Double Rotary Valve Engine Design

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Abstract. This paper proposes a new type of dual-rotation valve engine, which uses the intake rotary valve and the exhaust rotary valve to control the intake and exhaust of the engine, replacing the intake and exhaust valves and camshafts of the conventional engine. The basic mechanism and working principle of the machine are discussed. In this paper, the combustion chamber structure and lubrication method of the machine are also designed. The compression ratio of the machine is calculated, the gas distribution phase is designed, and the ventilation passing ability is analyzed. It is concluded that the machine has the advantages of simple structure, few parts and strong ventilation capacity, that is, it is suitable for port injection and can also carry out in-cylinder injection.

Keywords: Double rotary air valve; Time-area value; Valve train; Engine; Design.

1. Introduction

With more and more mature engine technology, multi-valve technology is more and more popular. Taking a four-cylinder four-valve double-overhead camshaft engine as an example, the number of distribution mechanism parts on the cylinder head alone is as many as 240, as shown in table 1. The processing of these parts and components brings great processing cost and human and material consumption. Especially the hydraulic pressure is precision parts, high machining accuracy, camshaft line complex, more time-consuming and laborious processing. Moreover, in the process of using camshaft, the wear of CAM directly leads to the reduction of air exchange capacity, which directly affects the performance index of engine.

For this reason, many scholars have carried out research on rotary valve engine. The Weinburn RCV Engine Company Limited in the United Kingdom has designed a rotary cylinder liner engine. The basic structure of the RCV engine is that the cylinder liner is supported by bearings on the cylinder block and the cylinder head, and the cylinder liner is driven by gears to rotate around the piston for each working cycle. An air port on the side of the cylinder liner is connected with the intake and exhaust ports in the cylinder head at different times during the rotation of the cylinder liner, and the intake and exhaust control is completed during the rotation of the cylinder liner. There is no designed valve in the intake and exhaust duct, the gas channel is spacious enough, and the intake and exhaust pass capacity is good. This model is relatively mature, and nearly a thousand prototypes have been produced [1]. The rotary combustor engine, designed by Paul Hansen of Hansen Engines and Jay K. Martin of the University of Wisconsin-Madison, is similar to the RCV engine, with a rotating mechanism inside the cylinder head [2]. The complexity of these two mechanisms is much higher than that of the valve engine. The clearance fit between the rotary valve and the cylinder block and the cylinder head inevitably leads to the existence of leakage. As a result, the sealing problem has not been fundamentally resolved. And each cylinder must use a separate rotating mechanism, difficult to apply to multi-cylinder machine.
American Wallis invented the engine rotary valve with seal support \cite{3}. This mechanism takes axial intake and exhaust along the axis of the rotary air valve, but its intake and exhaust design is inside the rotary valve, so the axial intake and exhaust mechanism is only applicable to single-cylinder engines. A single cylinder engine grooved rotary valve proposed by Kanagawa international technical school, Chiba university and scholars from Mitsubishi heavy industries in Japan \cite{4, 5}. These two kinds of mechanisms have solved the problem of sealing and ventilation capacity well, and have the advantage of simple structure. The driving resistance of the valve mechanism is only 20\% of that of the valve engine, and its power performance and economy are equal to the comparison prototype. Therefore, these two kinds of mechanisms have a good promotion value, but they are only applicable to the single-cylinder engine, which limits the promotion. Jing Zhao and PK Wong from the University of Macau studied a kind of through-type double-rotating air valve for radial control of engine intake and exhaust \cite{6}. Two rotating shafts are set in the cylinder head, and a through-hole is opened in the shaft to control the intake and exhaust. Since the through-hole can ventilate in both directions during rotation, the transmission ratio between the control valve and the crankshaft becomes 1:4, so that if the center angle of the through-hole is 30\degree (and the air port on the cylinder head is 30\degree), the engine valve phase is 240\degree CA. Therefore, the through-hole width is limited to about a quarter of the diameter of the axis of rotation, and the sum of the diameters of the two axis of rotation should not exceed the cylinder diameter. Since the cylinder head bolts cannot be positioned once the cylinder diameter is exceeded, this limits the ability to pass through the rotary valve.

