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Sealing System Analysis of Rotary Piston Pump

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Abstract. Rotary piston pump is designed by the Wankel engine. The structure, working feature and sealing system of rotary piston pump are introduced. The mathematical model of the internal cylinder profile and the theoretical flow are obtained by analysing the structural characteristics of the new pump. The axial seal and face seal of the rotary piston pump and their structures are analysed. The force analysis of the sealing strip is carried out in various cases. It can be concluded from the analysis that, for axial sealing, the key parameters that affect seal strip wear are working pressure, rotate speed of the crankshaft and the friction coefficient between sealing strip and inner wall of the cylinder. For axial sealing, the force of the spring under the curved sealing strips, the size of the sealing rings and curved sealing strips and material of them are the key design parameters.

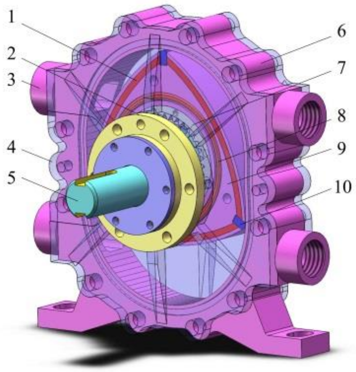
1. Introduction

In 1957, NSU's engineer Paschke proposed the original design of Wankel engine. In 1963, Wankel introduced the principle of the engine in detail [1].Although many manufacturers have tried to adopt the Wankel engine, only Mazda began to use this new type of engine in its automobile products since 1962 [2].Similar to engine, Wankel's principle can be applied to the other systems. For example, the Rankine Cycle Expander, Badr[3] presents a steam plant power cycle system using Wankel expander. Like Wankel engine and Wankel expander, the rotary piston pump (RPP) offers a greater output density than piston pump, has higher specific power [4], and avoids the imbalance of inertia moment and inertial force caused by the reciprocating working mode of the piston, which causes the inertial load of the support member in the piston pump to be intensified and easily causes unstable vibration and noise of the whole device [5, 6]. Because of the good performance, RPP has been applied in some fields, such as artificial heart [7] and grouting [8]. However, the poor sealing system is still the key point which restricts the spread of Wankel engine and RPP.

2. Rotary piston pump

2.1. Structure of RPP

The main parts of single-cylinder RPP include a crankshaft, a rotor, a cylinder block, a gear seat, a bearing block and two cover plates, as shown in Figure 1. The gear seat is in the centre of the cover plate. The crankshaft includes a main journal and a connecting journal. The centre of the cross section of the main journal is concentric with the centre of the cylinder block, and the centre of the cross section of the connecting journal is concentric with the centre of the rotor. The gear form gear seat meshes with the annular gear in the rotor, and the gear ratio is 2:3. The internal cylinder profile is a double arc outer trochoidal, and the rotor divides the cylinder into three working chambers. The eccentric rotary motion of the rotor makes the volume of the three working chambers change constantly, so as to complete the suction and discharge.



1- Curved sealing strip, 2-gear seat, 3-inlet or outlet, 4-cover plate, 5-crankshaft, 6-cylinder block, 7-annular gear, 8-sealing ring, 9-rotor, 10-sealing strip

Figure 1. Structure of RPP

2.2. Working feature

The internal cylinder profile is also the envelope of the rotor vertices' moving trajectory[9,10]. In the X-Y coordinate system of Figure 2, the distance from the rotor center to the vertex is O_2B, which value is R, and the distance between the rotor center and the crankshaft's main journal center is O_1O_2, which value is e. When the rotor rotaries from Figure 2(a) to Figure 2(b), the motion angle of the point B is β, and the motion angle ogre point M is φ. Based on the regulation of the rotor motion, there are two equal curve appear: $\alpha\, r_2=\beta\, r_1$. From the gear radio of the two meshed gears, $\alpha/\beta=r_2/r_1=2/3$ can be worked out, then $\beta=\alpha+\varphi=3\varphi$. From the geometric relationship in Figure 3, the internal cylinder profile can be obtained:

$$\left.\begin{aligned} \mathrm{X} &= e\cos\beta + R\cos\frac{\beta}{3} \\ \mathrm{Y} &= e\sin\beta + R\sin\frac{\beta}{3} \end{aligned}\right\} \tag{1}$$

