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HYDRAULIC RESISTANCE OF SWIRL CHAMBERS WITH A FLUID LAYER

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UDC 532.55

The industrial use of swirl chambers (SCs) is hampered by inadequate study of a number of questions, including determination of the hydraulic resistance ΔP_0 of SCs containing a fluid layer. This question has been discussed many times in the literature. Thus in [1-3] the following relations are proposed for SCs whose housing is stationary and in which gas spins the fluid layer:

$$\Delta P = 2\Delta P_0/(\rho'' W''^2) = 1 \tag{1}$$

where ρ" is the gas density and W" is the velocity of the gas between the guide vanes;

$$\Delta P = 0{,}8; \tag{2}$$

$$\Delta P = 23k \tag{3}$$

where $k = s\eta$, s is the relative flow area, $\eta = h/r_0$, and h and r_0 are the height and radius of the guide vanes.

The values of the hydraulic resistance calculated from Eqs. (1)-(3) cannot be compared with the experimental data of [1, 2], since the geometric dimensions of the SC are not given there. At the same time these values differ by several times from the experimental data of [3].

In [4] the following relations are given for calculating the hydraulic resistance of the fluid layer in application to SCs with a stationary housing and gas-spun fluid layer:

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$$\Delta P_0 = 2\rho' g_+ h_0 \quad (4)$$

where ρ' is the density of the liquid, $g_+ = v_0^2/r_0$ is the centrifugal acceleration of the layer, r_0 is the radius of the chamber, h_0 is the height of the initial layer, and v_0 is the rotational velocity of the layer;

$$\mathrm{EuFr} = 1700 \quad (5)$$

where $\mathrm{Eu} = \Delta P_0/(\rho' v_0^2)$ and $\mathrm{Fr} = v_0^2/(g_+ h_0)$ are the Euler and Froude numbers. From Eq. (5) we obtain $\Delta P_0 = 1700\rho' g_+ h_0$, which contradicts Eq. (4).

In [5] a method is given for calculating the hydraulic resistance for SCs with stationary housing and in which the fluid layer is spun by gas or liquid. The method is based on the analogy between heat transfer and hydrodynamic processes under conditions of direct contact of the gas with liquid; as indicated by the author (see [5], p. 67), such an analogy practically does not exist.

The aim of the present work is to derive formulas that would be suitable for calculating the hydraulic resistance of SCs with the constructions indicated above and in the presence of a spinning fluid layer.

The hydraulic resistance of SCs with a fluid layer (Fig. 1) consists of the resistance of the guide vanes, the spinning fluid layer in the section from r_0 to r_1, and the section from r_1 up to the opening with radius r_2 for efflux of the gas.

The total hydraulic resistance of a SC with a fluid layer is determined by the formula

$$\Delta P_0 = \frac{\zeta \rho'' W''^2}{2} + \int_{r_1}^{r_0} \varepsilon \rho' v_0^2 \frac{dr}{r} + \frac{\zeta_2 \rho_2'' u''^2}{2}. \quad (6)$$

Here ζ and ζ_2 are the resistance coefficients of the guide vanes and the section from r_1 up to the gas-efflux opening; ε is the specific content of liquid in the fluid layer; and, ρ_2'' and u'' are the density and tangential velocity of the gas at the radius r_2.

Since for a spinning fluid layer in an SC the equality [6] $v = v_0/W'' = \text{const}$ is satisfied and since the average value of the specific content of liquid $\varepsilon = 0.5$ [7], the formula (6) can be integrated as follows:

$$\Delta P = \zeta - \rho_- v^2 \ln r + \zeta_2 \rho_+ u_-^2$$
$$(\rho_- = \rho'/\rho'',\ r = r_1/r_0,\ \rho_+ = \rho_2''/\rho'',\ u_- = u''/W''). \quad (7)$$

The first two terms in Eq. (7) are usually significantly larger than the last term. We study this case first:

$$\Delta P = \zeta - \rho_- v^2 \ln r. \quad (8)$$

In Eq. (8) ζ and v are unknown, and without them it is impossible to determine the total hydraulic resistance.

