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The Theoretical and Experimental Research of a Novel Rotary Cylinder Compressor

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Abstract. Rotary compressor has been widely used in home air conditioning. The sealing forms of roller-vane and roller-cylinder in rotary compressor are linear sealing, resulting in large leakage and low volumetric efficiency. The performance of the compressor tempestuously reduces with the running frequency decreasing. A novel positive displacement compressor was introduced in this paper: rotary cylinder compressor. The cylinder and shaft rotate around their own axes, and the piston reciprocates relative to them, in order to implement suction and exhaust process. Further, the volume efficiency and mechanical efficiency of rotary cylinder compressor and rotary compressor was analyzed and compared theoretically. The results indicated that the sealing forms of all leaking channels in rotary cylinder compressor are face sealing, which results in less leakage and higher volumetric efficiency than linear sealing. The novel compressor has a significant advantage at the medium and low frequency, and the advantage shows more obvious with the decreasing frequency. Finally, 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.

1. Introduction

Rotary compressor has the advantages of simple structure, easy production, small size, light weight, few wearing part, and high reliability [1]. It has been widely used in the field of home air conditioning. However, there are some defects of the rotary compressors [2]. The sealing about roller-cylinder and slider-roller are linear, which results in worse sealing effect and larger leakage than face sealing. The rotary compressor has the clearance volume, which results in finite pressure ratio. The slider bears large bending moment and belongs to the cantilever support structure, which results in wear easily. In order to reduce the vibration caused by eccentricity of the shaft, balance structure needs to be set up. These shortcomings limit further improvement of the performance of rotary compressor. In order to solve the shortcomings above, many researchers [3-9] investigate novel compressors.

Pan Shulin [3], Yang Lin [4], Lu Yong [5] et al. proposed a rolling piston compressor with a pinned blade. The two ends of vane are respectively hinged to the cylinder and the rolling hinge bearing which will effectively reduce the leakage loss. The disadvantages are as follows: a) there are



many parts requiring lubrication, b) the relative speed between roller and eccentric portion of the shaft is large, c) the friction loss is severe, and d) the process ability and reliability are poor.

In 1973, Design Engineering journal reported that Well-worthy Ltd of United Kingdom produced a novel rotary cylinder compressor [6] based on the mechanical principle of swing guide, which is simple in structure, small in size, and free from wearing parts such as suction valves. Wang Xiaolin et al. [7] of Xi'an Jiaotong University analyzed the geometric relationship, kinematics, dynamics, frictional power consumption of this compressor, and made important improvements in the structure according to its working principle, which further improved the performance.

Greg Kemp, Eckhard A. Groll et al. [8] proposed a novel spool compressor in 2008. This type of compressor is very similar to vane compressor. Its vanes are restrained by the eccentric cam to ensure that the slider head and the cylinder inner circle maintain a certain clearance to avoid contact. The leakage between high pressure chamber and low pressure chamber is avoided by the application of the dynamic sealing.

Y.L.THE et al. [9] of Nanyang Technological University proposed a rotary vane compressor in 2006. This type of compressor is mainly used to solve the problem of excessive frictional power consumption between vane head and roller of the conventional rotary compressor. The mechanical power consumption of rotary vane compressor can be reduced by about 20% compared with that of rotary compressor.

This paper proposes a novel compressor based on the mechanical principle of cross slide: rotary cylinder compressor, which has the features and advantages of the rotary compressor and the piston compressor. Then this paper further introduces the structure and operation principle of the rotary cylinder compressor, and makes a qualitative analysis of the mechanical efficiency and volumetric efficiency. Finally, the prototype was tested and analyzed.

2. Operating principle

2.1. Structure of rotary cylinder compressor

The rotary cylinder compressor pump body mainly contains seven parts: main bearing, shaft, cylinder, piston, cylinder sleeve, spacing board, and sub bearing as shown in Figure 1.

