THE HYDRAULIC RESISTANCE OF AN ORIFICE IN SWIRLED FLOW

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In calculating the exchange of gases in internal combustion engines we employ a number of experimental coefficients and the choice for the values of these coefficients depends in considerable measure on matching the theoretical data to the experiment. One such coefficient is the flow-rate factor μ_{ex} of the exhausts, the magnitude of this factor varying over a wide range during the period of the gas exchange [1]; however, its average value is frequently assumed in calculations. The factor μ_{ex} as a function of its determining parameters has not yet been studied adequately.

If we assume a relationship between the hydraulic resistance ζ_{ex} and the flow-rate factor μ_{ex} in the form

$$\mu_{ex}=\frac{1}{\sqrt{\zeta_{ex}+1}}, \tag{1}$$

when there is no swirling of the flow in the engine cylinder, and given the relationships between the round-off radius for the leading edge and the hydraulic diameter of the exhaust – which are usual for engines with straightline-slit air passage – the coefficient $\mu_{ex\,un}$ must be of the order of 0.85-0.92 [2]. However, for swirling flow the value of μ_{ex}, calculated from the indicator diagrams [1, 3], drops to 0.5 at certain periods of the cycle. Thus during an exhaust–intake cycle we have $\mu_{ex} \le \mu_{ex\,un}$.

To clarify the effect of flow swirling on the flow-rate factor of the exhausts, we performed experiments on a "cold" static model whose diagram is shown in Fig. 1.

Air is forced by means of ventilator 3 into receiver 5 through collector 1, calibrated to measure the flow rate, and through diffuser 2. To eliminate rotation of the air in the receiver, we installed nozzle diaphragm 4. The air was then passed through rotor 7 and connection tube 8 (which in conjunction with the rotor formed the blower sleeve), from which it reached exhaust sleeve 9 of the free-reciprocating OR-95 gas generator exhibiting 12 exhausts positioned uniformly about the circumference, with parallel side walls without tangential inclination.

The velocity fields at the center normal cross section of the cylinder were measured with a three-channel probe 11, and the static pressures were measured at the walls of the collector, the receiver, the connecting tube, and at the exhausts.

The rotor enabled us to alter the flow inlet angle β_1 (with respect to the radius) from 0 to 45°. Buckets 12 rotated on shafts 13 through the action of movable disk 14 into which the bucket-attachment slots 15 had been cut. The slots were positioned so that the buckets, on turning, remain pairwise parallel to each other. The pairs of nonparallel buckets are entirely covered with a thin rubber cuff 16 to prevent the passage of air between them. The bucket thicknesses and the curvature radii for their leading edges were chosen so that the conditions of flow entry and discharge would be independent of the setting angle for the diaphragm. The depth of the resulting channels for all bucket-setting angles was greater than the width of the buckets. Pistons 6 and 10 were able to occupy various fixed positions.

The experiments were performed at Reynolds numbers of $0.36 \cdot 10^5 \le Re \le 1.1 \cdot 10^5$, based on the parameters of the flow at the exhausts, which is in agreement with the self-similarity region for the flow-rate coefficients.

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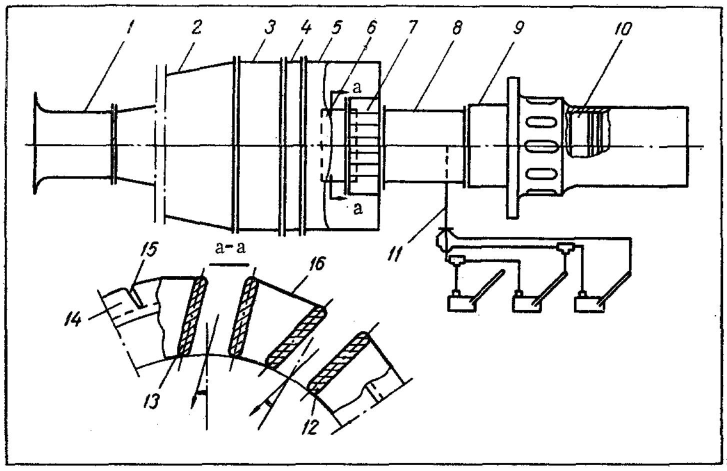


Fig. 1. Diagram of the experimental installation.

