Optimized design for micro Wankel compressor used in space-borne vapor compression heat pump

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ABSTRACT

For aerospace applications, vapor compression heat pump can be used as thermal control system to collect the heat from electronic devices and transport heat to radiator by which heat can be rejected to space. Heat pumps can be used in two cases. The first consists of raising the temperature of heat energy so that the amount of radiator surface required is reduced. The second involves situations where heat cannot be directly rejected by radiators, because the heat sink temperature is higher than that of the heat source. However, the key problem is to make a small and lightweight refrigeration compressor. In order to meet the need for aerospace applications, an innovative miniature hermetic Wankel compressor was proposed and designed in this paper. We fabricated the components such as shell, cylinder, rotor, piston gear, stationary gear, rotor and stator of motor. A compressor prototype was manufactured by integrating these components. The results indicated that the prototype have good performance, reliability and micro-gravity adaptability.

1. INTRODUCTION

With the extensions of the functions and scales of large spacecraft, integration level of electronics is growing greatly, while power consumption and heat dissipation increase. For aerospace applications, vapor compression heat pump can be used as thermal control system to collect the heat from electronic devices and transport heat to radiator by which heat can be rejected to space. Recently many investigations have been carried out. Trutassanawin *et al*. (2004) developed and designed a miniature refrigeration system for high heat dissipation electronics cooling. Brown *et al*. (2001) developed a miniature vapor compressor refrigeration system with the dimension of 41 cm ×18 cm × 6.4 cm, which had a cooling capacity of 130 W and coefficient of performance (COP) of 2.2~5.8. Mongia *et al*. (2006) designed a miniature-scale refrigeration system, the cooling capacity varied from 121 to 268 W, with a COP of 2.8 to 4.7.

Compressors are the most important component in vapor compression heat pump systems. How to improve the performance of aerospace refrigeration compressors is a key technology. Abhijit A Sathe *et al*. (2008) tested a rotary compressor in the vapor compression refrigeration system, and the estimated cooling capacity and the COP vary from 163 W to 489 W and 2.1 to 7.4, respectively.

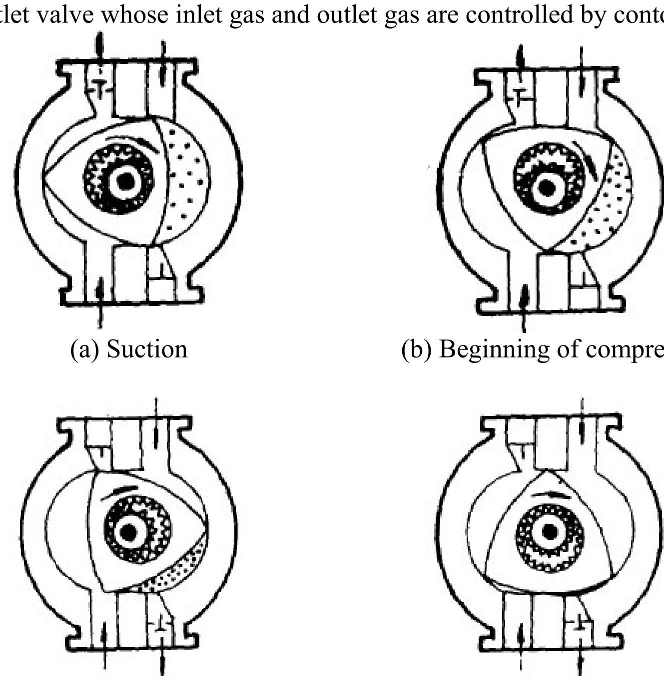
In order to meet the need for aerospace applications, an innovative miniature hermetic Wankel compressor was proposed and designed in this paper. We fabricated the components such as shell, cylinder, rotor, piston gear, stationary gear, rotor and stator of motor. A compressor prototype was manufactured by integrating these components.

2. METHODS CONFIGURATION PARAMETER DESIGN OF MINIATURE WANKEL COMPRESSOR

Miniature compressor, as the “heart” of micro climate cooling system, the optimization design of it is significant. The all-important aim of micro climate cooling system is lightweight for its applications. Wankel compressor is simple-structured, high efficiency, long life, low vibration, smaller and lighter (Mark and Rupert, 1998), so it is well suited to develop miniature compressor.

Wankel compressor consists of a triangular motor rotating within an epitrochoidal chamber and its working principle was shown in Figure 1. The rotor centerline is offset from the chamber centerline with eccentricity. As the rotor rotates about the epitrochoidal, all three points of the rotor remain in contact with the walls. Attaching the two end covers forms three sealed chambers. The movement of the rotor about the housing is controlled by a stationary spur gear mounted to the back housing and an annual gear in the rotor.

