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Gas Flow into Rotary Valve Intake and Exhaust Mechanism in Internal Combustion Engine

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Abstract**—**Simple design of a rotary valve system is capable of controlling intake and exhaust gases, which will eliminate the need of known complex mechanisms. The cost of material and production, maintenance, and noise level of the system can be further reduced. The new mechanism enables the elimination of the overlapping of valves work that reduces gas leakage. This paper examines theoretically the gas flow through the holes of a rotary valve design in a small engine. Preliminary results show that the new gas flow has many positive differences than a conventional poppet-valve system. New dependencies on the gas speed enable the finding of better solutions for the geometry of a rotary valve system that will result in a higher efficiency of an internal-combustion engine of the automotive industry.

Keywords**—**Gas arrangement, internal combustion engine.

I. Introduction

THE conventional gas intake and exhaust mechanism that is based on the camshaft–poppet valve system comprises of many moving parts and has many deficiencies like high production costs, high component wear, noisy operation and lower performance efficiency [1], [2]. Apart from these deficiencies which are due to camshaft design peculiarities, there is the high gas flow rate into holes of the valves and overlap period when the exhaust and intake valves are both open at the same time [3], [4]. This situation creates a number of flow effects that reduce the part load performance, reduces the volumetric efficiency resulting in unstable combustion, and reduces the engine efficiency [5]–[7]. This is the reason that there are many publications dedicated to modeling of the internal-combustion engine intake-exhaust system [8]-[10]. To replace the just mentioned components are the rotary valves, which rotate in their housings that are fitted to the cylinder-head. The rotary valves systems of the internal combustion engines are not new. There are companies that produce rotary valves heads [11], but there are not so much publications and results of investigation one, but there are not so much publications and results of investigation one [12]. Rotary valves run directly by the crankshaft via the chain mechanism. Each rotary valve incorporates a hole or window which controls the opening and closing of the intake or exhaust passage during its rotational motion. The opening and closing effects from the rotational motion of the bushes are timed precisely as to work in conjunction with the gas flow requirements of an internal-combustion engine. At this point, simple sketch of the new system and some preliminary studies on the fluid dynamics of the flow have been carried out (Fig. 1). Other studies like an exhaust gas motion, temperature and pressure of combustion gas are very important and need for the Computational Fluid Dynamics methods [13]. Real results of work in such a mechanism will have some differences due to mentioned assumptions. The scope of this paper is a presentation of principle of the new design work and availability of use for engines.

The objective of this new design of a gas intake and exhaust valve arrangement in an internal-combustion engine is to decrease and eliminate all work deficiencies in the existing mechanisms [14]. This new design provides a gas intake and exhaust system that is more long-lasting and reliable, technologically simpler to produce, highly stable hermetically, less wearing of surface elements, less gas leakage hence a more complete combustion is possible resulting in less environmental pollution.

This new design does not require high-level of maintenance and cheaper as compared to the former design. This new intake and exhaust system is cheaper and can be introduced to all kinds and types of internal-combustion engine designs such as in cars, tracks, lorries, motorcycles, ships, boats, tractors, etc [15].

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II. Brief Description of the Work of Rotary Valve Mechanism

Fig. 1 shows a sketch of an idealized model of a rotary valve system in the internal-combustion engine. The rotary valve assembly includes the intake and exhaust housing block. The intake and exhaust bush rotates freely like sliding bearings within the housing block. The intake and exhaust bush comprises one intake-exhaust hole in the combustion chamber. A passage of intake-exhaust holes is separated and located around the circumference of the intake-exhaust bush, which are aligned with the gas passage at different angles of rotation according to the angular crank positions of the crankshaft. The motion of the piston is kinematical matched with the rotary motions of the intake-exhaust bush. At the beginning of the gas intake process, the two side of the bush intake hole is aligned and connected with the intake hole of the carburetor and with the front intake-exhaust port of the combustion chamber. Fuel gas begins to run through the passage and into the cylinder. When the engine piston reaches the lowest point, the two sides of the bush intake hole passes, i.e., the intake hole of the carburetor and the front intake-exhaust port, and the cylindrical surface of the bush closed the carburetor hole and front housing port. According to the engine cycle, after the combustion stage, the engine piston in the cylinder pushes the combusted gases from the front exhaust bush hole through the outlet hole and into the atmosphere. When the engine piston reaches the highest level, the rotating front bush exhaust hole passes the front housing port and the cylindrical surface of the intake-exhaust bush closes the front housing port.