The following formula was proposed in [6] for calculating the spin rate of the fluid layer in an SC under conditions when the layer is spun by the gas and by a rotating housing:

$$v = \beta\omega - 0{,}5\alpha r + \sqrt{\alpha + 0{,}25\alpha^2 r^2 + (1 - \beta r)\alpha\omega - (\gamma - \beta^2)\omega^2}, \quad (9)$$

where $\beta = 0.75(1 - r^4)/(1 - r^3)$; $\omega = \omega_- r_0/W''$; ω_- is the angular velocity of the chamber housing; $\alpha = 3\psi\eta/(c_f \varepsilon \rho_-(1 - r^3))$; $\psi = s/\sin\theta$; θ is the angle between the direction of entry of the gas into the layer and the radius of the SC, drawn to the location of entry; and, c_f is the coefficient of friction of the layer against the end faces of the SC. For an SC with a fluid layer the following inequality is usually satisfied:

$$G'' W'' r_0 \gg G'' v_0 r_1 \quad (10)$$

where G'' is the mass flow rate of the gas. Using the inequality (10) the expression (9) can be put into the form

$$v \approx \beta\omega + \sqrt{\alpha + (1 - \beta r)\alpha\omega - (\gamma - \beta^2)\omega^2}. \quad (11)$$

Since for $0 < r z 1$ the inequality $\alpha(1 + (1 - \beta r)\omega) \gg (\gamma - \beta^2)\omega^2$ is satisfied, the formula (11) simplifies:

$$v \approx \beta\omega + \sqrt{\alpha + (1 - r\beta)\alpha\omega}. \quad (12)$$

TABLE 1

Designations of Fig. 4.	Type of vortex
1 — cold model	ENIN
2 — stand, liquid fuel	TsKTI
3 — stand, coal	ENIN
4 — cold model	TsKTI
5 — stand, coal	TsKTI
6 — cold model	KazNIIÉ
7 — "	TsKTI
8 — stand, coal	MVTU

Notes. ENIN-G. M. Krzhizhanovskii Institute of Power Engineering; TsKTI-I. I. Polzunov Central-Scientific Research, Planning, and Design Institute of Boilers and Turbines; KazNIIÉ-Kazakh Scientific Research Institute of Power Enginnering; MVTU-N. E. Bauman Advanced Technical School, Moscow.

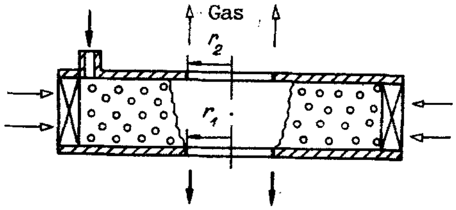

Fig. 1

In the case of a stationary housing the relation (12) has the simpler form

$$v \approx \sqrt{\alpha}. \tag{13}$$

Using the relation (13) and the empirical equality [6] $c_f\varepsilon = 0.0125$ with $\sin\theta \approx 1$ we obtain from the formula (8) for an water–air layer

$$\Delta P = \zeta + 240k \ln (1/r)/(1 - r^3). \tag{14}$$

In Fig. 2 the experimental data of [3] for SCs with h = 0.03 m [1) r = 0.66, r_0 = 0.074 m; 2) r = 0.80, r_0 = 0.124 m] are compared with the dimensionless hydraulic resistance calculated as a function of the complex k from the relations (1)-(3) and (14). Each group of close-lying experimental points is a set of values of ΔP obtained for W" ranging from 14 to 94 m/sec. The relations (1)-(3) differ strongly from the experimental dependences, while the dependences calculated from the formula (14) with ζ = 1 agree with the experimental data to within ±25%.

