Calculated determination of the flow coefficient through the intake system of the internal combustion engine

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Abstract. Taking into account the complexity and duration of creating the optimal shape of the flow part of the intake system, it is advisable to use mathematical models in its design and modernization. This not only reduces the cost and speeds up the creation of an optimal air path, but also provides conditions for automating the design process. The calculated determination of the flow coefficient using modern methods allows you to significantly reduce the amount of experimental research and solve the main problems by choosing the optimal combination of structural elements of the intake channels at the design and finishing stage of the engine. A method is proposed for calculating the flow rate through the intake system of an internal combustion engine (ICE) depending on the design features of the intake system elements: the flow resistance coefficient, the average speed of the piston, the cross-sectional area of the cylinder, the average effective flow of the valve slot, the number of valves, the value of the valve lift, the diameter of the neck. The influence of total losses from gas dynamic resistance is estimated.

Methods for calculating the intake system aimed at optimizing its parameters, taking into account the influence of engine operating conditions, non-stationary processes occurring in the intake tract, and valve movement, are usually based on experimental or theoretical determination of the flow coefficient. The applied static and dynamic purging of the intake channels of the cylinder heads, with which the flow rate is determined, requires significant time and material costs. The calculated determination of the expense coefficient is devoted to the works [1-8]. These studies are based either on strict laws of gas dynamics, or on the obtained empirical dependencies, which usually relate the flow coefficient only to the valve lift or to the ratio of the valve lift to the neck diameter. However, they do not take into account the design, type of channel with a valve and are private, that is, applicable to one channel design. In some studies, the flow coefficient is associated with compression and local resistance coefficients [9-17].

Let's consider a mathematical model for determining the flow coefficient that evaluates the gas-dynamic perfection of the inlet channel with a valve. It is in the valve slot that hydraulic losses are greatest. The movement of air flow through the valve in the cylinder head channel is accompanied by losses that reduce air flow. These losses are associated with the presence of increased hydraulic resistance in the section “channel-valve-cylinder” due to a sharp turn of the channel and flow in the valve slot, areas of turbulence, narrowing and friction. The disturbing influence of each of these resistances is interrelated, and, nevertheless, in this paper, with certain assumptions, it is proposed to
take into account these factors separately when determining the flow coefficient, and in general, to take into account the design of the inlet channel with the valve [18-27].

The discharge coefficient depends on the values (coefficients) of the resistances of the straight portion of the flow part $\xi_{st}$, when you turn the channel to the mouth $\xi_{tur}$ of compression in the flow path of $\xi_{com}$ and the valve slit $\xi_{val}$ kick $\xi_{hit}$ flow, and the channel profile (tangentially $\xi_{tan}$, screw $\xi_{scr}$) and the number of valves $i_{val}$ and influence one neck to another in the channel, four-valve heads $K$. The influence of the bushing, boss (if they exist and do not create much resistance) and the valve stem can be ignored [28-36].

Thus, the expense coefficient can be represented as:

$$
\mu = f(\xi_{st}, \xi_{tur}, \xi_{com}, \xi_{val}, \xi_{hit}, \xi_{tan}, \xi_{scr}, i_{val}).
$$  \hfill (1)

The coefficient of resistance on a straight section does not depend on the Reynolds number and is determined only by the absolute roughness:

$$
\xi_{st} = \frac{1}{(R_e + h)^2},
$$  \hfill (2)

where $r$ - radius of the channel cross section, m; $h$ - height of roughness bumps, m.

Coefficient of resistance when turning the channel:

$$
\xi_{tur} = K_{A} K_{R_e} \xi_{M} + 0.0175 \lambda R_o / D_r .
$$  \hfill (3)

where $K_{A}$ - the coefficient of roughness, is selected from the chart; $K_{R_e} = 1.3 - 0.29 \ln(10 R_e^{0.5})$ - determined when $R_o/D_o > 0.7$; $R_o$ - radius of rotation of the flow part of the inlet channel along the center line, m; $D_o$ - diameter in the cross-section of the channel, m; $\xi_{M} = A_1 B_1 C_1$ - coefficient of local hydraulic resistance; $\delta$ - the angle of the channel, hail; $\lambda$ - coefficient of hydraulic resistance; $D_r$ - hydraulic diameter, m.

A channel with a circular or square cross section with a rotation angle $\delta=90^o$ has the following coefficient values: $A_1=1.0; B_1=0.21(R_o/D_o)^{0.5}; C_1=1.0$.

The tangential inlet channel has a confusor section that provides an increase in the speed of the air flow directed tangentially to the cylinder wall. In this case, along the length of the tapering confusor section, which has smooth curved forming walls, the value of the resistance can be found from the expression:

$$
\xi_{tan} = K_{mit} \left(\frac{1}{\varepsilon} - 1 \right)^2.
$$  \hfill (4)

where $K_{mit}$ - the softening coefficient that depends on the taper angle.

The resistance of compression in the flow path of the intake channel of circular cross-section:

$$
\xi_{com} = 0.1L / D_r - 0/0017L / a_o b_o .
$$  \hfill (5)

elliptical cross-section

$$
\xi_{com} = 0.145L / D_r - 0/0017L / a_o b_o .
$$  \hfill (6)

where $L$ - length of the section from the compressed section of the flow part of the channel to the neck, m;
The coefficient of resistance in the valve gap associated with the compression of the jet can be determined by the formula:

$$\xi_{val} = \frac{1}{\varepsilon^2}.$$  \hspace{1cm} (7)

where $\varepsilon = f_{min}/f$ - compression ratio of the air stream;

$f_{min}$ - area of the narrowed section of the jet, $m^2$;

$f$ - geometric area of the hole, $m^2$.