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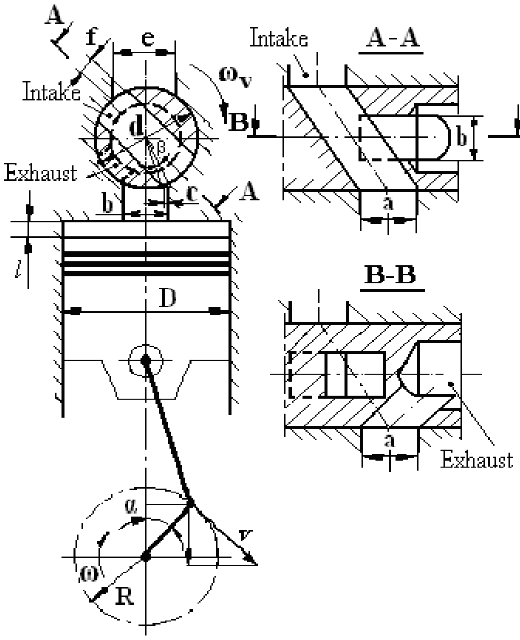

Fig. 1 Gas intake and exhaust in rotating valve

Gas leakage and sealing problems are a few of the areas that may need a careful attention. In fact, there are a few other areas that need a careful attention such as heat transfer and gas flow characteristics and behavior of this new intake and exhaust system. However, at this stage, the focus is more into the kinematics and workability of the system. The problems such as sealing and heat transfer will be dealt with at the later stage of this research. There may be modifications to the design of the system in order to eliminate the problems that may arise.

III. Analytical Approach

In this preliminary analytical study of the new system, air viscosity and pressure are assumed to remain constant (incompressible flow) throughout the system. This approach is normal for preliminary considerations as that mentioned in much research focuses [2]. This paper considers flow rate as incompressible flow for simplicity of analysis. In future research, the gas flow rate will be presented by a method of Computational Fluid Mechanics where all variable parameters such as viscosity, pressure and temperature will be analyzed.

It is known that the most significant airflow restriction in an internal-combustion engine is the flow through the intake and exhaust valves. The minimum cross-sectional area in the intake-exhaust system is at the rotary valve. The modeling of the gas flow through the valve and defining the boundary conditions of the gas flow can assist in the successful application of the new valve design. Intake-exhaust valve rotations can be presented as a function of the crankshaft rotation of the internal-combustion engine. The interdependence between the angular motion of the rotary valve and angular motion of the crankshaft are presented by the following.

The angular velocity of the crankshaft has the expression $\omega_c = 2\pi n$, (n – rev/min), and the tangential velocity of the end of crank is $v = R\,\omega_c$, then the linear velocity of a piston is presented by $v_p = R\omega_c \sin\alpha$, where R is the crank-shaft radius, α is an angular location of the crank-shaft (Fig. 1). The actual mass flow rate and isentropic mass flow rate through a valve are given by the following equations [13]

$$Q = C_d\, Q_{is}$$
$$Q_{is} = \rho_v A_h v_{is} \tag{1}$$

where C_d is a valve discharge flow coefficient (ratio of an effective flow area A_h to a representative area A_{max}), v_{is} is the reference isentropic velocity, A_h and ρ_v are the cross sectional area and fluid density at the valve, respectively.

The gas flow rate into the cylinder has the following expression $Q_c = (\pi D^2/4)v_p$, where D is the diameter of the bore; $v_p = v_t \sin\alpha$; $v_t = R{*}\omega_c = 2\pi Rn$ is the tangential velocity of the end of the crankshaft; R is the crankshaft radius; n is the number of revolutions of a crankshaft.

