Structure Design and Performance Test of CO₂ Scroll Compressor for Heat Pump

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Abstract. Scroll profile design and shell strength design are important in the development of CO₂ scroll compressors for heat pumps. In order to meet the multi-operating conditions of the heat pump, the non-clearance profile correction method and the clearance profile correction method are analysed, and the clearance profile correction method was adopted to complete the profile design. The safety factor design method was compared with the reliability design method, and the shell of the CO₂ scroll compressor for heat pump was designed based on the reliability design method. The test results show that the scroll tooth with clearance correction method meets the design requirements of heating capacity of 4.8kW±10%, the energy efficiency ratio is not less than 4.6, and the shell structure with 99.38% reliability can meet the structural safety requirements.

1. Introduction
A heat pump is an energy-saving device that transfers the heat energy of a low-temperature heat source to a high-temperature heat source, and is widely used in heating and domestic hot water in buildings such as homes, hotels, office buildings, and shopping malls. As a natural working fluid, CO₂ has excellent environmental protection characteristics compared with the most commonly used working fluid R22 (ODP=0.034, GWP=1810) in traditional heat pump systems, and has good economics, safety, stability and thermal properties. In the transcritical cycle, the higher temperature and the larger temperature slip that the CO₂ gas cooler has match the temperature rise process of the cooling medium, and it has the unique advantage of high efficiency and energy saving in the application of heat pumps [1].

As the key component of the heat pump system, CO₂ compressor has the characteristics of high working pressure, small structure size, small pressure ratio and large suction-discharge pressure difference. At present, the CO₂ compressors for heat pumps developed mainly include rolling rotor type, swash plate type, and piston type. Due to the characteristics of high reliability, low vibration, and low noise, scroll compressors have become one of the research hotspots in the field of heat pumps. China has just started its research on CO₂ scroll compressor, and units such as Shanghai Jiaotong University and Xi'an Jiaotong University have developed prototypes of CO₂ scroll compressors, but they are still far from industrial application. In this paper, a CO₂ scroll compressor for heat pump was developed. The modification of scroll profile and the shell strength were studied. The performance of the prototype was tested on the compressor performance test device, and the influence of suction and discharge pressure on the compressor performance was analyzed.
2. Structural Design of CO₂ Scroll Compressor For Heat Pump

2.1. Design and Modification of the Scroll Profile

2.1.1. Profile design
The working chamber of the scroll compressor is composed of a pair of scroll disks. The structure of the two disks is basically the same, which is composed of the bottom plate and the scroll teeth on it. Circular involutes are easy to be machined, and compared with other types of involutes, scroll compressors with the circular involute have a more compact structure and good working performance. Therefore, a circular involute was used to form the scroll profile [2]. The structural parameters of the CO₂ scroll compressor were determined as shown in Table 1 based on the nominal working conditions of the national standard and the thermodynamic calculation results. The scroll profile is shown in Figure 1.

| Items                  | Parameters | Units |
|------------------------|------------|-------|
| Base circle’s radius   | 0.00195    | m     |
| Scroll tooth’s thickness| 0.003      | m     |
| Scroll tooth’s pitch   | 0.01225    | m     |
| Radius of rotation     | 0.003      | m     |
| Scroll tooth’s height  | 0.0044     | m     |
| Inner diameter of shell| 0.112      | m     |

Figure 1. Scroll profiles

2.1.2. Profile modification
The most fundamental limitation of scroll profile modification is to ensure the internal volume ratio and processing conditions. Due to the operating characteristics of the heat pump system, scroll compressors are required to operate under different operating conditions. Therefore, the exhaust valve must be installed in the compressor to meet the requirements of different operating conditions. According to the nominal operating conditions of the summer operating conditions of the national standard and the winter operating conditions of the national standard, the final profile modification is determined according to the internal volume ratio under different operating conditions to prevent the occurrence of over or under compression. The actual exhaust angle during operation is determined by the back pressure.

The modification of the profile of scroll compressors operating under a single working condition generally adopts the method of no clearance modification, which can realize the zero clearance of the two scroll disks. The modified tooth shape with clearance is generally generated by further cutting the tooth end on the basis of the modified tooth shape without clearance. Based on the relationship between the geometric parameters of the two scroll disks, the method for determining the basic parameters without clearance modification is as follows [3].
\begin{align*}
\left((R + r)^2 - (2a)^2\right) &= (2d)^2 \\
R &= \rho + r \\
d &= a\beta - r
\end{align*}

In equation (1),
- \( R \) - Modified arc radius;
- \( r \) - Connecting arc radius;
- \( a \) - Base circle radius;
- \( \rho \) - Gyration radius;
- \( d \) - Length from the center of modified arc to the tangent of base circle;
- \( \beta \) - Expansion angle of the joint between the connecting arc and at the outer involute.

