Single Rotary Valve Engine Design

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Abstract. This paper presents a new type of rotary valve engine, and discusses the basic mechanism and working principle of the machine. We design the combustion chamber structure and the cooling lubrication mode, calculate the compression ratio of the machine, design the gas distribution phase, and analyze the ventilation passing ability. It is summarized that the machine has the advantages of simple structure, few parts and strong ventilation capacity.

Keywords: 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. For example, as shown in table 1, for a four-cylinder, four-valve, single-overhead camshaft engine, there are as many as 232 parts of the distribution mechanism on the cylinder head alone. The processing of these parts brings great processing cost and human and material consumption. Especially the processing of camshaft and hydraulic lifter, which is precision part, is more time-consuming and laborious. In addition, in the process of use, camshaft wear directly leads to the reduction of ventilation capacity, which directly affects the performance of the 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 [4]. 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 [5]. 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 [6]. 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 [7,8]. 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 [9]. 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° (and the air port on the cylinder head is 30°), the engine valve phase is 240°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.

To solve the above problems, this paper proposes a new rotary valve engine which can complete the above functions with only 17 parts. Moreover, these parts are not only easy to manufacture, but also low in cost, and they do not affect the ventilation capacity during use.

### Table 1. Statistics of valve engine parts (4 vat 4 valve)

| Number | Assembly name | Parts name | Number of parts |
|--------|---------------|------------|-----------------|
| 1      | Camshaft      | 1          |
| 2      | Rocker arm    | 8          |
| 3      | Intake valve  | 8          |
| 4      | Exhaust valve | 8          |
| 5      | Valve seat    | 16         |
| 6      | Valve guide   | 16         |
| 7      | Valve spring  | 16         |
| 8      | Valve spring seat | 16     |
| 9      | Spring lower seat | 16 |
| 10     | Valve guide oil seal | 16 |
| 11     | Valve lock clip | 32 |
| 12     | Hydraulic tappet | Body | 16 |
| 13     |               | Plunger   | 16             |
| 14     |               | Check valve | 16      |
| 15     |               | Spring    | 16             |
| 16     |               | Cam bearing cap | 5 |
| 17     |               | Camshaft bearing cap bolt | 10 |
|        | Sum           | 232        |

### 2. Institutional Design

#### 2.1. Overall Design

The basic mechanism of the rotary valve engine of this design is shown in Figure 1. The engine is mainly composed of a cylinder head, a rotary air valve, a body, a piston, a connecting rod and a 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.
1 cylinder head, 2 rotary air valve, 3 piston, 4 body, 5 links 6 crankshaft

**Figure 1.** Basic structure of a rotary valve engine

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 turn the valve once when the crankshaft turns twice. The air inlet (left), air outlet (right) and air outlet (under the rotation shaft) are arranged on the cylinder head. The half-moon gap is opened on the rotary air valve to control the switch of the air inlet 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. The first picture in figure 2 shows the exhaust stroke of the engine. 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. Then the second picture is the air intake stroke. The crankshaft rotates the piston clockwise, and the rotating air valve rotates clockwise under the drive of timing belt. The control gap on the rotating air valve leads the air inlet and cylinder, and the outside air is inhaled into the cylinder. At the same time, the injector sprays oil into the cylinder (see the cylinder head design below). The third picture is compression travel. The crankshaft rotates clockwise, the piston moves upward, and the rotating air valve rotates clockwise under the driving force of timing belt. The control gap on the rotating air valve and the cylinder do not conduct, the cylinder is closed, the mixture in the cylinder is compressed, and the upper dead center is reached. At last, the fourth picture is the work trip. The control gap on the rotating air valve and the cylinder do not conduct, the cylinder is closed, the high temperature and high pressure gas inside the cylinder pushes the piston to do work, the crankshaft is pushed to accelerate clockwise rotation. This completes a work cycle.
2.3. Cylinder Head Assembly Design

2.3.1. Combustion chamber design. Since the rotating valve occupies the position of sparkplug 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. Take an engine with cylinder diameter D=94.5mm and S/D=1 as an example. The combustion chamber is a trapezoidal cube with length L=76mm, width b=57mm, height h₁=10mm and bottom h₂=25mm. The volume is subtracted from the outer volume of a cylinder with a diameter of d=80mm, a length of L=76mm and an Angle of 90°.