The flow-rate coefficient is defined as the ratio of the true mass flow rate G_g of the air to the theoretical possible flow rate G_m for a given difference of static pressures:

$$\mu_{ex} = \frac{G_g}{G_m}. \tag{2}$$

Wind-tunnel tests at flow-entry angles between 0 and 45° (in intervals of 5°) demonstrated that the distributions of the tangential velocities along the radius of the cylinder (Fig. 2a) for completely open air passages are close to the quantitative relationships governing potential flow with constant circulation of the velocity vector [4]. The flow of the air in the region of the exhausts is regarded as a result of the fact that a plane potential vortex has been superposed on the flat source.

We found that the flow-rate coefficient is a function of the Γ/Q ratio (the vortex intensity to the power of the source):

$$\mu_{ex} = f\left(\frac{\Gamma}{Q}\right). \tag{3}$$

The vortex intensity for completely opened air passages is calculated with the formula

$$\Gamma_0 = 2\pi R W_1 \sin\beta_1. \tag{4}$$

The power of the source is calculated with the formula

$$Q = 2\pi R W_{2m}. \tag{5}$$

By alternating the bucket-setting angle and the fan output we were able to achieve a number of Γ/Q ratios in the range $0 \le \Gamma/Q \le 0.7$. For each of these we found the value of the relative flow-rate coefficient

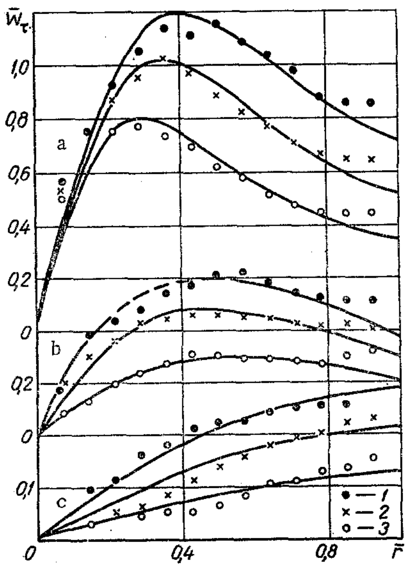
$$\bar{\mu}_{ex} = \frac{\mu_{ex}}{\mu_{ex\ un}}. \tag{6}$$

The magnitude of $\mu_{ex\,un}$ is determined exclusively by the relationship between the geometric parameters of the exhaust without flow swirling at the inlet to the exhaust [2]. The relative flow-rate coefficient $\bar{\mu}_{ex\,un}$ as a function of the Γ/Q ratio for completely open air passages $l_1 = 0.7$ R in length is given by the formula

$$\bar{\mu}_{ex} = 1 - 1.17\frac{\Gamma}{Q}, \tag{7}$$

whose agreement with the experimental data can be seen from Fig. 3 (curve 5). However, as will be demonstrated below, this quantitative relationship is retained even for partly open air passages, so that we have dropped the subscript 0 for the parameter Γ.

The values of Γ/Q for engine designs with straight-line slotted air passage fall within the range in which the experiments were carried out.



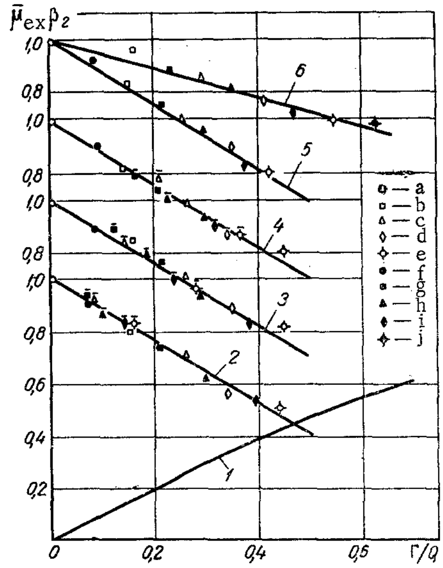


Fig. 2

Fig. 3

Fig. 2. Distribution of the tangential velocity over the radius of the cylinder (the air passages are: a) 100% open; b) 50% open; c) 25% open; 1) $\beta_1 = 40°$; 2) 30°; 3) 20°.