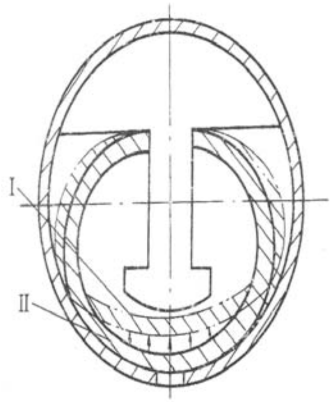
The mass, volume and cooling capacity of micro compressor are much smaller than those of conventional compressor, therefore, the difficulty of processing increases. Conventional compressor is generally equipped with exhaust valve shown in Figure 2. Exhaust valve opens or closes with the elastic deformation of the cylinder. When the cylinder gas pressure is higher than the exhaust pressure, the gas pressure in the cylinder makes elastic cylinder deform. Cylindrical face disengages from exhaust orifice, as shown at position Ⅰ in Figure 2 and gas comes into the exhaust pipe. At the end of gas exhaust, it returns to the position Ⅱ. The miniature compressor is much smaller than macro ones and the air outlet valve of miniature compressor is considerable small. It is difficult to machining such a small part. According to the characteristic of micro Wankel compressor, we designed a miniature Wankel compressor without air outlet valve whose inlet gas and outlet gas are controlled by contour line of rotor.



(a) Suction (b) Beginning of compression

(c) Beginning of exaust (d) End of exaust

Figure 1: The working principle of Wankel compressor



Ⅰ —Start position Ⅱ—End position

Figure 2: Exhaust valve of Wankel compressor

Fig.3 shows the cross-section of the working chamber of Wankel compressor. When the rotor is in the position shown in Fig.3, the angle between the rotor center Q_r and cylinder center Q_k is θ. Φ is the oscillating angle of rotor, which means that when the rotor rotates, the angle between the sealing sheet and the type line of cylinder. A is set as the area enclosed by the triangular rotor side and round epitrochoid between P_1 and P_2. b is the width of triangular rotor. $b = e \cdot Kb$ （Kb is width coefficient.), working chamber volume $V(\theta)$ is

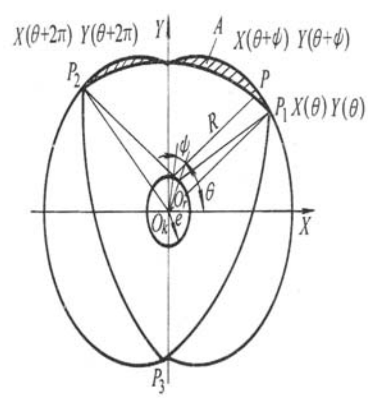


Figure 3: Cross-section of the working chamber

$$V(\theta) = Ab = \left\{\frac{\pi}{3} + K\left[\frac{2}{K}\sqrt{K^2-9} - \frac{3\sqrt{3}}{2}sin(\frac{2}{3}\theta + \frac{\pi}{6})\right] + (\frac{2}{9}K^2 + 4)\Phi_{max}\right\}e^2 b \tag{1}$$

where, $K = \frac{R}{e}$, is shape coefficient, which determines the size of rotor and the volume using coefficient of cylinder.

When $\theta = \frac{\pi}{2}$, the rotor is at stop position, the individual volume of working chamber is the smallest, which is shown in Figure 1 (d).

$$V_{\min} = \left[\frac{\pi}{3} + 2\sqrt{K^2-9} - \frac{3\sqrt{3}}{2}K + (\frac{2}{9}K^2 + 4)\Phi_{\max}\right]e^2 b \tag{2}$$

When $\theta = 2\pi$, the rotor is at bottom stop position, the individual volume of working chamber is the largest, which is shown in Figure 1 (a).

$$V_{max} = \left[\frac{\pi}{3} + 2\sqrt{K^2 - 9} + \frac{3\sqrt{3}}{2}K + (\frac{2}{9}K^2 + 4)\Phi_{max} \right] e^2 b \tag{3}$$