Combustion chamber space:

\[ V_c = \frac{LB(h_1 + h_2)}{2} - \left( \frac{d^2 \pi L}{32(4 - Ld^2)} \right) = 41154 \text{mm}^3 \]

Working volume:

\[ V_h = \frac{D^2 \pi S}{4} = 662468 \text{mm}^3 \]

Compression ratio:

\[ \epsilon = 1 + \frac{V_h}{V_c} = 17 \]

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 28000mm³, the compression ratio can be reduced to 11, meeting the requirement of gasoline engine for compression ratio.

2.3.2. Cooling water jacket design. The cylinder head is only equipped with rotating air valve and front air port, with few parts, and spark plug and fuel injector are arranged under the inlet port. The savings in space make jacket placement easier than with conventional engines.
Figure 3. Cylinder block structure layout

Figure 3 shows a case of arrangement. The arrangement of water jacket is convenient, and there are many spaces under the cylinder head to design the waterway corresponding to the cylinder block. Therefore, the conversion from traditional engine to rotary valve engine only needs to change the cylinder head assembly, without changing the cylinder body, which means the product substitution is very good.

2.3.3. Rotary valve assembly design. As shown in figure 4, the rotary valve assembly of the rotary valve engine 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. 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.

Figure 4. Rotating valve assembly diagram

Figure 5. Rotary valve circumferential direction sealing device

2.3.4. 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 5, 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 intake 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.

2.3.5. Distribution phase design. As shown in figure 6, the center angle of the inlet and outlet gap controlled by rotary air valve is 130. The included angle between the upper side of the exhaust channel and the hole center of the cylinder head is 134°. The respective angles of the inlet and exhaust channel openings are 56. The included angle between side opening of combustion chamber is 90°, and the included angle between inlet and combustion chamber and exhaust passage and combustion chamber is 12°.

The constant angles of intake and exhaust are obtained:

$$\theta = 2(90 + 8 + 20) = 236^\circ\text{CA}$$

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.

2.3.6. 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.

$$A\theta = \int_0^\theta F(\theta)d\theta$$

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 $D= 0.85d =80\text{mm}$, the opening length is $L= 0.8d =76\text{mm}$, and the included angle of the rotating axis is $56^\circ$. 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.
The area of the airway opening process increases from the rotation axis of 0° to the rectangular area of the rotation axis of 56°. Although the distance from 56° to 59° is increasing, the air opening limits the flow area. At this stage, the flow area of air inlet is fixed at the maximum flow area. However, considering that the distance between 56° and 59° is not much different, the upper limit of the integral is directly calculated by 59°, with little error. Put the half-cycle opening angle of the rotary valve $\beta = 59^\circ$ into the above equation.

$$F_A(\theta) = 20D^2 = 18000\text{mm}^2$$

Figure 7. Schematic diagram of the valve opening channel structure

Figure 8. Valve lift curve

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 respectively are the diameter of valve head, inner diameter of valve seat ring and valve cadre.

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 $[3,4]$.

$$F(\theta) = \pi(d_2 + h \cos(\gamma) \sin(\gamma)) h(\theta_1) \cos(\gamma)$$

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, 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 $S$. As shown in figure 8, there is an inflection point where the area does not change with the valve lift and the valve opens at $\theta$. 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 $\theta = 180^\circ + \alpha + \beta$, 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 30mm. 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 $\theta_2 = 240^\circ$CA, $AF_\theta = 150000\text{mm}^2$ is calculated.
When the valve phase increases to 260°CA, the angle-area value increases to 170000 mm²°. 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.

3. Conclusion
A new single 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 17 simple parts for scavenging mechanism, while the four-valve engine needs 232 parts. Therefore, the design of the engine greatly simplified the structure, reduce the cost of manufacturing.

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