The center of shaft is different from the center of cylinder. The distance between two different axes e is the eccentricity of compressor. The piston stroke L is twice the eccentric amount $L=2\cdot e$. The compressor displacement formula is as follows.

$$V = 2 \cdot L \cdot S = 4e \cdot S$$

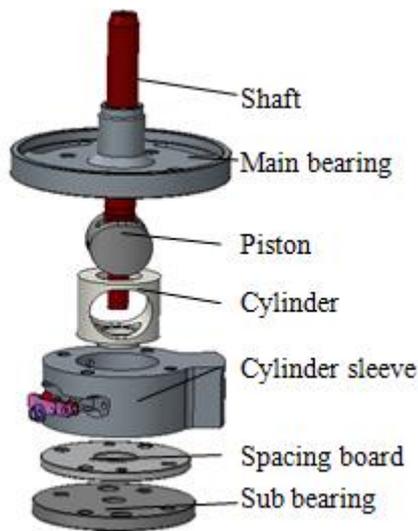


Figure 1. Structure decomposition diagram

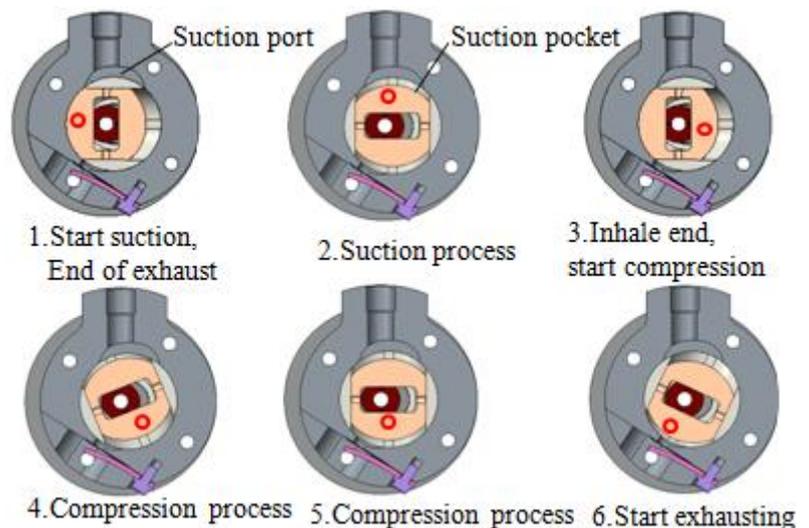


Figure 2. Schematic diagram of suction and exhaust process

2.2. Suction and exhaust process

During operation of the compressor, motor drives the shaft to rotate, shaft drives the piston to rotate, and piston drives the cylinder to rotate. The cylinder and shaft rotate around their respective axes. The piston reciprocates relative to shaft and cylinder simultaneously. Two different reciprocating motions are perpendicular to each other. As the cylinder always rotates, the compressor is named rotary cylinder compressor (RCC).

The piston reciprocates relative to cylinder so that the volume of cavity formed by piston, cylinder and cylinder sleeve changes periodically. The cylinder performs a circular motion relative to the cylinder sleeve so that former volume cavity periodically links with suction port and discharge port. Under the joint action of the above two relative movements, RCC completes the suction, compression and exhaust processes, as shown in Figure 2.

3. Structure characteristics

3.1. Movement characteristic analysis of the piston

Centroid motion trajectory of piston in RCC is a circle with the diameter of the connecting line between cylinder and shaft center. Its center of rotation is the midpoint of the center line of the cylinder and the shaft, as shown in Figure 3.

The angular velocity of piston centroid is different from the shaft speed and the cylinder speed. The following relationship exists between them:

$$\begin{aligned} \text{Angular velocity of shaft} & \quad \omega = \frac{d\theta}{dt} \\ \text{Angular velocity of piston centroid} & \quad \omega_1 = \frac{d\theta_1}{dt} \\ \text{Since } \theta_1 = 2\theta, \text{ it can be further obtained as follow.} & \quad \omega_1 = \frac{d\theta_1}{dt} = 2 \frac{d\theta}{dt} = 2\omega \end{aligned}$$

The centroid of the piston generates centrifugal force during the circular motion. The centrifugal force center is a virtual center. When designing a balancing system, it is difficult to set the balancing system directly on the shaft. This centrifugal force affects the vibration characteristics of the compressor, so it is necessary to analyze it, as shown in Figure 4.