The annular gear is fixed, and drives the internal cylinder profile to move by the gear on gear seat, forming three envelopes, which are the sides of rotor. There are three equivalent arcs to be used as the sides of the rotor. AC whose dot is G is one of them, and its radius GA is

$$\mathrm{GA} = \sqrt{\mathrm{GH}^2 + \mathrm{HA}^2} = \frac{(R-e)^2 + 3e^2}{R-4e} \tag{2}$$

The areas S_{ADF} can be expressed by Equation (1):

$$S_{\mathrm{ADF}} = \int_{\pi}^{\frac{2\pi}{3}} \left(e\sin 3\varphi + R\sin\varphi\right)\left(e\cos 3\varphi + R\cos\varphi\right)'d\varphi \tag{3}$$

The areas S_{AEF} can be expressed by the conditions known:

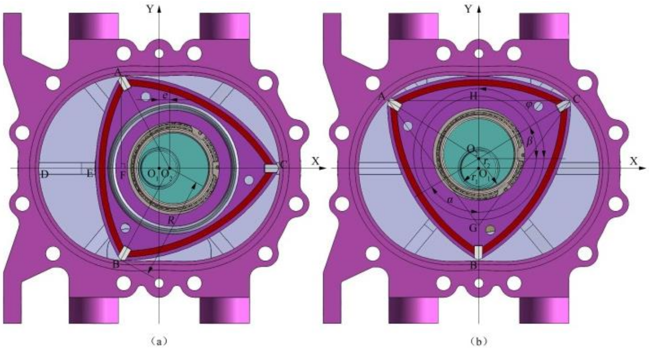


Figure 2. The geometric model of the RPP

$$S_{\mathrm{AEF}} = (\frac{\pi}{4} - \frac{3\sqrt{3}}{8})R^2 \tag{4}$$

In Figure 2(a), the working chamber of ADBE gets the largest volume, and the area S_{ADBE} is

$$S_{\mathrm{ADBE}} = 2S_{\mathrm{ADE}} = 2\left(S_{\mathrm{ADF}} - S_{\mathrm{AEF}}\right) = \pi e^2 + \frac{3\sqrt{3}eR}{2} - \left(\frac{\pi}{6} - \frac{\sqrt{3}}{2}\right)R^2 \tag{5}$$

Finally, the theoretical flow rate (q_0) of the RPP is

$$q_0 = 2nsS_{\mathrm{ADBE}} = \left(4s\pi e^2 + 6\sqrt{3}eRs - \frac{2\pi}{3}R^2 s + 2\sqrt{3}R^2 s\right)\mathrm{n} \tag{6}$$

The three working chambers (W-C) alternate in their suction and discharge. The volume of a W-C changes with the rotary angle φ of the crankshaft, as shown in Figure 3. S. Li [11] studied the fluctuation process of flow rate and pressure in the W-Cs and found that flow and pressure fluctuated regularly, and the fluctuation amplitude was large.

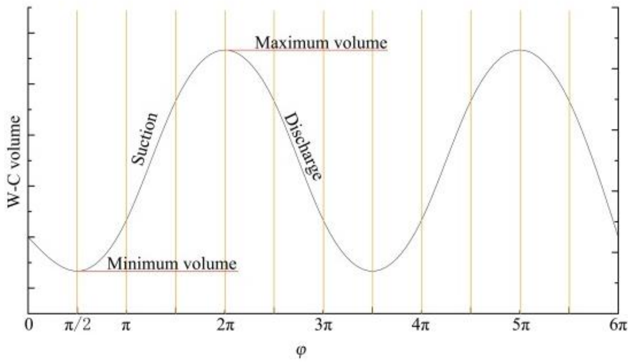


Figure 3. The volume of a W-C changes with the rotary angle φ of the crankshaft

3. Sealing system

3.1. Sealing structure

Compared with the Wankel engine, the liquid pressure in RPP is higher than the gas pressure in engine. In addition to this, the liquid which RPP pumps can corrode the rotor faces and the internal faces of the cover plates. These lead to the worse working conditions. Therefore, the structure, size and material of the sealing system are important. If the parameters are not designed properly, there will be deformation and severe wear, as shown in Figure 4.