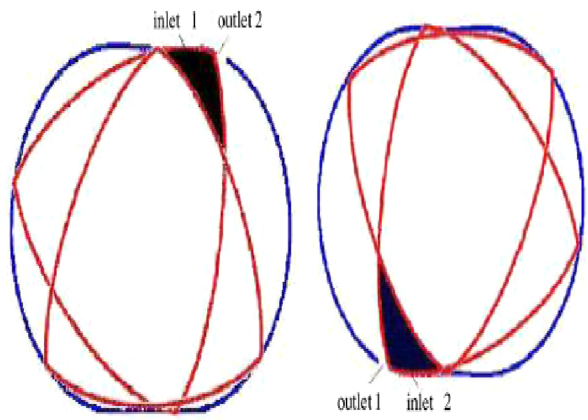
The single difference between the maximum and minimum volume of the working chamber is the element volume V_e. n is the rotation speed. Theoretical volume flow rate is:

$$q_V = 2V_e n = 6\sqrt{3}eRbn \tag{4}$$

When θ equals a certain value α, theoretical compression ratio χ is:

$$\chi = \frac{V_{max}}{V_\alpha} = \frac{\frac{\pi}{3} + 2\sqrt{K^2 - 9} + \frac{3\sqrt{3}}{2}K + (\frac{2}{9}K^2 + 4)\Phi_{max}}{\frac{\pi}{3} + K\left[\frac{2}{K}\sqrt{K^2 - 9} - \frac{3\sqrt{3}}{2}sin(\frac{2}{3}\alpha + \frac{\pi}{6}) \right] + (\frac{2}{9}K^2 + 4)\Phi_{max}} \tag{5}$$

In this paper, we use MATLAB to simulate micro-compressor, and the required line, inlet and outlet position of miniature Wankel compressor are also calculated. Theoretical volume flow of the compressor is 70cm3/min. Volumetric efficiency is set at 70%. Compressor rotation speed is 2000rpm, and the theoretical compression ratio is set at 4. The results are shown in Table 1, and Figure 4 shows the inlet and outlet position of miniature Wankel compressor.



(a) Inlet 1 and outlet 2 (b) Inlet 2 and outlet 1

Figure 4: Inlet and outlet position of miniature Wankel compressor

Table 1: Design parameters of Wankel compressor

Generating radius	**Translational distance**	**Shape coefficient**	**Internal long diameter**	**Internal short diameter**
R=12mm	a=1mm	K=13/2	28mm	20mm
Eccentricity	**Rotor width**	**Spread factor**	**External long diameter**	**External short diameter**
e=2mm	b=12mm	Kb=6	38mm	30mm
Exhaust position 2	**Exhaust position 1**			
θ=9.6°	θ=189.6°			

3. RELIABILITY DESIGN FOR AEROSPACE APPLICATION

In order to meet the need for a miniature refrigeration system, we developed a miniature Wankel compressor design and fabricated every parts of the compressor by using micro electric discharge machining technologies. Two generation miniature Wankel compressors with the cooling capacity of 300W were developed, which was shown in Fig. 5. The first generation compressor was fabricated from cast iron and the second generation compressor was manufactured from high-Si aluminum alloys. The weight of first generation compressor is 700 g and that of second generation is 400 g. The second generation compressor is 5 cm in diameter and 7 cm in height. An experimental system for the miniature Wankel compressor was set up. The tests of the performance of miniature refrigeration system were done. The experimental results indicated that the compression ratio of the compressor is above 3.0, the refrigerating output of the system is above 300W and the coefficient of performance of the developed micro climate cooling system was about 2.3.

(a) First generation miniature compressor (b) Second generation miniature compressor

Figure 5: Miniature compressor prototypes

However, we also found that there are still some problems for aerospace application about the first and second generation miniature compressors, such as long term sealing and lubrication in microgravity environments. Therefore, we have optimized the design and processed new generation Wankel compressor to ensure that the compressor can achieve better performance.

The characteristics of micro Wankel compressor include the seal designs of motor and compressor, rotor and cylinder, oil, and microgravity adaptation design.

① Seal design of motor and compressor

Almost small and medium sized compressors are used enclosed structure from the investigations. Compressor and motor are enclosed in a casing, thus it can greatly reduce the technical difficulty of seal. Therefore, we use closed structure for the micro Wankel compressor, and seal the compressor and motor in a case.

② Seal design of rotor and cylinder

The rotor gas seal system of Wankel rotor consists of seal sheet on the top of rotor, seal strip at the end of rotor, and the seal pin to link up the seal sheet and strip. Seal sheet is used for sealing the radial gap to prevent the week leak among the working chambers. Seal strip is used for sealing axial gap to prevent axial leak. Seal pin plays the role of both of the above aspects. The above seals are mounted in their respective slots and holes, and springs are on their backs. These form a reliable, closed and continuous seal lines around each working chamber. In order to make sealing parts expand freely and prevent jamming after heating, it is necessary to ensure the air tightness of the structure and leave adequate clearance. Also the contact surface of the seal parts should have proper film in order to improve the seal effect and reduce the friction and wear. Holes are drilled on the rotor end face, so that the gas on both of the two end surfaces is connected. Pressure can be balanced to prevent the friction between end faces and cover caused by uneven gas leakage on the two end faces.