Fig. 3. The angle β_2 (1) and the relative flow-rate coefficient as functions of the parameter Γ/Q for exhausts without tangential inclination (2-5) and for windows set in at an angle of 30° (6) (exhausts without tangential inclination are 100% open when the air passages are 25% open (2); 50% open (3); 75% open (4); 100% (5); a) $\beta_1 = 0°$; b) 10°; c) 20°; d) 30°; e) 40°; f) 5°; g) 15°; h) 25°; i) 35°; j) 45°.

It is important to note that it is only because of the swirling of the flow in the engine cylinder that the flow-rate coefficient for the exhausts varies by a factor of almost two, since with all other conditions being equal, the intensity of the vortical motion in the cylinder, governing the inlet condition at the exhausts, plays a decisive role in the hydraulic resistance of the exhaust.

It is therefore of practical interest to raise the flow-rate coefficients for the exhausts by matching their setting angles with the kinematics of the flow reaching the exhausts from the cylinder.

The choice of the angle of tangential inclination for the air passages and the corresponding circulation are generally based on the conditions of satisfactory mixing, the extent to which the cylinder has been cleansed of the products of combustion during the passage of the air, etc. The power of the flat source Q is completely determined by the quantity of gas passing through the engine cylinder.

To determine the optimum angle of tangential inclination for the exhaust, when the Γ/Q ratio has been specified, it is convenient to employ the recommendations of gas dynamics for potential flow, according to which the exhaust walls must line up with the streamlines of the vortex source. In the case under consideration, such lines are formed by logarithmic spirals [5], which are described by the equation

$$r = C \exp\left(\frac{Q}{\Gamma}\varphi\right). \tag{8}$$

The angle between the radius and the streamline of the vortex source is

$$\beta_2 = \operatorname{arc\,tg}\frac{\Gamma}{Q}. \tag{9}$$

Thus an optimum angle of tangential inclination for the exhausts corresponds to each angle of tangential inclination for the air passages. This angle can be calculated from (9) or it can be taken from curve 1 in Fig. 3.

These relationships have been derived without consideration of compressibility. During the period of free exhaust, when the effect of compressibility is particularly pronounced, the swirling of the flow has little effect on the losses at the exhausts. However, in the remaining periods of gas exchange the pressure differences across the exhausts are slight and it is permissible to employ the quantitative relationships governing the flow of an incompressible fluid.

In practical terms, it is difficult to shape each of the two walls of the orifice differently. It is sufficient that the axis of the exhaust is tangent to the streamline of the potential flow at the inlet, and that the side walls are made parallel.

In engines with opposed pistons, the piston phases are shifted through some angle to provide for a better operating cycle.

In this connection, we performed experiments to clarify the effect exerted on the intensity of the vortical motion in a cylinder by the shifting of the exhaust piston during the time that the air-supply piston occupied a number of stable positions. The experiments demonstrated that the profile of the tangential velocities W_τ in the cylinder is governed entirely by the position of the air-supply piston, while the position of the exhaust piston seemingly governs the changes in the scale of the velocities plotted on the profile, in proportion to the volume flow rate of the air through the cylinder.

As the air-supply piston is shifted through the orifice there is a change in the distribution of the tangential velocities along the cylinder radius (Fig. 2b and c).

The intensity of the vortex can therefore be calculated from formula (4) only for air passages that are completely open. In the remaining cases, the intensity of the vortex is lower and can be determined only with consideration of the deformation of the velocity profiles.

To determine the vortex intensity in the cylinder with partly opened air passages, we approximated the profiles of the tangential velocities which we obtained in the experiments by means of the relationship

$$W_\tau = \frac{\Gamma_\nu}{2\pi r}\left[1 - \exp(-kr^2)\right]. \tag{10}$$

Relationship (10) was chosen because the profiles of the tangential velocities, obtained for various lengths of the open portion of the air passages, are analogous to the profiles of the velocities induced by the instantaneous dissipating vortex in a viscous liquid for various intervals of time [6].