The gas flow rate into the hole of the valve has the following expression $Q_v = A_h v_h$, where A_h is the area of the opening of the valve hole. A_h is calculated from Fig. 1. The continuity principle of flow rate gives the formula $Av_c = Av_v$ because the gas flow rate into the cylinder, and into the hole of the valve is the same. Then after substitutions and transformation, the gas speed into the hole of the valve has the following expression

$$V_h = \frac{\pi D^2}{4A_h} R(2\pi n)\sin\alpha = \frac{\pi D^2}{2A_h} R\pi n \sin\alpha \tag{2}$$

According to the kinematical ratio of the valve and crankshaft rotations, the angular speed ω_v of the valve rotation is twice less than that of the angular speed ω_c of a crank rotation. Subsequently, $\omega_v = (1/2)\,\omega_c$ or $\beta(t) = \alpha(t)/2$ or $\beta = \alpha/2$, where β is the angular coordinate of the rotating valve (Fig. 1).

Equation (1) is for an isentropic flow from an upstream reservoir to a minimum valve throat area, A_f. In the idealized model of a rotary valve shown in Fig. 1, there is an evident possibility of a variable minimum area, A_f

The variable opening of the rectangular area for the intake valve hole (Fig. 1) is presented in the geometrical form by the following expression

$$A_h = ac = \frac{a*(d/2)*2\pi\beta}{360^0} = \frac{ad\alpha\pi}{720^0} \tag{3}$$

where a is the length of the valve hole and d is the diameter of the rotary valve, $c = \frac{d}{2}\left(\frac{2\beta\pi}{360^0}\right) = \frac{d}{2}\left(\frac{\alpha\pi}{360^0}\right)$ is the width of the variable slit between the rotary valve and the inlet port of the cylinder.

The maximum area, A_{max} can be expressed by the following after the substitution of $\alpha = 90^0$ into (3)

$$A_{\max} = \frac{ad\pi}{8^0} = ab \tag{4}$$

Equation (1) assumes an isentropic flow from the upstream reservoir to a minimum throat valve area, A_h. In the idealized model of the rotary valve shown, the variable area of the valve is changed from the minimum, $A_h = 0$ to maximum, $A_{max} = ab$ that is equal to the area of the cylinder port size (Fig. 1). A discharge flow coefficient is expressed by the following equation

$$C_d = \frac{A_h}{A_{\max}} = \frac{ad\alpha\pi}{720^0(ad\pi/8^0)} = \frac{\alpha}{90^0} \tag{5}$$

The discharge flow coefficient, C_d for the rotary valve varies according to the angle, β of rotation of the valve or angle, α of rotation of the crankshaft. The flow coefficient increases monotonically from zero and further increases with the turn of the valve since the effective area through the valve increases with the turn, while the representative area ab is constant. The maximum value of $C_d = 1.0$ when $\alpha = 90^0$.

The change of the discharge flow coefficient C_d is illustrated in Fig. 2.

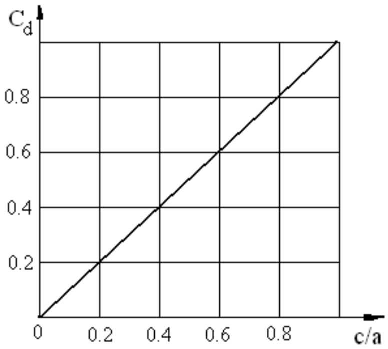

Fig. 2 Discharge flow coefficient vs. turn of rotary valve

It is known that the discharge flow coefficient, C_d is not a strong function of the turn of the valve when the gas passes the small area of the valve slit and results for the valves work [2]. At this condition, the coefficient, C_d should be defined experimentally and calculated by Reynolds number because the inlet gas jet is attached to both the rotary valve and the inlet port, and thereby affected by viscous shear. When the inlet area is sufficiently large, the flow coefficient is independent of the Reynolds number.

The rotary valve design provides also for the shape of the intake hole. From a constructive point of view, it is preferable to design a rectangular valve hole and from technological point of view, it is preferable to have circular parts for the opposite sides of the rectangular hole.

For the rectangular form of the intake port, the ratio of the width, b to length, a is $k = b/a$. The optimal ratio, k should be defined based on the calculation of optimal thermodynamics regimes of the rotary valve work.

