Analysis and Optimization of Over Compression for Rotary Cylinder Compressor Based on PV Test

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Abstract. Rotary cylinder compressor is a novel positive displacement compressor. Theoretical analysis shows that the compressor may have large over compression loss. Based on PV test, the over compression characteristics of rotary cylinder compressor was analyzed, and the over compression loss accounts for 5.5\% of the indicated power. The over compression was optimized, and the optimized over compression loss is only 0.5\% of the indicated power. By further comparing the energy efficiency improvement of the whole compressor, it is found that the improvement effect is equivalent to that of the over compression, and the effectiveness of the scheme is confirmed.

1. Introduction
The over-compression of positive displacement compressor has a great influence on its performance. In view of the over-compression problem, domestic and foreign scholars have done a lot of research. Peng Xueyuan et al. [1] established a mathematical model of the discharge process of a single-tooth rotor compressor, and believed that the over-compression was inevitable in the late and middle stages of the discharge process, which would significantly increase the power consumption in the discharge process. The study of Xiong Wei et al. [2] on the compound gear compressor shows that, with a proper clearance volume, the discharge over-compression can be solved by enlarging the flow passage area of the diversion groove. Huang Weicai et al. [3] realized the synchronous monitoring of compressor rotation angle and pressure by positioning the rotation angle of the rotor compressor. Hu Yusheng et al. [4] carried out CFD simulation analysis on the internal refrigerant pressure pulsation of the rolling rotor compressor, combined with experimental research, obtained the relationship between the...
pressure in the compressor pump body and the rotation angle, and calculated the indicated work of the compressor.

The Rotary Cylinder Compressor (RCC) is a novel displacement compressor, its pump body mainly contains seven parts: main bearing, shaft, cylinder, piston, cylinder sleeve, spacing board, and sub bearing is shown in Figure 1. The piston reciprocates relative to the cylinder, and the cylinder moves in a circular motion relative to the cylinder sleeve. Under the joint action of the above two relative movements, RCC completes the suction, compression and discharge processes, is shown in Figure 2.

RCC has a significant advantage at the medium and low frequency, and the advantage shows more obvious with the decreasing frequency. The experimental results of the prototype fully verified the performance advantages of rotary cylinder compressor at volumetric efficiency and electrical efficiency, which was consistent with the theoretical analysis. [5] However, RCC’s PV characteristics have not been studied yet.

The starting angle of suction is defined as 0 °, 0 ° ~ 180 ° is the process of suction, and 180 ° ~ 360 ° is the process of compression and discharge. The relationship between the working chamber volume and the angle is as follows [5]

\[ V = eS(1 - \cos \theta) \]  

(1)

The volume change rate is as follows

\[ \dot{V} = eS \sin \theta \cdot \dot{\theta} \]  

(2)

The effective discharge port area \( S \)

\[ S = \begin{cases} \pi r^2, & \pi r^2 > 2\pi e(1 - \cos \theta) \\ 2\pi e(1 - \cos \theta), & \pi r^2 < 2\pi e(1 - \cos \theta) \end{cases} \]  

(3)
Discharge rate $v$

$$v = \frac{\dot{V}}{S}$$  \hspace{1cm} (4)

The calculation results show that the discharge rate of the RCC compressor is too large at the end of the discharge stage, and there may be a large over-compression, which affects the compressor performance. It is necessary to study the over-compression of RCC compressor.

2. PV test principle and scheme

2.1 Test principle

The PV test system of RCC consists of compressor performance test bench, compressor, angle positioning system, and pressure test system, the compressor for PV test is shown in Figure 3. The relationship between pressure and angle (P-θ) can be obtained by testing the pressure of RCC compressor at various angles. Combined with the relationship between volume and angle, the pressure and volume curve (P-V) of the compressor can be obtained. In the PV curve, the indicated power is the area enclosed by P and V. The calculation diagram of indicated power is shown in Figure 4. The indicated power can be calculated by the following formula.

$$W = \sum_{i=1}^{n} \Delta V_i \Delta P_i$$ \hspace{1cm} (5)

The indicated power of the compressor can be obtained and the loss of the compressor can be further evaluated.