Centrifugal force

$$F = m\omega_1^2 r$$

Centrifugal force at x1 axis component

$$F_{x1} = m\omega_1^2 r \times \cos 2\theta$$

Centrifugal force in the y1 axis component

$$F_{y1} = m\omega_1^2 r \times \sin 2\theta$$

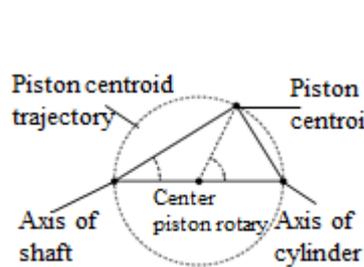


Figure 3. Piston centroid trajectory

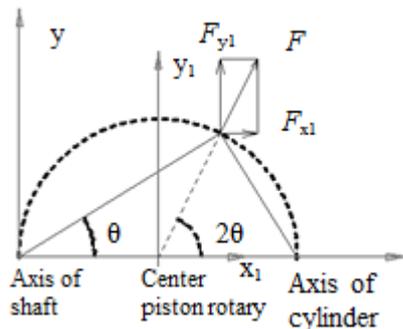


Figure 4. Centrifugal force of piston

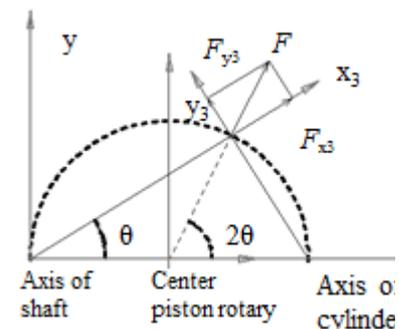


Figure 5. Centrifugal force components in auxiliary coordinate system

If the two components F_{x1} , F_{y1} of the centrifugal force are directly translated to the coordinate origin of the x-y coordinate system, it will be more complicated. So an auxiliary coordinate system x3-y3 is introduced, as shown in Figure 5.

In the auxiliary coordinate system, the obtained centrifugal force components on the x3 and y3 axes are as follow.

Centrifugal force

$$F = m\omega_1^2 r$$

Centrifugal force at x3 axis component

$$F_{x3} = m\omega_1^2 r \times \cos \theta$$

Centrifugal force in the y3 axis component

$$F_{y3} = m\omega_1^2 r \times \sin \theta$$

As shown in Figure 6 centrifugal force decomposition in x-y principal coordinate system and the additional generated moment are presented. By shifting the F_{x3} and F_{y3} components obtained by the centrifugal force decomposition in the auxiliary coordinate system x3-y3 to the coordinate origin under the xy main coordinate system, the component forces F_1 , F_2 , and the additionally generated moment M can be obtained, respectively.

Centrifugal force at x-auxiliary axis component

$$F_1 = F_{x3} = m\omega_1^2 r \times \cos \theta$$

Centrifugal force at y-auxiliary axis component

$$F_2 = F_{y3} = m\omega_1^2 r \times \sin \theta$$

Additional generated moment

$$M = F_{y3} \times a = m\omega_1^2 r \times \sin \theta \times e \cos \theta$$

$$e = 2 \times r$$

$$M = F_{y3} \times a = m\omega_1^2 r \sin \theta \times 2r \cos \theta = m\omega_1^2 r^2 \sin 2\theta$$

By decomposing and synthesizing the x-axis and y-axis of the component F_1 and F_2 in the principal coordinate system, the force component and moment produced by the centrifugal force of the piston relative to the center of the rotating shaft can be obtained, respectively.

Centrifugal force at x-axis component

$$F_x = m\omega_1^2 r \times \cos 2\theta = \frac{1}{2} m\omega_1^2 e \times \cos 2\theta$$

Centrifugal force at y-axis component

$$F_y = m\omega_1^2 r \times \sin 2\theta = \frac{1}{2} m\omega_1^2 e \times \sin 2\theta$$

Additional generated moment

$$M = m\omega_1^2 r^2 \sin 2\theta = \frac{1}{4} m\omega_1^2 e^2 \sin 2\theta$$

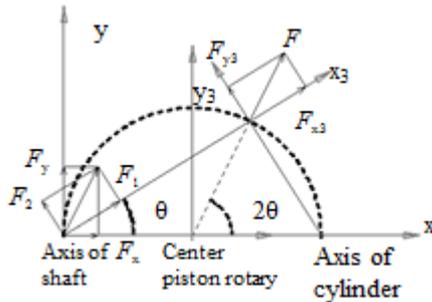


Figure 6. Force component and moment produced by the centrifugal force in x-y coordinate system