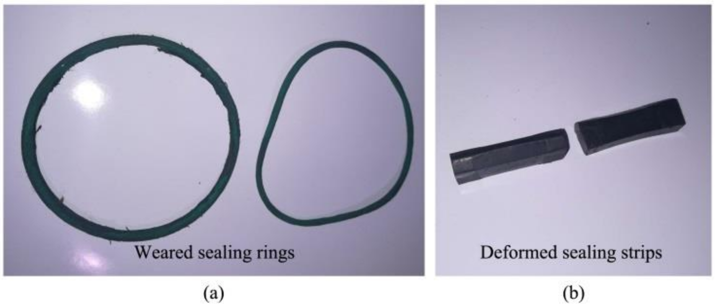


Figure 4. Wear and deformation of sealing rings and strips

3.2. Axial sealing

The axial sealing strips between working chambers are designed to prevent leakage between the each chamber. With the fluctuation of the flow and pressure, the sealing strips swing back and forth in the grooves. When one of the sealing strips comes to the position A in Figure 5(a), the differential pressure and rotor rotation have the same direction. The force analysis is shown in Figure 5(b).

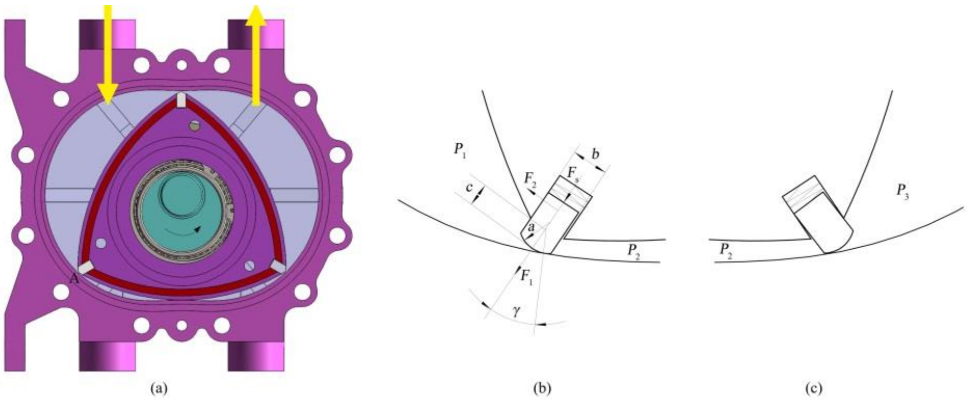


Figure 5. Analysis of the sealing strip

(1) Friction can be ignore

If the material of the sealing strip is hard enough to ignore the friction, like the Wankel engine, F_2 can be expressed as [12]:

$$F_2 = lhP_2 - lcP_1 + m\omega^2 e\sin\frac{2}{3}\varphi \tag{7}$$

And F_1 can be expressed as:

$$F_1 = lbP_2 - P_2\left(\frac{b}{2} - a\sin\gamma\right) - P_1\left(\frac{b}{2} + a\sin\gamma\right) + m\omega^2\left(\frac{r}{9} + e\cos\frac{2}{3}\varphi\right) + F_s \tag{8}$$

Where, l is the length of the sealing strip. h is the height of the sealing strip. P_1 and P_2 are pressures of working chambers. c is the length of the sealing strip outside the groove. m is the mass of the sealing strip. ω is the angular velocity of the crankshaft. b is the width of the sealing strip. a is the radius of the sealing strip head. γ is the contact angle. r is the length of the sealing strip from the center of rotor. F_s is the force of spring.

The hard materials that are available are alloy cast iron, iron titanium sintered alloy and hot press silicon nitride. When the sealing strip comes to the other side, and the differential pressure and rotor rotation have the opposite direction, the sealing strip will incline in the groove because the opposite forces, as shown in Figure 5(c). F_1 and F_1 become:

$$\left.\begin{aligned} F_1 &= lbP_2 - P_2\left(\frac{b}{2} - a\sin\gamma\right) - P_3\left(\frac{b}{2} + a\sin\gamma\right) + m\omega^2\left(\frac{r}{9} + e\cos\frac{2}{3}\varphi\right) + F_s \\ F_2 &= lhP_2 - lcP_3 + m\omega^2 e\sin\frac{2}{3}\varphi \end{aligned}\right\} \tag{9}$$

Where, P_3 is the pressure of another working chamber.