The rotary valve performance requires determining the effect of valve on an engine volumetric efficiency. The volumetric efficiency at limiting case in which the flow is always choked has the equation [5] $e_v = 0.58\frac{(\alpha_{ic} - \alpha_{io})}{\pi Z}$, where α_{ic} and α_{io} are the angles at which the intake valve closes and opens respectively, Z is the inlet Mach index (in average Z = 0.6, $\gamma = 1.4$ is the specific heat ratio). For the poppet valve system, the ratio $(\alpha_{ic} - \alpha_{io})/\pi = 1.3$, due to reasons of the valves work overlapping. For the new rotary system, this ratio is equal to 1.0, and thus the volumetric efficiency will have the following expression $e_v = 0.58/Z = 0.97$.

After substituting the expressions of the variable area of the valve hole (3), the angular velocity, and the valve turn coordinate as a function of the crankshaft angle into (2), the variable gas speed into the hole of the valve of an engine cylinder will have the following equation

$$v_h = \frac{720^0\,\pi D^2}{2ad\alpha\pi} R\pi n \sin\alpha = \frac{360^0\,\pi D^2 Rn\sin\alpha}{ad\alpha} \tag{6}$$

Analysis of (6) shows there is a maximum gas speed into the valve hole that defined by the first derivative of (6) with variable α gives

$$\frac{dv_h}{d\alpha} = 0, \quad \begin{aligned} &360^0\,\pi D^2 Rn\sin\alpha(ad) - \\ &360^0\,\pi D^2 Rn\cos\alpha(ad\alpha) = 0 \end{aligned}$$

After transformation and simplifications, the angle α of the valve rotation that gives the maximum gas speed has the following equation

$$\alpha = \tan\alpha \tag{7}$$

Equation (7) is a transcendental equation where roots cannot be found analytically. Solutions of a transcendental equation can be found by using graphical methods. The left-hand side of the equation is expressed as a linear function while the right-hand side is a trigonometric function. Graphical solving of this equation gives the result of the angle of the crank rotation, which the maximum gas speed into the hole of the rotary valve will occur to be $\alpha \approx 5^0$ (Fig. 3).

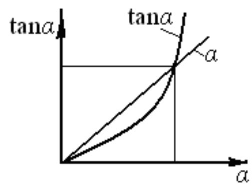

Fig. 3 The angle of the crank rotation gives maximum gas speed into the valve hole

After substitution, the equation of the maximum gas speed into the valve hole will have the following equation

$$v_{h\max} = \frac{360^0\,\pi D^2 Rn\sin 5^0}{ad * 5^0} = \frac{19.7D^2 Rn}{ad} \tag{8}$$

The diagram of the gas speed into the hole area A of the rotary valve versus the angle α of a crank-shaft is shown in Fig. 4. This diagram is based on (6) when n = 3000rev/min

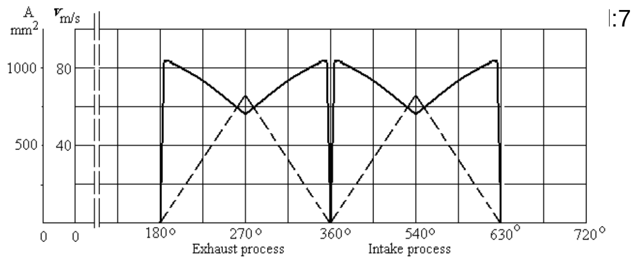

Fig. 4 The gas speed into the valve hole versus the angle of the crankshaft rotation
Valve hole area A is the dotted line for the hole sizes

This diagram shows that the maximum gas speed into the hole of valve occurs at the beginning of the hole opening of valve and at the end of the hole closing of valve. The difference between maximum and minimum gas speed into the hole of the valve is around 35%. The diagram shows that result of the high gas speed for the high speed of the crankshaft rotation is far from the situation of the gas choking into the valve hole. The rotary valve gives the lowest gas flow speed when the piston is at a high speed of motion. The maximum gas speed into the hole of the rotary valve is also many times less than the maximum gas speed into the hole of the poppet valve design. The obtained results prove that the new rotary valve system is acceptable and can perform proper work in internal-combustion engines at different regimes, including at the high level of piston speeds.