In view of the above problems, this paper proposes a new type of four-cylinder engine with double rotating air valves that can accomplish the above functions with only 50 parts. In addition, these parts are very simple parts, easy to manufacture, low cost, and the use of the process will not affect the ventilation ability.

| Number | Assembly name                  | Parts name                  | Number of parts |
|--------|--------------------------------|-----------------------------|-----------------|
| 1      | Camshaft                       |                             | 2               |
| 2      | CAM bearing cover              |                             | 10              |
| 3      | Intake valve                   |                             | 8               |
| 4      | Exhaust valve                  |                             | 8               |
| 5      | Valve retainer                 |                             | 16              |
| 6      | Valve guide pipe               |                             | 16              |
| 7      | Valve spring                   |                             | 16              |
| 8      | Valve spring seat ring         |                             | 16              |
| 9      | Spring seat ring               |                             | 16              |
| 10     | Valve duct oil seal            |                             | 16              |
| 11     | Valve key                      |                             | 32              |
| 12     | Cylinder                       |                             | 16              |
| 13     | Plunger                        |                             | 16              |
| 14     | Check valve                    |                             | 16              |
| 15     | Spring                         |                             | 16              |
| 16     | Camshaft bearing cover bolt    |                             | 20              |
|        | **Sum**                        |                             | **240**        |

2. Mechanism Design

2.1. Overall Design

This design of rotary valve engine the engine is mainly composed of cylinder head, rotary valve, body, piston, connecting rod and crankshaft. Compared to conventional engines, this engine only changes the cylinder head assembly, and the crankshaft flywheel assembly, piston rod assembly, intake and exhaust system and other systems do not change.
The basic mechanism of cylinder head components is shown in figure 1. The cylinder head assembly is replaced by a rotary valve and its sealing mechanism. A formal transmission between the crankshaft and the rotating shaft is carried out by means of timing pulley and toothed belt mounted on the front end of the crankshaft and the front end of the rotating shaft. The transmission ratio is still 2:1 as for a four-stroke engine, which means that the crankshaft turns clockwise twice and the valve turns once. The intake port (left side), exhaust port (right side) and the air port connected with the combustion chamber (under the rotating shaft) are arranged on the cylinder head. The half-moon gap is opened on the rotary air valve to control the switch of the intake and exhaust port.

2.2. Operating Principle of Rotary Valve Engine

The hybrid combustion theory of rotary valve engine is consistent with that of traditional engine. There is no need to go into details here. What is mainly discussed here is the control method of intake and exhaust, which is the biggest difference between the two engines. The rotary valve engine also consists of exhaust stroke, intake stroke, compression stroke and power stroke. To begin with, the first figure in figure 2 shows the engine intake stroke. The crankshaft rotates clockwise to push the piston down. The rotating air valve also rotates clockwise under the driving of timing belt. The control gap on the air inlet rotating air valve conducts the air inlet and combustion chamber, and the external air is sucked into the cylinder (the air inlet is injected and inhaled with combustible mixture). At this point, the exhaust rotary valve will separate the exhaust port from the combustion chamber, domestic gas cannot enter the exhaust channel. Following, the second figure is compression stroke. The crankshaft rotates clockwise to push the piston upward and the rotary valve rotates clockwise under the timing belt. The rotary intake valve closes the passage between the inlet and the combustion chamber, while the rotary exhaust valve closes the passage between the exhaust passage and the combustion chamber. The cylinder is closed, the mixture is compressed (direct injection engine in the cylinder at this time), and the piston goes up to the spark plug near TDC for ignition. The spark plug is arranged in the spark plug installation hole under the intake rotary valve. In the cylinder direct jet engine, fuel injector and spark plug are arranged side by side.). The third figure is the work trip. Rotary inlet and exhaust valves respectively close the connecting passage between the inlet and exhaust ports and the combustion chamber. The combustion chamber and inlet and exhaust passages are not conductive, and the cylinder is closed. High temperature and high pressure gases in the cylinder push the piston to do work, and the crankshaft is pushed to accelerate clockwise rotation. Finally, the fourth figure is exhaust stroke. The crankshaft rotates the piston clockwise, and the rotary air valve rotates clockwise under the drive of timing belt. The control gap on the rotary air valve conducts the exhaust port and cylinder, and the exhaust gas in the cylinder is discharged from the cylinder. In this way, the engine completes a complete working cycle.
2.3. Cylinder Head Assembly Design