③ Oil seal design

The structure of oil seal is oil ring, O-shape of silicone rubber and wave spring, which are mounted on the outside of center hole on rotor end face. Between the seal strip and oil ring, there is a gas recovery slot to collect the gas leaking from working chamber.

④ **Microgravity adaptation design**

For micro Wankel compressor, refrigerant and lubricating oil is completely miscible solution, eliminating the oil tank and extractor. In the microgravity environment the refrigerant and lubricant easier uniformly mix, therefore, it is better to ensure long-term stable operation of the compressor.

4. DEVELOPMENT OF NEW GENERATION MINIATURE WANKEL COMPRESSOR PROTOTYPE

The main components of Wankel compressor are triangular rotor, cylinder, front cover, back cover, external back cover, motor rotor, motor stator, needle bearing, single-row radial ball bearing, valve and so on. Assemble Wankel compressor prototype for new generation is shown in Fig.6.

Figure 6: New generation Wankel compressor prototype

① **Triangular rotor**

Triangular rotor is the core component of Wankel compressor, by which the Wankel compressor is achieved the processes of suction, compression and discharge. Because of the complex of triangular rotor geometry profile, the type line can not be directly expressed. Triangular rotor profile is obtained by calculating profile equation for discrete points coordinates. Each point is taken on the type line by every 0.05°, and 3604 data points in total are taken on the type line. Triangular rotor can be processed through imputing the discrete data points into the numerical control machine (Fig.7).

Figure 7: Triangular rotor

② **Cylinder**

The cylinder surface of Wankel compressor is double arc round epitrochoid. Working closely triangular rotor and cylinder can ensure flexible rotation of triangular rotor in the cylinder and the engagement gap as small as possible. Because of the complex of cylinder geometry profile, the type line can not be directly expressed. Cylinder profile is obtained by calculating type line equation for discrete points coordinates. Each point is taken on the type line by every 0.05°, and 21601 data points in total are taken on the type line. Cylinder can be processed through imputing the discrete data points into the numerical control machine (Fig.8).

Figure 8: Cylinder

③ **Shell**

Shell of Wankel compressor is shown in Fig.9.

Figure 9: Shell

④ **Front cover and back cover**

Compression chamber of the compressor consists of front cover, back cover and cylinder. The front and back covers of Wankel compressor are also a component of compression chamber (Fig.10 and 11).

Figure 10: Front cover

Figure 11: Back cover

⑤ **External back cover**
External back cover is shown in Fig.12.

Figure 12: External back cover

⑥ **Motor**
The motor selected for new generation Wankel compressor has a better match with the other components inside the compressor package. It can achieve fully enclosed compression and is benefit for operational requirements under microgravity conditions. The parameters are listed in Table 2, and the motor is shown in Fig.13.

Table 2: Parameters of brushless motor

Name	**Voltage（VDC)**	**Voltage range（V)**	**Current range（A)**	**Maximum current（A)**	**Drive mode**
Motor(Brushless DC)	24 VD C	20-30 V	1-9.5 A	9.5 A	No sensor feedback

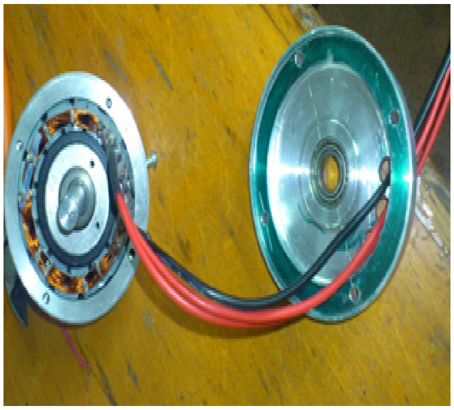


Figure 13: Brushless motor

4. CONCLUSIONS

An innovative miniature hermetic Wankel compressor was proposed and designed in this paper. The components such as shell, cylinder, rotor, piston gear, stationary gear, rotor and stator of motor were fabricated. A compressor prototype was manufactured by integrating these components. New generation miniature Wankel compressor was developed. The prototype has good performance, reliability and micro-gravity adaptability.

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