The work of a known poppet valve system in internal-combustion engines shows that a valve opening and closing time in relation to the crankshaft rotation is not perfect. There is quite a substantial amount of early opening of intake valve (0-30^o) and late opening of intake valve (40^o-60^o). Exhaust valve opens early (40^o-60^o) that leads the high pressure gases do not use for engine work. The early opening of exhaust valve also cut short the working stroke of the engine. Some amount of the gas expansion pressure $\Delta P \approx 15\%$ in the working stroke is wasted by the early opening of the exhaust valve. Intake valve closes late (40^o-60^o) leads to pushing fuel gases to carburetor [2]. The early opening and closing of the valves certainly would reduce the efficiency and fuel economy of the engine.

To avoid the high gas speed phenomena into the intake and exhaust hole, it is possible to have some early opening and late closing of this hole by increasing the area of the hole into the housing of the rotary valve. However such trick has some positive and negative circumstances. Early opening of the hole for gas intake process can reduce the pick of the gas high speed into the channel of the rotary valve. For this case (6) of the variable gas speed into the hole of the valve of an engine cylinder will have the following equation ($\beta = \alpha/2$),

$$v_h = \frac{180^0 \pi D^2 Rn \sin\alpha}{ad(\beta+\gamma)} = \frac{180^0 \pi D^2 Rn \sin\alpha}{ad[(\alpha/2)+\gamma]} \tag{9}$$

where γ is the angle of earlier opening of the rotary valve.

Equation (9) gives a maximum gas speed into the valve hole that defined by the first derivative with variable α gives

$$\frac{dv_h}{d\alpha} = 0,$$

$$\frac{360^0 \pi D^2 Rn}{ad}[(1/2)\sin\alpha - \{(\alpha/2)+\gamma\}\cos\alpha] = 0$$

After transformation and simplifications, the angle α of the valve rotation that gives the maximum gas speed has the following equation

$$\alpha = \tan\alpha - 2\gamma \tag{10}$$

Equation (10) is also a transcendental equation, where the solution is found by graphical methods. Graphical solving of this equation gives the result of the angle of the crank rotation, which the maximum gas speed into the hole of the rotary valve will occur (Fig. 5).

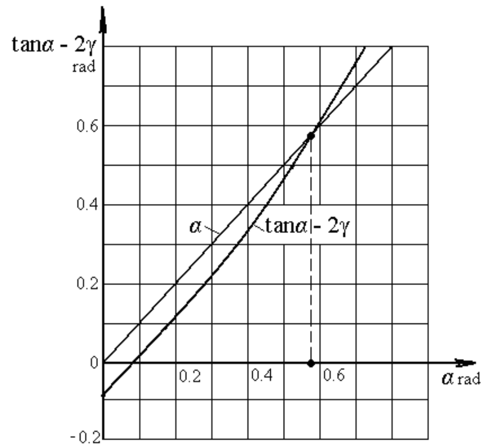

Fig. 5 The angle of the crank rotation gives maximum gas speed into the valve hole with its earlier opening

As mentioned earlier the maximum gas speed into the hole of the valve will occur at $\alpha \approx 5^0$. At this moment, the rotary valve turned on $\beta \approx 2.5^0$. If arrange early opening of the hole for gas flow process at this angle, then the gas speed into the valve hole versus the angle of the crankshaft rotation will have the diagram that presented on Fig. 6. This diagram is based on (9) when n = 3000 rev/min.

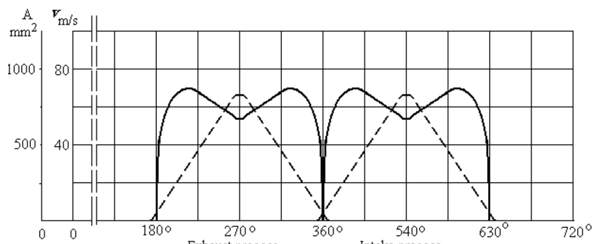

Fig. 6 The gas speed into the valve hole with early opening of the hole for gas flow (the rotary valve turned on $\beta \approx 2.5^0$) vs. the angle of the crankshaft rotation
Valve hole area A is the dotted line for the hole sizes

The maximum gas speed is calculated by (9), when $\alpha \approx 34^0$ (defined graphically) and $\gamma = 2.5^0$. The variation of the maximum and minimum gas speed into the hole of the valve is around 22%, and the pick of the gas speed does not have the sharp form like in Fig. 6.