2.3.1. Combustion chamber design. Since the cylinder head is equipped with a rotating air valve for intake and exhaust, in order to increase the intake volume, the direct and thicker rotating air valve is selected as far as possible. Two rotating air valves are arranged within the given spacing of cylinder head bolts, and the smaller the distance between the two air valves is the better. The diagonal layout shown in figure 1 would be an effective approach. Since the rotating valve occupies the position of spark plug and fuel injector on the cylinder head of a conventional engine, the fuel injector and fuel injector can only be arranged under the air inlet, so the combustion chamber shape will be most reasonable with the wedge-shaped combustion chamber. Wedge-shaped combustion chamber has the advantages of good squeezing effect and fast gas flow speed, which is beneficial to increase combustion speed. As shown in figure 3, the spark plug and fuel injector are arranged side by side under the air inlet at an Angle of 15. Because of its rich horizontal size, it can arrange fuel injector in the middle and two spark plugs on both sides, so it is easy to design multi-point ignition.

![Figure 3. Cylinder head structure layout](image)

The best solution is to link the cylinder head to the cylinder with a rectangular cylinder diameter. As shown in the upward view in FIG. 3, in the engine with cylinder diameter D=94.5mm and S/D=1, the rectangular opening between cylinder head. combustion chamber and cylinder is L=77mm long and b=54mm wide.

To analyze the volume of the combustion chamber, as shown in figure 4, we can divide the combustion chamber into two trapezoidal prisms on the right and left and a small triangular prism in the middle. Section size is shown in figure 4, and the length of prism is L=77mm. Naturally, the actual volume needs to be subtracted from the outer volume with a diameter of d=52mm(inlet rotary valve) and 42mm (exhaust rotary valve) and a length of L=76mm with an angle of 60°.

$$V_{c1} = L(a + b)\frac{h}{2} = \frac{77 \times 25 \times (26 + 30)}{2} = 53900 mm^3$$

$$V_{c2} = L(a + b)\frac{h}{2} = \frac{77 \times 20.8 \times (5.6 + 11.4)}{2} = 13600 mm^3$$

$$V_{c3} = La\frac{h}{2} = 77 \times 7 \times \frac{9}{2} = 2400 mm^3$$

$$V_{c4} = d^2\pi \frac{L}{4 \times 6} - \frac{Ld^2}{4 \times 2 \sin(60^\circ)} = 52 \times 52 \times 77 \times \left(\frac{\pi}{6} - \frac{1.732}{4}\right) = 18800 mm^3$$

$$V_{c5} = d^2\pi \frac{L}{4 \times 64} \times \frac{Ld^2}{2 \sin(60^\circ)} = 42 \times 42 \times 77 \times \left(\frac{\pi}{6} - \frac{1.732}{4}\right) = 12270 mm^3$$

Combustion chamber space:

$$V_c = V_{c1} + V_{c2} + V_{c3} - V_{c4} - V_{c5} = 38830 mm^3$$

Working volume:
Compression ratio:
\[
\varepsilon = 1 + \frac{V_h}{V_c} = 18
\]

The compression ratio is suitable for diesel engine, so it can be seen that the engine is suitable for both gasoline engine and diesel engine. In order to make the compression ratio suitable for gasoline engine, the compression ratio can be reduced by increasing clearance volume. With the increase of compression clearance volume of 31000mm³, the compression.

2.3.2. Rotary valve assembly design. The rotary valve assembly of the rotary valve engine, which is shown in figure 5, includes a timing belt wheel, two sliding bearings, a rotary valve body, two single-cylinder machines, and an axial opening sealing ring between each cylinder. If it is a four-cylinder machine, there are five axial sealing rings, then a total of nine parts constitute the distribution mechanism. If there are two shafts, then eighteen parts.

![Figure 4. Combustor volume analysis diagram](image)

The rotary valve assembly connects the timing pulley and timing belt to the timing pulley on the crankshaft to realize timing transmission. Support is provided by sliding bearings designed at both ends of the rotating valve, which are lubricated by pressure. A large gap fit is used between the rotary air valve and the installation hole of the rotary air valve on the rigid cover. Even under the action of explosion pressure, the deformation is smaller than the fit gap. Therefore, there is no frictional wear between the rotary valve and the mounting hole on the cylinder head, and it occurs only in the part where the sliding bearing contacts the rotating shaft. In addition, the intake and exhaust control air port will not wear. Therefore, there will be no dynamic degradation caused by insufficient intake due to CAM wear as a traditional engine.