![Figure 3. Compressor for PV test](image1)

![Figure 4. Schematic diagram of indicated power calculation](image2)

2.2 Angle test

A positioning plate is arranged on the top of the compressor shaft, and a gear groove with regular distribution is arranged on the positioning plate, and the displacement sensor is aligned with the gear groove plane, as shown in Figure 5. When the compressor is running, the distance between the displacement sensor and the positioning plate will change periodically, and the pulse signal will be
The schematic diagram of pulse signal is shown in Figure 6. By analyzing the pulse signal, the running angle of the compressor can be known [3].

![Schematic diagram of installation position of displacement sensor and positioning plate](image1)

**Figure 5.** Schematic diagram of installation position of displacement sensor and positioning plate

**Figure 6.** Schematic diagram of pulse signal

### 2.3 Pressure test

The pressure sensors are arranged along the radial direction of the cylinder sleeve. In order to ensure the complete pressure curve, when the pressure sensor is arranged, it is necessary to ensure that any two adjacent sensors have a certain overlap in the test angle range. The schematic diagram of the position of the pressure sensor is shown in Figure 7. In this experiment, the pressure sensor pressure test angle range is shown in Table 1. Kulite XTC-142B-190M pressure sensor is used in this experiment. Before the test, the test pressure of the sensor is compared with the theoretical pressure to ensure the accuracy of the test.

![Schematic diagram of the position of the pressure sensor](image2)

**Figure 7.** Schematic diagram of the position of the pressure sensor

| Sensor | Starting angle | Ending angle |
|--------|----------------|--------------|
| S₁     | 0°             | 180°         |
| S₂     | 175°           | 290°         |
| S₃     | 280°           | 390°         |

**Table 1.** Angle range of pressure sensor in pressure test

### 3. PV test analysis

Based on the PV test scheme designed above, the PV test of RCC is carried out, and the test conditions are shown in Table 2. Through the PV test, the valve opening loss, over-compression loss and suction loss of RCC compressor can be studied. This paper mainly studies the discharge over compression loss of RCC compressor, and optimizes the design of RCC compressor based on the research results; other characteristics of PV test will be discussed in detail in other papers, and this paper will only briefly describe.
Table 2. Compressor operating parameters

|                     |        |
|---------------------|--------|
| Refrigerant         | R410A  |
| Condensation Temp(℃)|  40    |
| Evaporation Temp(℃) |  20    |
| Volume(cc)          |  9.6   |
| Operating frequency (Hz)| 60    |

3.1 Sensor curve analysis

3.1.1 P-θ curve of Sensor 1
The sensor 1 is installed in the suction tank, which is used to monitor the pressure value in the suction chamber at different angles during the suction process; combined with the theoretical suction pressure, the suction loss of RCC compressor can be evaluated. P–θ curve of the sensor 1 is shown in Figure 8. According to the test results, there is an obvious pressure valley near 70°, indicating that the compressor has a certain suction loss.

3.1.2 P-θ curve of Sensor 2
The sensor 2 is mainly responsible for monitoring the pressure value in the suction chamber at different rotation angles during the compression process, and can also be used to evaluate the air-tightness between the cylinder and cylinder sleeve. P-θ curve of the sensor 2 is shown in Figure 9. In the range of 280° to 350°, sensor 2 is in the clearance between cylinder and cylinder sleeve, and the pressure change in this angle range can reflect the sealing performance: the better the tightness is, the slower the pressure reduction rate is, and the higher the pressure value is at 350°.