Solve the equation (1),

\begin{align*}
r &= a\beta + \frac{a^2 - \left(a\beta + \frac{\rho}{2}\right)^2}{2\left(a\beta + \frac{\rho}{2}\right)} \\
R &= a\beta + \rho + \frac{a^2 - \left(a\beta + \frac{\rho}{2}\right)^2}{2\left(a\beta + \frac{\rho}{2}\right)} \\
d &= -\frac{a^2 - \left(a\beta + \frac{\rho}{2}\right)^2}{2\left(a\beta + \frac{\rho}{2}\right)}
\end{align*}

There are generally two cutting methods for generating a tooth shape with clearance modification from a basic tooth shape without clearance. One is to cut the tooth end with a line segment, and the other is to cut the tooth end with a circular arc. The method of cutting the tooth end of the line segment will form a sharp apex at the tooth end. During the operation of the \( \text{CO}_2 \) scroll compressor, due to the greater force on the tooth end, the tooth end needs to have a higher strength to ensure the normal operation of the mechanism. Therefore, the method of circular arc tooth end modification was used here. In order to ensure the smooth transition of the tooth end, the two-point smooth modification method was used for modification [4,5]. The modification result of the profile was shown in Figure 2. The two disengagement points A and B are smoothly connected to the tooth wall. The tooth wall between the two disengagement points of the tooth end is circumscribed by a large and small two-phase arc (modified arc) and BC (connected arc) instead. This modification method not only ensures the internal volume ratio of the structure, but also makes the tooth end have sufficient strength and is easy to be processed.
2.2. Shell Strength Design of the Scroll Compressor

The shell of the scroll compressor for heat pump belongs to the pressure-bearing structure. With reference to the pressure volume design specification GB150.3-2011:

\[
 tb = \frac{p_c \times (2 \times RT)}{2 \times [\sigma] \times \phi - p_c} + C
\]

In equation (5),
- \( tb \) -- Shell thickness, mm;
- \( p_c \) -- Calculation pressure, Pa;
- \( RT \) -- Inner radius of the shell;
- \( [\sigma] \) -- Allowable stress, Pa;
- \( \phi \) -- The welding seam coefficient, taken as 1;
- \( C \) -- Additional value of shell thickness, taken as 1 mm.

According to the design conditions, the negative deviation of the steel plate thickness was 0.5mm, and rounded to the standard specification of the steel plate, the thickness of the shell was 6mm. The thickness of the head could adopt the value of the shell thickness.

The shell structure of the scroll compressor was shown in Figure 3. \( RT = 56\text{mm}, \, th = 220\text{mm}, \, R = 33\text{mm}, \, L = 50.5\text{mm} \).
The calculation pressure is 14MPa, the allowable stress value is 189MPa, the elastic modulus is 200e9Pa, the Poisson's ratio is 0.3, and the material yield limit is 345MPa. Finite element verification of the shell design results was taken, and the cloud diagram of the shell equivalent stress was shown in Figure 4. It could be obtained that the middle area of the upper and lower heads in the shell structure was a weak link, and its maximum stress is 257 MPa, which exceeds the allowable stress value of 189 MPa, but far below the material yield limit of 345 MPa. According to the traditional safety factor method, the shell thickness needs to be increased to reduce the stress value of the structure from the results of finite element analysis [6].

![Figure 4. Stress of the shell](image)

To further evaluate the design results of the shell, based on the results of the finite element static analysis of the shell structure, a reliability analysis method [7,8] was introduced, and the statistical values of the random input variables were defined as shown in Table 2.

| Items                        | Distribution type    | Mean    | Standard deviation |
|------------------------------|----------------------|---------|--------------------|
| Radius of bottom head L (m) | Normal distribution  | 0.0505  | 0.00025            |
| Shell thickness of head t(m)| Normal distribution  | 0.006   | 0.0001             |
| Operation pressure P(Pa)    | Normal distribution  | 14e6    | 0.5e6              |
| Yield limit S(Pa)           | Normal distribution  | 345e6   | 25e6               |
| Radius of top head R(m)     | Normal distribution  | 0.033   | 0.00015            |
| Thickness of shell tb(m)    | Normal distribution  | 0.006   | 0.0001             |
| Height of shell th(m)       | Normal distribution  | 0.22    | 0.0005             |
| Elastic modulus EX(Pa)      | Normal distribution  | 200e9   | 6.2e9              |

The reliability analysis results were shown in Figure 5.
It could be obtained from Figure 5. that the reliability of the shell structure is 99.38% with a confidence of 95%. Therefore, referring to the size of the scroll compressor shell determined by the pressure volume design specification GB150.3-2011, it could meet the structural safety requirements without increasing the shell thickness.

3. Performance Test

3.1. Compressor Performance Test Device

The schematic diagram and the picture of the compressor performance test device were shown in Figure 6.

![Figure 5. Cumulative distribution of output variable](image)

Figure 5. Cumulative distribution of output variable

1-compressor 2-intercooler 3-pneumatic ball valve A 4-oil separator 5-oil reservoir 6-metal rotor flowmeter 7-gas cooler 8-reservoir 9-Supercooler 10-mass flow meter 11-dry filter 12-pneumatic ball valve B 13-evaporator 14-superheater 15-pneumatic ball valve C

![Figure 6. CO₂ compressor performance test device](image)

Figure 6. CO₂ compressor performance test device

3.2. Test Results and Analysis

The test results were shown in Table 3 below.

| Items                          | Units   | Experiment results |
|-------------------------------|---------|--------------------|
| Main and auxiliary deviation  | %       | 0.129              |
| Measured power                | kW      | 0.972              |
| Measured heating capacity     | kW      | 4.756              |
| COP                           | W/W     | 4.893              |

Table 3. Performance of CO₂ scroll compressor under GB conditions
It could be obtained from the test results that the prototype of the CO₂ scroll compressor for heat pumps had a heating capacity of 4.756kW, a COP of 4.893 under the national standard, and has reached the design requirement of heating capacity of 4.8kW ± 10%, an energy efficiency ratio of not less than 4.6.

4. Conclusion
Research on the design and modification of the CO₂ scroll compressor profile was carried out. The prototype was experimentally verified on the CO₂ compressor performance test device, and the various indicators met the design requirements.

5. Acknowledgments
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