Earlier opening and later closing of the hole of the rotary valve is accompanying with the gas leakage. The process of exhaust of the burned fuel gives penetration of some volume of burned gas into the intake hole of the rotary valve and mix with fresh fuel gas. The volume of the burned fuel with the fresh gas should be small and does not influence on the whole content of the fresh fuel gas that intake to the cylinder.

During gas exhaust processes the piston is coming up to top level of the location and pushing out the burned fuel. At the location of the piston that close to its top level, the remaining volume of burned fuel can be calculated by the following equation

$$W = (\pi D^2/4)\, R(1 - \cos\alpha) \tag{11}$$

where all parameters presented in Fig. 1

After transformation of (11) the angular location of the crank shaft α for earlier opening of the exhaust hole will have the following equation

$$\alpha = \arccos\left(1 - \frac{4W}{\pi D^2 R}\right) \tag{12}$$

The minimum volume W of the burned fuel that can be mixed with fresh gas fuel is calculated on a basis of the limit of its quality. There is some percentage limit of burned gases into the fresh fuel gas that does not reduce its quality.

For the gas intake manifold, it is possible to decrease the gas speed until its minimum one.

To avoid the high speed gas into entry part of the intake channel of the rotary valve that connects the carburetor or injection manifold, it is recommended to make the width e of the hole of the manifold wider then width of the intake channel of the rotary valve (Fig. 1).

The quarter of the width of the intake hole of the valve can be presented as the initial slit f between the intake manifold and the channel of the rotary valve. This slit can be expressed by the angle of the rotation of the valve by the following equation

$$\beta = \frac{360 * a/4}{\pi d} = \frac{90a}{\pi d} \tag{13}$$

Fig. 7 demonstrates the diagram of the gas speed into the manifold hole with early opening of the valve hole for gas flow when the rotary valve turned on the quarter of the hole ($\beta \approx 11.5^0$). This diagram is based on (9) when n = 3000rev/min.

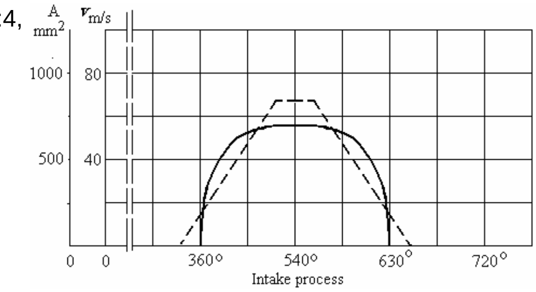

Fig. 7 The gas speed into the manifold hole with early opening of the valve hole for gas flow (the rotary valve is turned on, $\beta \approx 11.5^0$) vs. the angle of the crankshaft rotation
Valve hole area A is the dotted line for the hole sizes

The gas speed into the manifold hole of the rotary valve is increasing with its rotation and reaches the maximum with opening of the full area of the hole (Fig. 7). The gas speed through the hole of the rotary valve can be changed by varying the area of this hole. It is possible to increase the area of the hole by increasing the length a, and the diameter, d of the rotary valve ($b = d/8$), (6). The optimal size of the hole of the rotary valve can be calculated on a basis of gas dynamics and other parameters of a running internal-combustion engine.

IV. A Working Example

It is given: D = 70mm – diameter of a bore, R = 35mm – a crank-shaft radius, d = 50mm – diameter of a rotary valve, a = 40mm – length of the hole of rotary valve, b = 20mm – width of the hole of rotary valve, n = 3000 rev/min – rotary speed of the crankshaft. ($v = R2\pi n$ = 0.035*2*π*3000/60 = 11.0 m/s).