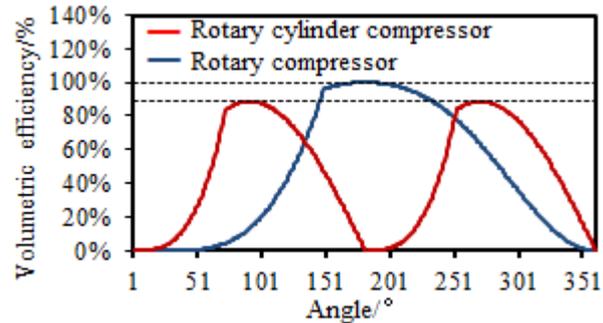


Figure 7. Comparison of torque curves

3.2. Torque characteristics

3.2.1. Torque evaluation

The relationships about chamber volume, pressure with rotation are as follows.

$$V_\theta = e \cdot S \cdot (1 - \cos \theta)$$

$$P_\theta \cdot V_\theta^n = P_s \cdot V_s^n$$

$$P_\theta = \begin{cases} P_s & 0 \leq \theta < \pi \\ P_s \left(\frac{2}{1 - \cos \theta} \right)^n & P_s \left(\frac{2}{1 - \cos \theta} \right)^n \leq P_d \text{ \& } \pi \leq \theta < 2\pi \\ P_d & P_s \left(\frac{2}{1 - \cos \theta} \right)^n > P_d \text{ \& } \pi \leq \theta < 2\pi \end{cases}$$

According to the above formulas, the relationship between torque and angle can be obtained.

$$T = F_\Delta \cdot e' = P_\Delta \cdot S \cdot e' = [(P_{\theta+\pi} - P_\theta) \cdot S] \cdot e \cdot \sin \theta \quad 0 \leq \theta < \pi$$

RCC has the structural feature of a single-cylinder with double-compression chamber: the suction, compression and exhaust processes are completed within 2π . Suction process completes within the first π while compression and exhaust processes complete within the last π . Two volume chambers are independent of each other. And there is a phase difference of π among two volume chambers. The former features make the torque cycle π .

3.2.2. Torque contrast

Figure 7 shows the variation of torque with rotation angle of RCC and single-cylinder rotary cylinder at the same displacement. From the Figure 7, torque cycle of RCC is π while the rotary compressor's is 2π . With the same displacement, the average moment of two kinds of compressors is equal. But the maximum torque of RCC is 12% smaller than that of the single-cylinder rotary compressor. In general, the smaller the torque fluctuation is, the more stable the operation is. In other words, RCC runs more smoothly than rotary compressor in the same displacement condition.

4. Analysis of efficiency

4.1. Volumetric efficiency

4.1.1. Leaking channels

RCC has two leaking channels: cylinder-cylinder sleeve, cylinder-piston. Both leaking channels are facing sealing. The rotary compressor has five leaking channels: roller-cylinder, roller-vane, roller-main bearing, roller-sub bearing and vane slot. The first two sealings are linear sealing, as shown in Figure 8. Because the effect of linear sealing is less than face sealing, the leakage of these two leaking channels is relatively large in the total leakage. RCC is superior to the rotary compressor in terms of the sealing effect or the number of leaking channels, as shown in Figure 9.

Table 1. Sealing comparison of RCC and rotary compressor

Rotary compressor		RCC	
Distribution	Sealing type	Distribution	Sealing type
Vane/Roller	Linear	Cylinder/ Cylinder sleeve	Facing
Roller/Cylinder	Linear	Cylinder/Piston	Facing
Roller/Main bearing	Facing	/	/
Vane/Vane slot	Facing	/	/
Roller/Sub bearing	Facing	/	/