Figure 3 summarizes the experimental data of [3, 4] on the hydraulic resistances of SCs with a stationary housing [1) with cylindrical guides and dimensions r_0 = 0.074 m, h = 0.03 m, r_1 = 0.049 m, and s = 0.0526, 0.0726, 0.1026, 0.1578, 0.042, and 0.085; 2) with conical guides and dimensions r_0 = 0.119 m, r_0' = 0.11 m, h = 0.038 m, and s = 0.0792, 0.1056, and 0.1320) and a rotating housing [3) s = 0.045, r_0 = 0.1 m, h = 0.037 m, n = 100, 200, 300, 400 rpm, h_0 = 2.0, 5.3, 8.0, 10.6, 13.5, 16.0, 16.9 mm, W" = 43.0, 53.8, 64.6, 75.3, 86.1, 96.9 m/sec].

The relation $\varepsilon\rho' \ln r \approx \varepsilon\rho' H/r_0 \approx \rho' h_0/r_0$ was employed, because in [4] in calculations based on the formula (8) the layer thickness h_0 determined from the volume of the liquid poured in instead of the thickness H of the fluid layer was fixed for the hydraulic-resistance data. As one can see from Fig. 3, using ζ = 1 makes it possible to fit to within ±25% the published experimental results on the hydraulic resistance of SCs with a fluid layer. On this basis it can be concluded that for θ ≈ 90 the resistance of the guides in the SCs is equal to unity.

The contribution of the resistance of the section from r_1 to the gas-efflux opening to the total hydraulic resistance can be taken into account by noting that for this purpose the method proposed in [8] for calculating the hydraulic resistance of swirl chambers themselves is suitable. In [8] the following formula is proposed for the resistance of a swirl chamber on the basis of fitting the aerodynamic-resistance data for swirl chambers with a straight line representing their relative resistance versus the ratio of the diameter of the output opening to the guide diameter d/D (d = $2r_2$, D = $2r_0$) for d/D = 0.3-0.7:

$$\Delta P_+ = \Delta P_-/(\Delta P_-)_{0,45} = (0,9D/d - 1) \tag{15}$$

where ΔP_- is the resistance of the swirl chamber itself, and the index 0.45 indicates that the resistance is taken for a chamber with d/D = 0.45.

According to Eq. (15), the expression for the resistance of a swirl chamber has the form

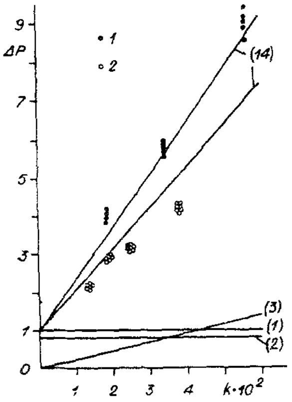

Fig. 2

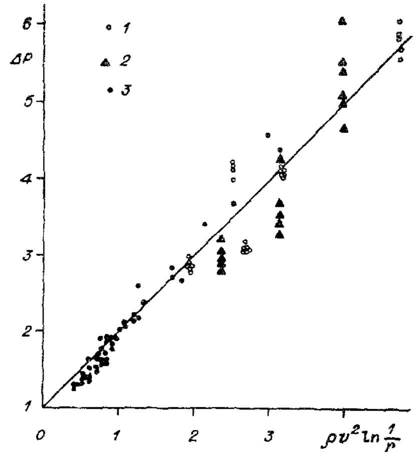

Fig. 3

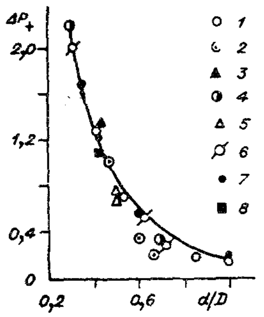

Fig. 4

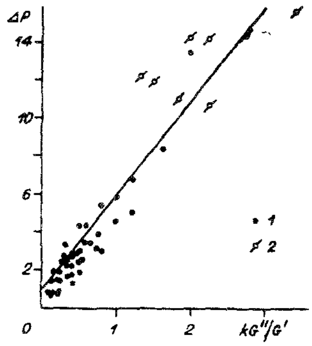

Fig. 5

$$\Delta P_- = (\zeta_2 \rho_2'' u''^2/2)_{0,45}(0{,}9D/d - 1)$$

where ζ_2 is the aerodynamic-resistance coefficient.

