap deformation caused by temperature difference must be taken into account in addition to the pressure deformation. By adopting the slope shape, even if the orbiting scroll is deformed by pressure during operation, the clearance at the tip of the wrap can be reduced, thus reducing the sliding loss and local contact caused by contact between the orbiting scroll and the fixed scroll, and thereby the leak loss can be also reduced.

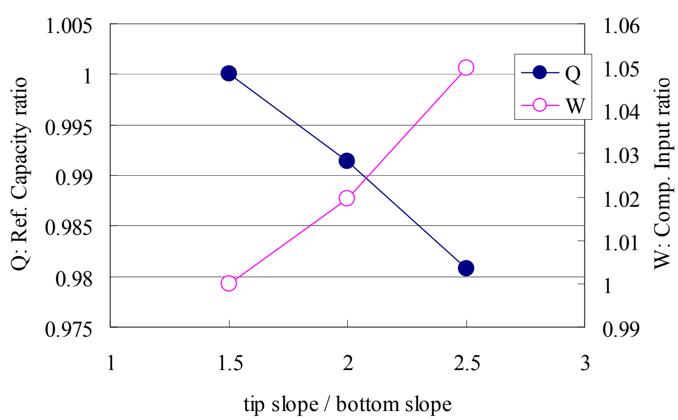


Fig.11 Performance characteristics of the tip/bottom slope

5. CONCLUSIONS

We examined a scroll compressor for a CO_2 heat-pump system to obtain the following conclusions:

- Deformations of the fixed scroll were analytically and experimentally investigated for significant factors during operation.
- Based on the analysis results, deformations during operation can be minimized by providing proper stiffness and initial deformation to the fixed scroll.
- A slope shape was introduced, taken into account with pressure and thermal deformations of the orbiting scroll, and both high efficiency and high reliability were satisfied.

Based on the above developments, the present study contributed to achievement of the industry's top-class COP in CO_2 heat-pump water heaters, which can be maintained at its high performance, even when high-pressure CO_2 refrigerant is used.

NOMENCLATURE

Q	Refrigeration capacity ratio
W	Compressor input ratio

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