(2) Friction cannot be ignore

When the pressure required is less than 0.7Mpa, rigid sealing strip is feasible. But if the pressure is greater than 0.7Mpa, flexible sealing material is required, and the friction of the sealing strip cannot be ignored. The hard materials that available are polytetrafluoroethylene containing carbon fiber, high strength nylon and rubber. Under the influence of pressure F_N, the sealing strip is subject to the friction F_μ in the opposite direction of motion, as shown in Figure 6.

F_N can be expressed as:

$$F_N = F_1\cos\gamma - F_2\sin\gamma \tag{10}$$

Then, the friction F_μ can be obtained:

$$F_\mu = \mu\left(\frac{b\cos\gamma l}{2} + al\sin\gamma\cos\gamma + lh\sin\gamma - lcP_1\sin\gamma\right)(P_2 - P_1) + m\mu\omega^2\left(\frac{r\cos\gamma}{9} + e\cos\gamma\cos\frac{2}{3}\varphi - e\sin\gamma\sin\frac{2}{3}\varphi\right) + \mu F_s\cos\gamma \tag{11}$$

In conclusion, the key parameters that affect seal strip wear are working pressure, rotate speed of the crankshaft and the friction coefficient between sealing strip and inner wall of the cylinder.

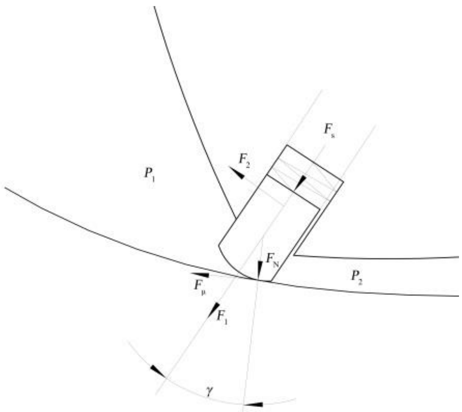


Figure 6. Friction analysis of the sealing strip

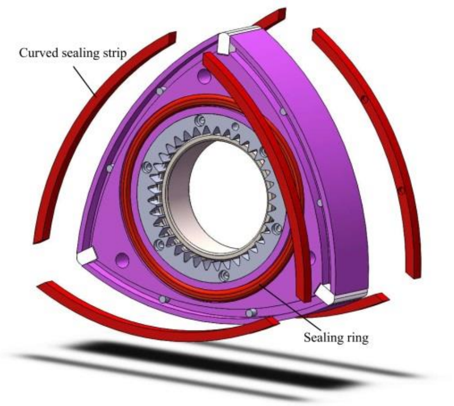


Figure 7. Radial sealing

3.3. Radial sealing

The function of the radial sealing, also called end seal, is to prevent the liquid from the working chamber to leak to the end face of the rotor, shown in Figure 7. The radial sealing includes curved sealing strips, sealing rings, and the axial end face of sealing strips. The curved sealing strips work by the spring at the bottom of grooves and the pressure of the liquid in working chambers. The sealing rings work by the self-elasticity and the extrusion of cover plates. The curved sealing strips and sealing rings are two seals to make sure there's no leak. The force of the spring under the curved strips, the size of the sealing rings and curved sealing strips and material of them are the key design parameters. However, as the friction force and inertia force of all points on the curved sealing strips and sealing rings are different, it's difficult to generalize the relationship between each parameter and the degree of wear. Therefore, each parameter can only be quantified through a large number of experiments.

4. Conclusion

Based on the Wankel engine, a rotary piston pump is designed. The working principle, structure and double arc outer trochoidal model of RPP are introduced in detail. This article focuses on the components of the RPP axial seal and face seal and their structures. The force analysis of the sealing strip is carried out in various cases. It can be concluded from the analysis that, for axial sealing, the key parameters that affect seal strip wear are working pressure, rotate speed of the crankshaft and the friction coefficient between sealing strip and inner wall of the cylinder. For axial sealing, the force of the spring under the curved sealing strips, the size of the sealing rings and curved sealing strips and material of them are the key design parameters.

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