For the entire range of d/D the following formula, obtained from the law of conservation of momentum (neglecting friction), under the assumption that in the equation $\Delta P_- = \zeta_2 \rho_2'' u''^2/2$ ζ_2 does not depend on d/D, is physically better grounded:

$$\Delta P_-/(\Delta P_-)_{0,45} = (d/D)^2_{0,45}/(d/D)^2 = 0{,}2025\,(D/d)^2, \quad (16)$$

The agreement between the formula (16) (line) and the experimental data of [8] can be judged from Fig. 4. Thus

$$\Delta P_- = 0{,}2025\,(D/d)^2 (\zeta_2 \rho_2'' u''^2/2)_{0,45}. \quad (17)$$

The method proposed in [8] for calculating the resistance of swirl chambers is recommended in [9] for calculating the resistances of swirl burners with axial fuel injection. Therefore the formulas (16) and (17) are also valid for swirl burners with axial fuel injection. The designations employed in Fig. 4 and the types of vortices corresponding to them are indicated in Table 1.

The total hydraulic resistance of an SC with fluid layer cannot be determined computationally, if the SC has end walls with a complicated surface and the distribution of the liquid content and the tangential velocity in the fluid layer are not known. This refers completely to SCs of centrifugal heat exchanges (CHEs) [5].

Since in this case the first two terms also make the main contribution to the total hydraulic resistance of SCs, the following relation should be observed experimentally:

$$\Delta P = 1 + \Delta P_1 \quad (18)$$

where $\Delta P_1 = \Delta P_1^!/(\rho_1'' W''^2)$ and $\Delta P_1^!$ is the hydraulic resistance of the fluid layer.

The experimental data of [5, p. 17] are plotted in Fig. 5 in the coordiantes dimensionless hydraulic resistance and the complex kG'/G'' [1) r_0 = 0.055 m, η = 1.45, G'/G'' = 3.33, 6.25, 4.17, 2.08, 5.56, 8.33, 13.89, s = 0.02, 0.04, 0.06, 0.08, 0.10 and r_0 = 0.055 m, η = 0.73, s = 0.10, G'/G'' = 3.33, 6.25, 4.17, 2.08, 5.56, 8.33, 13.89; 2) r_0 = 0.055 m, η = 4.54, s = 0.12, G'/G'' = 2.38, 2.78, 3.33, 4.17, 3.57, 4.17, 5.00, 6.25]. Since liquid was injected in the indicated SCs of CHEs with high fluid flow rates G' and it was injected tangentially and with high velocity, increasing the flow rate of the liquid resulted in an increase of the spin rate of the fluid layer and the corresponding component of the total hydraulic resistance.

The observed linear relation between the dimensionless hydraulic resistance and the indicated complex is described approximately by the equation $\Delta P = 1 + 5kG'/G''$, which has the form (18). This once again confirms the correctness of the approach expounded here, though the last equation contradicts the relations proposed in [5, p. 83].

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CAPILLARY INSTABILITY OF AN EXTENDING JET

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The development and breakup of a capillary liquid jet, formed by axisymmetric extension, between two surfaces of a volume of liquid was investigated experimentally. The extension jet is formed during the operation of a monodispersed-drop generator (MDG) of the type "vibrating needle." The volume of the liquid participating in the extension process falls in the range $V_0 = (0.5\text{-}15.0)\cdot 10^{-11}$ m^3. The characteristics of the process of generation of extension jets are established. It is shown that instability of a cylindrical extension jet can arise both with and without axisymmetric oscillations.

1. Flows which can be termed extension jets arise in different processes (for example, deformation and fragmentation of drops in a gas flow, rupture of a connecting neck between drops in the process of merging of particles), resulting in axisymmetric extension of a liquid neck, i.e., a volume of liquid between two surfaces. In the study of such phenomena two aspects are distinguished: the form which the neck assumes under the action of the extension forces and surface tension and the breakup of a capillary extension jet.

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