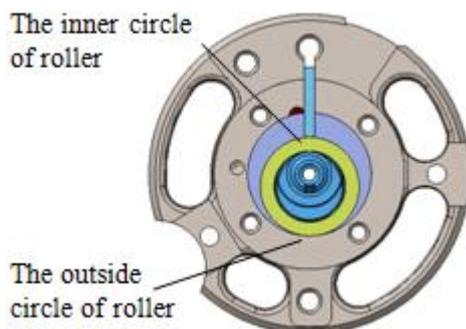


Figure 8. Schematic diagram of linear sealing of rotary compressor

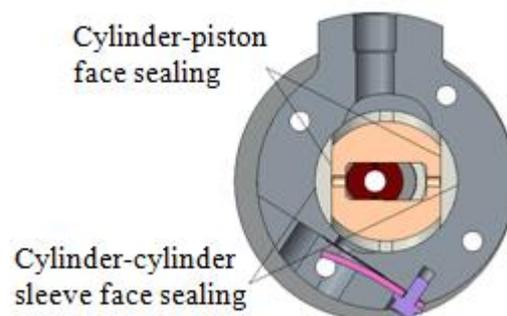


Figure 9. Schematic diagram of face sealing of RCC

4.1.2. Clearance volume

After the exhaust process, there is still some space where exists high pressure gas. This space is clearance volume. During operation of the compressor, high pressure gas in the clearance volume expands to the suction chamber. This part of the gas will be used by next compression cycle. The above process will reduce the actual suction volume of compressor and volume efficiency. As the volume of cavity is changing, this part of the gas is recompressed. Repeated compression process will increase the indicator work of compressor.

The clearance volume of rotary compressor mainly comes from the vent hole and the exhaust oblique incision, as shown in Figure 10. Suction chamber of RCC is separated from the compression chamber. Suction and exhaust processes are independent of each other. At the end of the exhaust process, the high pressure gas of exhaust port is closed in the vent hole, but it can't enter suction chamber. So, there's no more expansion. From this view, RCC has no clearance volume as shown in Figure 11.

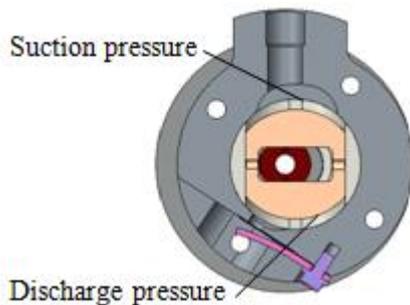


Figure 10. Clearance volume of RCC

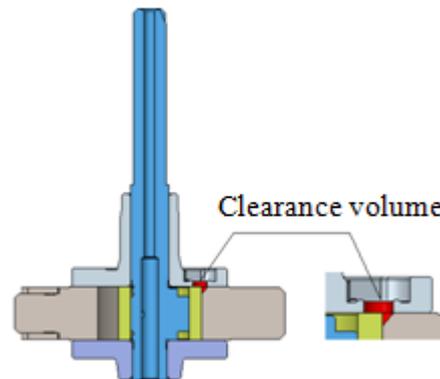


Figure 11. Clearance volume of rotary compressor

In summary, RCC has less leaking channels and no clearance volume compared to rotary compressor, which are beneficial to increase cooling capacity and reduce indicated power of compressor.

4.1.3. Mechanical efficiency

In addition to volumetric efficiency, mechanical efficiency also greatly influences the compressor efficiency. Figure 12 shows the variation of the mechanical power consumption with the compressor frequency under the conditions as Table 2. Below 40 Hz, the power dissipation of RCC is less than the rotary compressor. The advantage shows more obvious with the decreasing frequency. At 12 Hz, it is only 40% of the rotary compressor. But over 40 Hz, the trend of power consumption with frequency is opposite. At this time, RCC power consumption is larger than the rotary compressor. At 60 Hz, it is 126.9% of the rotary compressor, as shown in Figure 13.

Table 2: Compressor operating parameters

Refrigerant	R410a
Condensation Temperature(°C)	40
Evaporation Temperature(°C)	20
Volume(cc)	9.6

The main reason for difference in power consumption between the two compressors is that the frictional power consumption of the cylinder outer circle and the upper and lower end faces of RCC accounts for a large total mechanical loss. This friction pair belongs to the rotary friction pair, and the friction power consumption is proportional to the square of rotational speed, three cubed diameter. And it is inversely proportional to the clearance according to hydrodynamic lubrication. On the premise of ensuring sealing, fit clearance of friction pair should be enlarged appropriately. When the rotational speed is increased, the power consumption increases greatly. The first generation prototypes do have high power consumption on high frequency, but the second generation prototype scheme has avoided this problem. Because the prototype is in the stage of research development, it can not be made public for the time being.