2.3.3. Rotary shaft sealing mechanism design. Axial seal of rotating air valve adopts the sealing method of open ring. An opening ring is set between each cylinder. The opening ring is in the installation hole of the rotary axis with a certain initial elastic expansion, and the ring and the hole are matched by the initial elastic force. There is a gap between the ring and the ring groove. When the rotary valve rotates, the sealing ring does not rotate with the rotary valve, and can be tilted toward the low pressure cylinder under the pressure of a certain cylinder, and then the side is changed to facilitate the ring groove to realize the steering seal. When the split ring is installed, an opening gap of about 0.2 mm is left to prevent the thermal expansion from being stuck in the hole to affect the axial seal.
The fit between the rotary valve and the rotary valve mounting hole on the cylinder head is a clearance fit. Therefore, the circumferential seal between the intake and exhaust ports and the combustion chamber will be critical. The circumferential seal is shown in figure 6, which is sealed with the seal strip structure. The sealing strip (2) is mounted on the cylinder head in a sealing groove mounting groove between the combustion chamber and the intake and exhaust passages in a large clearance fit manner. The back side of the sealing strip is pressed against the rotary valve by the spring piece 3 with a certain elastic force, so that the gas in the cylinder is sealed in the circumferential direction through the sealing strip. Each cylinder is designed with a sealing strip between the inlet and outlet and the combustion chamber. The length of the sealing strip is greater than the width of the air inlet and the distance between the two axial sealing rings. In this way, a sealing space is formed between the intake and exhaust ports and the axial seal ring and the rotary valve to complete the sealing of the cylinder. If it is a four-cylinder engine, there are eight seals. There are sixteen sealing strips and sixteen spring plates on two rotating air valves.

2.3.4. Distribution phase design.

As shown in figure 3, the center angle of the inlet and outlet gap controlled by rotary air valve is 150. The included angle between the upper side of the exhaust channel and the hole center of the cylinder head is 210°. The respective angles of the inlet and exhaust channel openings are 60. The included angle between side opening of combustion chamber is 60°, and the included angle between inlet and combustion chamber and exhaust passage and combustion chamber is 30°.

The constant angles of intake and exhaust are obtained:

\[ \theta = 2 \times 2 \times 60 = 240° \text{CA} \]

This distribution phase angle can ensure that there is no short circuit between the inlet and exhaust channels when the upper TDC is compressed. Early exhaust opening and late intake are both 40°CA, which can effectively reduce the work loss caused by large exhaust advance Angle. At the same time, compared with the large intake angle, the actual compression ratio of the engine can also be improved.

2.3.5. Air port capacity calculation.

The angle-area value is the integral of the actual area of the opening of the air port against the Angle of the crankshaft that continues to open. Record the opening area of the valve, \( F(\theta) \), from opening the valve to passing through a certain angle of the crankshaft, then calculate the angle-area value from opening the valve to this point in this way.
\[ AF(\theta) = \int_{0}^{\theta} F(\theta)d\theta \]

The integral of the valve from open to close is the angle-area value of the valve. According to the design of engine cylinder diameter \( D = 94.5 \text{mm} \), the diameter of rotary air valve shaft is set as \( d = 0.55 \) and \( D = 52 \text{mm} \), the opening length is \( L = 0.81 \) and \( D = 77 \text{mm} \), and the included angle of the rotating axis is 60°. Since the angle-area value of the air orifice is the integral of the open area of the air orifice with respect to the open angle. For any opening angle of \( \theta \), the opening area of the air port is the product of the mysterious length and the length of the air port.