On the basis of experimental data, following the Gauss–Seidel method on a Nairi digital computer, for each position of the air-supply piston we found Γ_ν and k. The unknown intensity of the flat ideal vortex is given by

$$\overline{\Gamma} = \overline{2\pi r W\tau} = \frac{1}{R}\int_0^R \Gamma_\nu\left[1 - \exp(-kr^2)\right] dr. \tag{11}$$

The calculations are simplified if we make use of the fact that

$$\int_0^R \exp(-kr^2)\, dr = \sqrt{\frac{\pi}{4k}}\, \Phi\left(R\, \sqrt{2k}\right).$$

Here Φ is a probability function of the form

$$\frac{2}{\sqrt{2\pi}}\int_0^x \exp\left(\frac{t^2}{2}\right) dt.$$

The profiles of the tangential velocities calculated with formula (10) are shown in solid lines on Fig. 2 in the form $\overline{W}_\tau = W_\tau/W_1$. Calculations with formula (11) showed that for completely open air passages the values of the vortex intensity in the cylinder coincide with those calculated from formula (4). As the passages are closed, the intensity of the vortex diminishes, while the intensity ratios calculated from formula (4) and from formula (11) are independent of the angle of flow entry and are completely governed by the relative length of the open portion of the passages. Numerous experiments have demonstrated that the vortex intensity is proportional to the relative length of the open portion of the air passages and is in satisfactory agreement with the formula

$$\Gamma = \Gamma_0 \bar{l}_1. \tag{12}$$

The values of the relative flow-rate coefficients for the exhausts, given partially opened air passages, have been calculated from formula (7), in conjunction with (12) and they have been plotted in Fig. 3 (curves 2-4). Here we also find plotted the values of $\bar{\mu}_{ex}$ for the partly closed exhausts in the presence of completely open air passages (these symbols are identified with an overscore).

Having substituted the values of Q and Γ from (5) and (12) into (7), assuming

$$W_{1m} = \sqrt{2\frac{\Delta P_1}{\rho_1}}, \quad W_{2m} = \sqrt{2\frac{\Delta P_2}{\rho_2}}, \quad \rho_1 = \rho_2,$$

which can be assumed for the period of the air supply, and noting that $W_1 = W_{1m}\mu_s$, we obtain an analytically extremely convenient relationship between $\bar{\mu}_{ex}$ and its determining parameters:

$$\bar{\mu}_{ex} = 1 - 1.17\sqrt{\frac{\Delta P_1}{\Delta P_2}}\,\bar{l}_1 \mu_s \sin\beta_1. \tag{13}$$

The satisfactory agreement between the $\bar{\mu}_{ex}$ values from the experiments and those calculated with the formula for completely and partially open air passages provides the basis for our recommendation of the following scheme of calculating the flow-rate coefficients for exhausts without tangential inclination in engines with straight-line slotted air supply.

We have to determine the coefficient $\mu_{ex\,um}$ for an unswirled flow (i.e., for static passage of air or, for example, according to the data of [2]), we have to calculate the power of the source from formula (5), and we have to calculate the intensity of the vortex in the cylinder with formula (12). We then have to use the Γ/Q ratio and formulas (7) and (6) to find the flow-rate coefficients $\bar{\mu}_{ex}$ and μ_{ex} for the exhausts. The maximum value of μ_{ex} can be achieved if the angle of the tangential inclination for the exhausts is chosen according to formula (9) or from curve 1 in Fig. 3.

The Γ/Q ratio varies during the cycle and its values differ for identical positions of the piston in the forward and reverse strokes.

In practical terms, the angle for the tangential inclination of the exhausts may be constant over their length, or it may vary, but in this case we must proceed from the condition of minimum total hydraulic losses during the cycle.

Let us note that for Γ/Q values close to zero (for example, at the instant of free exhaust), the flow-rate coefficients for the exhausts are virtually independent of the angle of tangential inclination and these can be determined in precisely the same manner as for the case of discharge from a reservoir through equivalent orifices as, for example, according to the data of [2]. The values of the flow-rate coefficients found in this manner for the variously shaped exhausts are comparatively high (0.85-0.92) and they are in good agreement with the magnitudes of μ_{ex} during the period of free exhaust, as calculated from the indicator diagrams for the 2D100 diesel [1], the GS-34 free-piston gas generator [3], and similar engines.

It is obvious that having determined the coefficient μ_{ex} and the source power Q from the indicator diagrams, we can calculate with (6) and (7) the intensity of the vortex motion in the air, as well as its angular momentum.

This method can be used to calculate the flow-rate coefficients for the exhausts of engines operating in various regimes, since experiments have demonstrated that the direction of the absolute-velocity vector at any of the radii of the cylinder is independent of the volume flow rate of air through that cylinder and that it remains constant for each position of the piston controlling the passage of air; however, the magnitude of the vector is proportional to the volume flow rate.