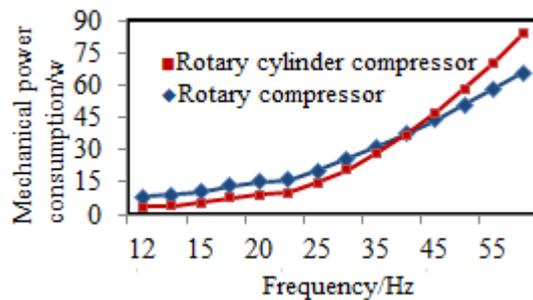


Figure 12. Mechanical efficiency (theoretical) with frequency

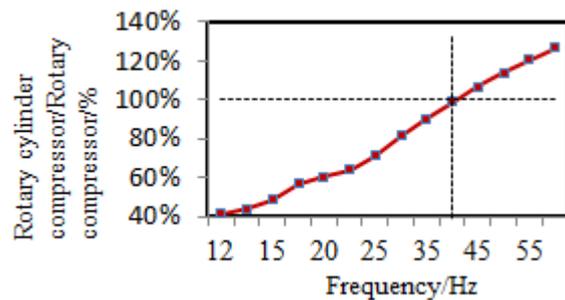


Figure 13. Contrast of theoretical results

5. Experimental results

The prototype of the first generation rotary cylinder compressor has been trial-produced, which is relative to the displacement and load of the rotary compressor. Therefore, the same motor was selected and the performance tests have been carried out according to the working condition of Table 2. Compared with the performance of a certain type of rotary compressor at the same frequency:

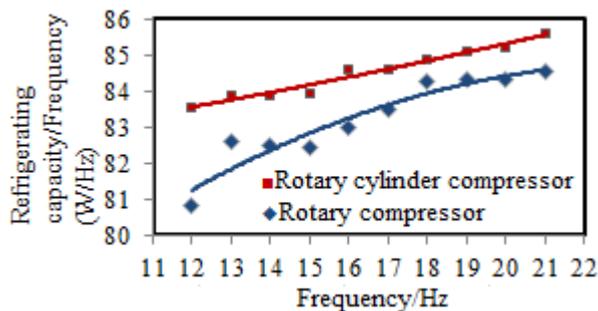


Figure 14. Refrigeration capacity with frequency

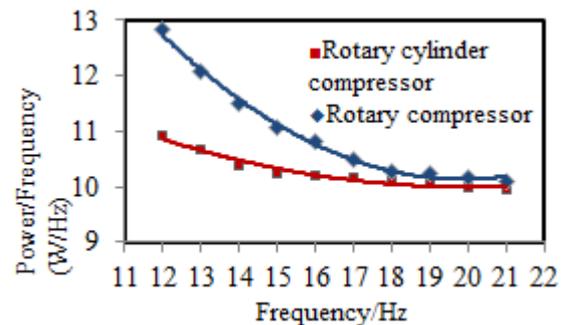


Figure 15. Energy consumption with frequency

- 1) Refrigeration capacity per unit frequency of RCC and rotary compressor decreases with the decreasing of frequency. When the operating frequency below 21 Hz, refrigeration capacity of RCC is obviously superior to rotary compressor. The advantage shows more obvious with the decreasing frequency. For example, differences of refrigeration capacity per unit frequency between RCC and rotary compressor at 12 and 21 Hz are 2.71, 1.05 W respectively, as shown in Figure 14.
- 2) Power consumption per unit frequency of RCC and rotary compressor increases with the decreasing of frequency. When the operating frequency below 21 Hz, power consumption per unit of RCC is less than rotary compressor. The advantage shows more obvious with the decreasing frequency. For example, differences of power consumption per unit frequency between RCC and rotary compressor at 12 and 21 Hz are 1.9, 0.18 W respectively, as shown in Figure 15.

6. Contrast between experimental and theoretical results

6.1. Contrast of efficiency

6.1.1. Contrast of volumetric efficiency

Experimental results show that volumetric efficiency of RCC is better than that of rotary compressor. The advantage shows more obvious with the decreasing frequency. At 12 and 21 Hz, volumetric efficiency of RCC is 2.96%, 1.2% higher than that of rotary compressor respectively, which is consistent with theoretical analysis results. Figure 16 shows the measured volumetric efficiency comparison curves of the two compressors.