The angle-area value of the rotary valve engine can be calculated by the following formula.

\[ FA(\theta) = 2L \times 2\pi \times \frac{180}{\pi} \int_{0}^{\theta} \sin \frac{\theta}{2} d\theta = 77D^2 \int_{0}^{\beta} \sin \frac{\theta}{2} d\theta = 77D^2 \left(2 - 2\cos \frac{\beta}{2}\right) \]

The area of the airway opening process increases from the rotation axis of 0° to the rectangular area of the rotation axis of 56°(Airway angle). Put the half-cycle opening angle of the rotary valve \( \beta = 60° \) into the above equation.

\[ FA(\theta) = 13.6D^2 = 123000 \text{mm}^2 \]

Figure 7 shows the valve opening channel configuration of a valve type engine. At the beginning of the valve, the channel area is controlled by the side area of the circular platform between the valve back cone and the seat ring. \( d_1, d_2 \) and \( d_3 \) in the figure are respectively the diameter of valve head, inner diameter of valve seat ring and valve cadre.

![Figure 7. Valve lift curve](image)

It can be seen from the structural analysis that the minimum area of the passage is controlled by the area of the outer cone of the circular platform formed between the valve and the seat ring. At this point, \( F(\theta) \) can be calculated by using the formula for calculating the outer cone of the stage[7-9].

\[ F(\theta) = \pi (d_2 + h \cos(\gamma) \sin(\gamma))h(\theta) \cos(\gamma) \]

In the equation, \( h(\theta) \) is determined by the valve mechanism and CAM profile. Given the law equation of valve lift, the specific opening area at this time can be determined.

As the valve keeps opening, the area of the outer cone of the circular platform gradually increases. If the valve lift is sufficient, as shown in figure 8(The maximum valve lift is 11mm), it is possible that the area of the outer surface of the circular platform is larger than the throat area between the valve seat ring and the valve rod. The passage area will not increase even if the valve is opened again. At this point, the channel area is a fixed value \( S \)(The actual valve lift is 7.2mm at this time). As shown in figure 7, there is an inflection point where the area does not change with the valve lift and the valve opens at \( \theta_1 \). This fixed area can be calculated by the following equation.

\[ S = \pi (d_2^2 - d_3^2) = F(\theta_1) = \pi (d_2 + h \cos(\gamma) \sin(\gamma))h(\theta_1) \cos(\gamma) \]

In both cases, if the valve phase Angle is \( \theta_2 = 180° + \alpha + \beta \), then the actual angle-area value of the valve \( AF \), can be obtained by the following formula. Where \( \alpha \) is the inlet advance angle, \( \beta \) is the inlet late closing angle.
\[ AF_\theta = 2 \int_\theta^{\theta_1} \pi (d_2 + h \cos(\gamma) \sin(\gamma)) h(\theta) \cos(\gamma) \, d\theta + 2 \int_{\theta_1}^{\theta_2} S \, d\theta \]

The engine data for comparison reference are as follows: cylinder diameter is 94.5mm, valve diameter is 34mm, and throat diameter is 28mm. It is a four-valve engine with a valve rod diameter of 6mm and a maximum valve lift of 10mm.

When the distribution phase is \( \theta_2=240^\circ\text{CA} \), \( AF_\theta=130000\text{mm}^2\text{°} \) is calculated.

It can be seen that the ventilation capacity of the rotating valve engine designed with 236°CA valve phase angle is comparable to that of the traditional four-valve engine with 260°valve phase angle. However, due to the rotary air valve of this design, the air inlet channel is unobstructed when the air port is fully open, as shown in first figure in figure 2. Therefore, the intake resistance will be smaller than the valve engine, the ventilation effect will be better. In the valve type engine, even if the valve is fully open, the gas entering the cylinder will be affected by the local resistance on the back of the valve, changing the direction and affecting the actual inflation effect.

### 3. Conclusion

A new double rotary valve engine is designed in this paper. The engine is a four-stroke engine that can be designed as a gasoline engine or a diesel engine, and the compression ratio range can be adjusted. In this paper, the design of the engine's distribution phase, combustion chamber structure and overall structure layout is completed. The working principle of the engine was analyzed and the ventilation capacity of the engine was calculated. According to the calculation, the ventilation capacity of the engine is equivalent to that of the four valve engine with the same cylinder diameter.

If applied to a four-cylinder engine, compared with a four-valve engine with the same scavenging capacity, the new rotary valve engine has only 50 simple parts for scavenging mechanism, while the four-valve engine needs 240 parts. Therefore, the design of the engine greatly simplified the structure, reduce the cost of manufacturing. This paper can provide reference for the design of new engine.

### Acknowledgments

This paper is supported by the National Undergraduate Innovation and entrepreneurship project.

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