3.1.3 P-θ curve of Sensor 3
The sensor 3 is mainly responsible for monitoring the pressure state in the discharge process, which can be used to evaluate the loss in the valve opening stage and the over compression loss; at the same time, the re-expansion process of the high-pressure refrigerant in the clearance volume can be evaluated. P-θ curve of the sensor 3 is shown in Figure 10.
3.1.4 Complete $P-\theta$ curve

The pressure curves of sensor 1 ($0^\circ$ to $360^\circ$), sensor 2 ($0^\circ$ to $90^\circ$ and $180^\circ$ to $270^\circ$) and sensor 3 ($90^\circ$ to $180^\circ$ and $270^\circ$ to $360^\circ$) can be respectively taken to form a complete $P-\theta$ curve within a compression period. The complete $P-\theta$ curves is shown in Figure 11.

![Figure 10. P–θ curve of the sensor 3](image1)

![Figure 11. Complete P–θ curves](image2)

3.2 Loss calculation

According to the relationship between volume and Angle, the $P-\theta$ curve was transformed into the $P-V$ curve to calculate the indicated work losses. The $P-V$ curve is shown in Figure 12, and the distribution of indicated power loss is shown in Table 3. From the test results, the over-compression loss accounts for the largest proportion.

![Figure 12. P-V curve](image3)

**Table 3. Distribution of indicated power loss**

| Name                  | Power consumption(W) | Proportion |
|-----------------------|-----------------------|------------|
| W                     | 407.1                 | 100%       |
| W$_1$(Suction)        | 11.1                  | 2.7%       |
| W$_2$(Over-compression)| 22.4                  | 5.5%       |
| W$_3$(Valve opening)  | 13.4                  | 3.3%       |
4. Optimization design and PV test comparison

4.1 Optimization design
In the first PV test, the over-compression loss accounted for 5.5% of the indicated power, which seriously affected the performance of the prototype. Analyzing the discharge rate of the prototype, it is found that the discharge rate is larger at the end of the discharge. Enlarging the area of the discharge passage can effectively reduce the discharge rate and discharge resistance, thereby reducing the over-compression loss. Based on the above analysis, the scheme of setting auxiliary discharge port is designed. The diameter of the auxiliary discharge port is 3 mm, and the working angle range is 253° to 369° (73° to 189°). The schematic diagram of auxiliary discharge port is shown in Figure 13, discharge rate before and after optimization is shown in Figure 14.

![Figure 13: Schematic diagram of auxiliary discharge port](image)

Figure 13. Schematic diagram of auxiliary discharge port

![Figure 14: Comparison of discharge rate before and after optimization](image)

Figure 14. Comparison of discharge rate before and after optimization

4.2 Analysis of test results
With the addition of auxiliary discharge port, the pressure at the end of discharge is significantly reduced, and the over-compression is improved significantly. P–θ curve of the pressure sensor 3 before and after optimization is shown in Figure 15. P-V curve before and after optimization is shown in Figure 16. The distribution of indicated power loss before and after optimization is shown in Table 4. The calculation results show that the over-compression loss is reduced from 5.5% to 0.5%, and the COP of the prototype is increased by 9.1%.
Figure 15. P–θ curve of the pressure sensor 3 before and after optimization

Figure 16. P-V curve before and after optimization

Table 4. Indicated power loss distribution before and after optimization

| Name                      | Proportion before optimization | Proportion after optimization |
|---------------------------|--------------------------------|-------------------------------|
| W                         | 100%                           | 100%                          |
| W1(Suction)               | 2.7%                           | 2.9%                          |
| W2(Over-compression)      | 5.5%                           | 0.5%                          |
| W3(Valve opening)         | 3.3%                           | 3.2%                          |

5. Conclusions
If the effective discharge area is too small, the RCC compressor will be over compressed at the end of the discharge stage, which will reduce the performance of the compressor. By setting the auxiliary discharge port, the effective discharge area at the end of the discharge stage can be increased, the discharge rate can be reduced, so as to reduce the over-compression.

6. Next step
From the PV test results, the over-compression of RCC compressor has been effectively improved, and the valve opening loss after improvement accounts for the largest proportion. The next step is to study the loss of the valve in the opening stage to further reduce the discharge loss of the compressor.

References
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