6.1.2. Contrast of electric efficiency

Experimental results show that when the operating frequency below 21 Hz, electric efficiency of RCC is better than that of rotary compressor. The advantage shows more obvious with the decreasing frequency. At 12 and 21 Hz, electric efficiency of rotary cylinder compressor is 9.87%, 1.16% higher than that of rotary compressor respectively. Figure 17 show electric efficiency curves of the two compressors.

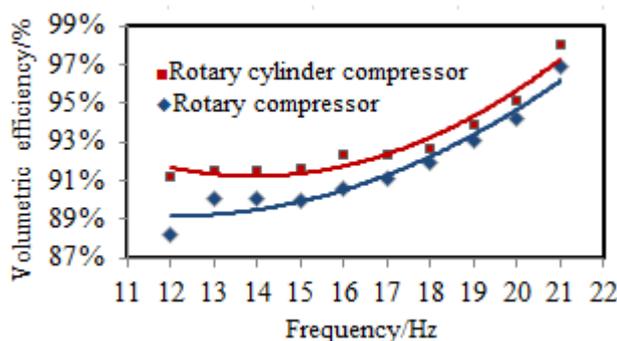


Figure 16. Contrast of volumetric efficiency

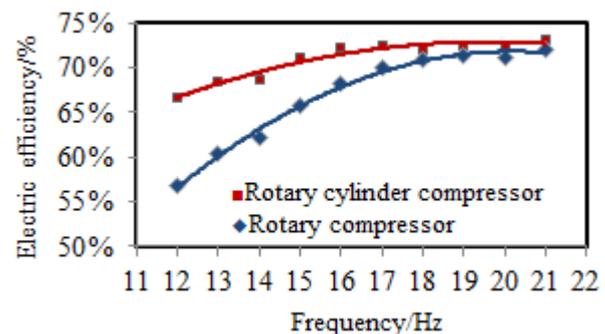


Figure 17. Contrast of electric efficiency

6.2. Contrast of power consumption

Experimental results show that cooling capacity per unit frequency of RCC increases with the increasing of frequency, which indicates that the larger the frequency, the lower the leakage of compressor. And RCC has obvious advantages in cooling capacity, which is consistent with the theoretical analysis results. Experimental results show that face-sealing effect is better than the line-sealing under the same conditions. As the frequency increases, Refrigeration capacity of RCC is gradually close to rotary compressor.

Power consumption of RCC is also significantly better than rotary compressors at low frequencies, and the relationship between RCC power consumption and frequency is the same with theoretical analysis. Power consumption of the whole compressor mainly consists of mechanical power consumption, indicated power consumption, motor loss (copper loss, iron loss). The main difference of power consumption lies in difference of mechanical loss with the same motor, refrigerant, frequency and pump displacement. The relation of the difference of power consumption between RCC and rotary compressor with the frequency in experimental and theoretical results was showed as follows:

- 1) Experimental results and theoretical calculation results have the same trend with the frequency. The lower the frequency, the greater the power consumption difference between experimental and theoretical results.
- 2) With the increase of frequency, the experimental difference of power consumption between two compressors is first greater than theoretical difference, then slightly smaller than it.

The reasons why the difference of experimental result is larger than the theoretical result are as follows. There is a large sealing surface between the suction chamber and the compression chamber in RCC. For rotary compressor, the sealing style of both roller-cylinder and roller-vane are line sealing, which results in bigger leakage than face sealing. The leakage above leaks to the next suction cycle, resulting in increasing of temperature, pressure and exponential power consumption. The leakage and the power consumption are increasing with the decrease of frequency. But, theoretical calculation of mechanical power consumption does not consider this phenomenon.

7. Conclusions

A novel structure of compressor: rotary cylinder compressor (RCC) was introduced in this paper. The novel compressor has a significant advantage in the medium & low frequency. Finally, experimental results of the prototype fully verified the performance advantages of RCC at medium & low frequency. Then volumetric efficiency and electrical efficiency of RCC is higher than rotary compressor at 12 Hz by 2.96%, 9.87% respectively.

RCC is essentially a piston compressor. However, there is no suction valve, which means that the suction resistance is less than piston compressor. RCC is simpler and the operation is more stable as a result of no crank linkage mechanism. All these indicate that RCC has a wide application prospects.

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