The jet compression ratio is determined according to table 1.

### Table 1. Dependence of the jet compression coefficient on the ratio of the valve lift to the neck diameter.

| $h/d_r$ | 0.05 | 0.1 | 0.15 | 0.2 | 0.25 | 0.269 | 0.3 | 0.35 |
|--------|------|-----|------|-----|------|-------|-----|------|
| $\varepsilon$ | 0.674 | 0.672 | 0.6705 | 0.668 | 0.665 | 0.664 | 0.661 | 0.656 |

In the screw inlet, the primary rotation of the air flow is created in the cochlea directly above the valve plate. In this case, the profile of the flow part of the snail can be built on a logarithmic spiral, or Archimedes spiral. In the first case the current radius of the logarithmic helix $R_o$ is determined by the formula:

$$R_o = \frac{250}{ed} \phi^2.$$  \hspace{1cm} (8)

where $d_o$ - diameter of the output section, $m$;

$e$ - base of natural logarithms;

$\phi$ - angle of opening of the spiral, deg.

The coefficient of resistance in the cochlea of the screw channel is determined from the characteristics of the cochlea, while almost all losses in the flow part of the channel are associated with losses in the cochlea of the channel $\xi_{scr} = \xi_{sn}$.

According to the results of processing a large number of experimental materials by the authors [45-53] using the method of least squares, the resistance in the cochlea of the inlet screw channel $\xi_{sn}$, depending on the relative value of the intake valve lift $h/d_r$, can be represented as a polynomial of the fifth degree:

$$\xi_{sn} = -10.13 \cdot 10^4 (h/d_r)^5 + 97.96 \cdot 10^3 (h/d_r)^4 - 33.05 \cdot 10^3 (h/d_r)^3 +$$

$$+ 55.13 \cdot 10^2 (h/d_r)^2 - 373.6 \cdot (h/d_r) + 15.1.$$  \hspace{1cm} (9)

Actual processes of air flow outflow in the form of an annular jet from the valve slot of the intake channel of the engine cylinder head are accompanied by shock losses $\xi_{sn}$ due to a sharp increase in the cross-section area:

$$\xi_{sn} = \left(1 - \frac{f_{val}}{F_c}\right)^2,$$  \hspace{1cm} (10)

where $f_{val}$ - area in the valve slot, $m$;

$F_c$ - the cross-sectional area of cylinder, $m$.

The necessary increase in the effective flow section in the valve slot can be achieved by using two valves at the inlet. Based on the authors processing of a large experimental material on purges of various channels (channels with incident flow, tangential, screw) and the theory of gas dynamics, using the least squares method, the following expressions are obtained for determining the flow coefficient for inlet channels with a valve:

- intake channel with falling flow
\[ \mu = 1 - \left[ (\xi_{s} + \xi_{s_{tur}}) \frac{h_{k}}{d_{r}} + (\xi_{com} + \xi_{val}) \left( \frac{h_{k}}{d_{r}} \right)^{2} + \xi_{sn} \left( \frac{h_{k}}{d_{r}} \right)^{3} \right]; \quad (11) \]

- tangential inlet channel

\[ \mu = 1 - \left[ (\xi_{s} + \xi_{s_{tur}} + \xi_{scr}) \frac{h_{k}}{d_{r}} + (\xi_{com} + \xi_{val} + \xi_{scr}) \left( \frac{h_{k}}{d_{r}} \right)^{2} + \xi_{sn} \left( \frac{h_{k}}{d_{r}} \right)^{3} \right]; \quad (12) \]

- screw inlet channel

\[ \mu = 1 - \left[ (\xi_{s} + \xi_{s_{tur}} + \xi_{scr}) \frac{h_{k}}{d_{r}} + (\xi_{com} + \xi_{val} + \xi_{scr}) \left( \frac{h_{k}}{d_{r}} \right)^{2} + \xi_{sn} \left( \frac{h_{k}}{d_{r}} \right)^{3} \right]; \quad (13) \]

- intake channel of 4-valve cylinder head

\[ \mu = 1 - K_{i} \left[ (\xi_{s} + \xi_{s_{tur}} + \xi_{scr}) \frac{h_{k}}{d_{r}} + (\xi_{com} + \xi_{val} + \xi_{scr}) \left( \frac{h_{k}}{d_{r}} \right)^{2} + \xi_{sn} \left( \frac{h_{k}}{d_{r}} \right)^{3} \right]; \quad (14) \]

where \( K_{i} \) - coefficient of influence of intake ports. 

In general, the formula for calculating the air flow coefficient for inlet channels with different flow configurations can be represented by the expression:

\[ \mu = 1 - K_{i} \left[ (\xi_{s} + \xi_{s_{tur}} + \xi_{scr}) \frac{h_{k}}{d_{r}} + (\xi_{com} + \xi_{val} + \xi_{scr}) \left( \frac{h_{k}}{d_{r}} \right)^{2} + \xi_{sn} \left( \frac{h_{k}}{d_{r}} \right)^{3} \right]. \quad (15) \]

Checking the convergence of the values of the air flow coefficients obtained during purging and during calculation showed that the mathematical model has a static confidence criterion of 95% [54-65].

Thus, the calculated determination of the flow coefficient of inlet channels with valves allows you to evaluate the design of the inlet channel at the design stage, simplify the mathematical model for calculating the working cycle, which no longer requires experiments on channel purging, and also outline ways to improve the channels.

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