This is in agreement with the conclusions of [7], to the effect that the change in tangential velocity is proportional to engine revolutions.

The flow-rate coefficients calculated from the indicator diagrams are shown in Fig. 4 for the exhausts of free-piston gas generators whose side walls exhibit no tangential inclination, while the air passages are inclined at an angle of 30°.

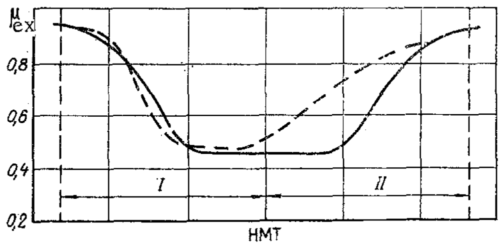


Fig. 4. Change in the flow-rate coefficients for the exhausts of a free-piston gas generator within a cycle (the solid curve represents the data of [3], while the dashed curve is plotted according to formula (6)); I) forward stroke; II) reverse stroke.

We find agreement for μ_{ex} values on the expansion line and we find divergence on the compression line. It is noted in [3] that the coefficients μ_{ex} on the expansion lines have been calculated, while those on the compression lines are assumed to be symmetrical to the former.

In conclusion let us examine the results derived in experiments with a sleeve whose exhausts have parallel side walls inclined at an angle of 30°.

Figure 3 shows the quantitative relationship governing the change in the relative flow-rate coefficients for completely opened exhausts for various values of the Γ/Q ratio (the air passages are completely opened). Line 6 corresponds to the $\overline{\mu}_{ex}$ values calculated from the static pressures at the cylinder wall, if these are measured, as is usual, at the midsection of the cylinder (by means of nozzles). It is clear from these results that appropriate tangential inclination of the exhausts can markedly increase their flow-rate coefficients.

NOTATION

$\mu_{ex\,un}$	is the flow-rate coefficient for the exhausts with unswirled flow;
$\mu_{ex}, \overline{\mu}_{ex}$	are, respectively, the true and relative flow-rate coefficients of the exhausts;
μ_s	is the flow-rate coefficient for the air passages;
ζ_{ex}	is the coefficient of hydraulic resistance for the exhausts;
β_1, β_2	are the tangential angles of inclination for the air passages and the exhausts, respectively, in rad;
Re	is the Reynolds number;
G_m, G_g	are, respectively, the theoretical and actual mass flow rates for the air;
Γ, Γ_ν	are, respectively, the vortex intensities in the ideal and viscous fluids;
Q	is the power of a flat source;
r, R	are, respectively, the instantaneous and inside radii of the cylinder;
W_1, W_{1m}	are the actual and theoretical velocities in the air passages;
W_{2m}	is the theoretical velocity in the exhausts;
$l_1, \overline{l}_1, l_2, \overline{l}_2$	are the actual and relative lengths of the open portion of the air passages and the exhausts, respectively;
C	is a constant;
$W_\tau, \overline{W}_\tau$	are, respectively, the actual and relative tangential components of the air velocity in the cylinder;
k	is a coefficient by means of which we take into consideration the viscosity and time [6].
φ	is the polar angle;
$\Delta P_1, \Delta P_2$	are, respectively, the static pressure differences across the air passages and across the exhausts;
ρ_1, ρ_2	are the gas densities behind the air passage and in front of the exhausts;
g	is the gravitational acceleration.

LITERATURE CITED

1. A. E. Simpson, Gas-Turbine Supercharging of Diesels [in Russian], Mashgiz, Moscow (1964).
2. I. E. Idel'chik, Handbook on Hydraulic Resistance [in Russian], Énergoizdat, Moscow (1963).
3. He Hsueh-Liang, Trudy KhPI im. Lenina, Seriya Énergomashinostroeniya, 43, No. 3 (1963).
4. M. G. Kruglov, The Thermodynamics and Gas Dynamics of Two-Cycle Internal Combustion Engines [in Russian], Mashgiz, Moscow (1963).
5. N. Ya. Fabrikant, Aerodynamics [in Russian], Nauka, Moscow (1964).
6. H. Routh, Fluid Mechanics [Russian translation], Stroiizdat, Moscow (1967).
7. D. N. Vyrubov and M. M. Él'kotb, Izv. Vuzov, Mashinostroenie, No. 4, Izd. MVTU im. Baumana (1965).