In these preliminary studies and calculations at this stage, engine speed is taken to be at 3000 rev/min. This speed is taken as average working speed for small engines. However, in later stage of research, a variable of engine speed will be taken into consideration. The maximum value of the gas speed into the valve hole is defined by substituting the given technical data into (8)

$$v_h = \frac{19.7 D^2 R n}{ad} = \frac{19.7 * 0.07^2 * 0.035 * (3000/60)}{0.04 * 0.05} = 84.4 m/s$$

The obtained result proofs that the new rotary valve system is acceptable and can perform proper work for internal-combustion engines at different regimes, including at high piston speed levels.

The inlet area of the valve hole can be checked based on the maximum gas speed without the choked flow rate for which the engine is designed [2]. The maximum gas speed through the inlet valve should be less than the sonic velocity at a condition where the intake flow is not choked. For the given technical data, the maximum gas speed, v_h = 84.4 m/s is more than four times less than the sonic velocity, v_s = 330 m/s. This means the gas flow is not choked.

Equation (8) can be used to give various possibilities of the area for an intake valve hole and can be used in calculations to obtain appropriate solutions. The variable size of the area of the rotary valve hole can be checked based on the gas choking when it is at the maximum speed (8) by the following equation [5].

$$A \geq 1.3D^2 v_h \sin\alpha / v_s$$

where v_s is the sonic velocity in the hot gas, $v_h = 2\pi Rn$.

The minimum area of the valve hole is calculated to be

$$A \geq 1.3*0.07^2 * 2\pi*0.035*(3000/60)*\sin 5^0/330 = 1.85*10^{-5}\ m^2 = 18.5\ mm^2.$$

The real size of the valve hole area (3) is

$$A_f = ad\frac{\alpha\pi}{720^0} = 40*50*\frac{5^0*\pi}{720^0} = 43.63 \quad mm^2$$

The real size of the hole area at the critical gas speed is more than the minimum size of the hole area, $A_f \geq A$ or $43.63 > 18.5$. This means there is no gas choking in the valve hole at maximum gas speed.

The volume of the burned gas when the piston locates at the top position and in case of earlier opening of the intake hole that reduces the gas speed is calculated by (10) with $\alpha = 5^0$

$$W = (\pi D^2/4)R(1 - \cos\alpha) = (\pi 70^2/4)*35(1-\cos 5^0) \approx 513\ mm^3$$

The piston pushes out this volume of the burned gas trough the two holes. One leads to the intake channel, second to the exhaust channel. The area of the variable valve hole of the exhaust channel is twice more than the area of the variable valve hole of the intake channel. It means that only 1/3 of the burned gas volume W will go to the intake channel of the valve.

During the gas intake process, piston goes to dawn and 1/3 of the burned gas volume W from the exhaust hole will go to the cylinder. The total volume of the burned gases that locate into the intake and exhaust channels and involved into filling of the cylinder will be 2/3 of the volume W.

The volume of the cylinder of the engine filled by the fresh gas fuel is presented by the following

$$W_c = (\pi 70^2/4)*35(1-\cos 180^0) \approx 269392\ mm^3$$

The percentage of the burned gases into the fresh fuel gas is presented by the following

$$\delta = [(2/3)W/(W_c - W)]*100\% = [(2/3)513/(269392 - 513)]*100\% \approx 0.13\%$$

This component of the burned gas into the fresh fuel gas does not play the role and the earlier opening of the rotary valve hole on the turned angle $\beta = 2.5^0$ can be used for the design of the rotary valve.

V. Conclusion

The rotary valve design of the intake and exhaust flow system is capable of controlling the intake and exhaust gases and shows better technical characteristics of the cylinder-head work. Gas flow in the new system is acceptable and gives good results. Gas fluid dynamic calculations indicate that the new system is capable of increasing the efficiency of the gas intake and exhaust mechanism performance and show that the speed of gas flow in the new system has many differences than that of the conventional camshaft-valve system. The new mechanism enables the elimination of the overlapping of valves work, like early valves opening and late closing, which leads to less gas leakage. These positive attributes of the new design will result in a higher efficiency of internal-combustion engines.

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