A SHORT SWIRL CHAMBER

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The flow in a short air-operated swirl chamber is studied by contactless methods. An engineering technique is suggested to calculate the parameters of a swirled gas flow in this chamber.

Apparatuses with swirled flows of the working body are finding ever-widening application in modern technologies. These are swirl energy separators, plasma guns, combustion chambers, filters, mills, valves, etc. A simplified aerodynamic scheme of these devices can be presented as short ($H/R_0 < 1$) or long ($H/R_0 \geq 1$) swirl chambers or their combinations. Knowledge of the specific features of a flow in swirl chambers allows one to more accurately formulate the problem for analytical studies and to find correct engineering solutions for a specific technical device.

The present paper deals with a study of a short swirl chamber (see Fig. 1).

The flow in a short swirl chamber is conventionally divided to four regions [1]: a region of jet flow, a flow core, boundary layers on the end walls, and a near-axis region. The jet-flow region lies between the chamber wall at radius R_0 and the flow core. Its length is usually insignificant and equals one or two heights h of the intake channels. The velocity of initial flow swirling is formed in the jet zone.

Multiple exceeding of the circumferential component over the radial ($V/U \gg 1$) and axial ($V/W \gg 1$) ones in the flow core as well as radial overflows of the working body through the wall boundary layers that are caused by an imbalance between centrifugal and pressure forces are specific features of a short swirl chamber. Depending on the ratio of these forces in the flow core and wall boundary layers not only the redistribution of the flow rate over the chamber height is possible, but also the origination of secondary flows [2] that exert a substantial effect on the distribution of the parameters of the working body flow in a short swirl chamber.

Studies were performed in swirl chambers with one- and two-sided outflows with geometric parameters $40 \leq D_0 \leq 90$ mm, $6 \leq d_0 \leq 32$ mm, and $5 \leq H \leq 20$ mm within a range of variation of the area of the tangential intake channels of from 3.14 to 144 mm^2. The intake channels were round or rectangular. Air was used as the working body; the flow rate amounted to 4 g/sec.

During the studies the velocity was measured by a laser anemometer consisting of standard units and devices. The anemometer was designed by a differential scheme with direct scattering. The anemometer and the measurement technique are described in detail in [3].

The static pressure distribution over the radius of a swirl chamber as well as the pressure in the intake channels and on the side surface of the chamber were registered by pressure sampling through openings made in the studied models.

It was found in the experiments that the flow in short swirl chambers has specific features at the periphery. Instead of the anticipated growth of the chamber geometric parameters (R_0, F, H) and flow rate, a decrease to some radius R_p is observed, from which the velocity increases as $Vr^n = \text{const}$ (zone of quasipotential flow).

Reduction of the area of the intake opening leads to an increase in the intake velocities, but in the region of the discharge opening the increase in the circumferential velocity is not proportional to its growth at the inlet. Experiments with a variable gas flow rate in chambers of constant geometry showed that the length of the zone of circumferential velocity decrease is reduced with an increase in the flow rate.

Figure 1 presents radial profiles of the circumferential velocity for swirl chambers of one- and two-sided outflow in the middle cross-section over the chamber height, and Fig. 2 shows profiles of the circumferential velocity

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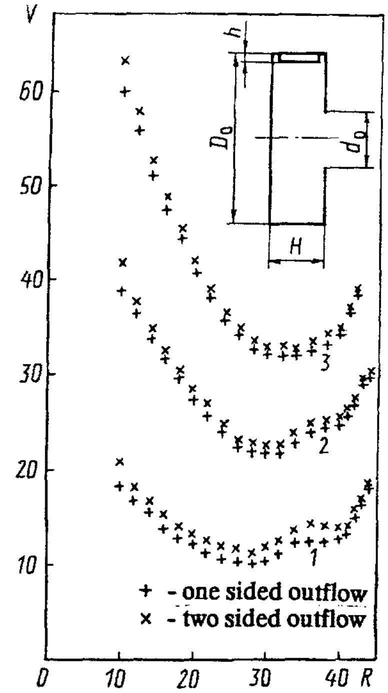

Fig. 1. Diagram of swirl chamber and radial profiles of circumferential velocity of one- and two-sided outflow, D_0 = 90 mm, H = 9 mm, d_0 = 16 mm, F = 72 mm^2; 1, 2, 3, flow rate, 1, 2, 3 g/sec, respectively. V, m/sec; R, mm.

over the chamber height. On all the profiles of Fig. 1 and profiles 1 and 2 of Fig. 2 a zone of decrease in circumferential velocity is seen, whose length equals about two heights of the intake channels. This zone can be defined as a jet zone. As the flow rate grows the dimensions of this zone remain constant, whereas the dimensions of the second zone of decrease in circumferential velocity, which lies behind the jet zone, are reduced.

The effect of the swirl chamber height within limits of its variation of from 5 to 20 mm on the distribution of circumferential velocities was insignificant. The profiles of circumferential velocities over the chamber height beyond the limits of the jet zone are filled as in a turbulent flow. In the jet zone, in the plane of the intake openings, maxima caused by jets entering the chamber are readily apparent. To reveal the causes of the decrease in tangential velocity in a wide peripheral zone of the chamber, experiments were conducted on flow visualization by a laser light knife. For this purpose the space of the swirl chamber was filled with smoke before the onset of the main flow rate. At flow rates of up to 0.2 g/sec a sharp flow picture was visualized in the swirl chamber that lasted several seconds. As the flow rate grew the sharpness was lost, though the contours were traced.

With an increase in the flow rate, first the near-end boundary layers in the chamber peripheral zone became clear, whereas smoke particles remained for a longer period of time farther from the walls, near the chanber symmetry axis. The contours of the smoke zone approximately coincided with the boundary of the zone of circumferential velocity decrease at the chamber periphery.

Observations allowed one to suppose the formation of at least two approximately symmetric closed flows in the peripheral zone of the decrease in gas circumferential velocity. These flows had the shape of deformed toroidal rings with the radial velocity in the middle cross section over the chamber height directed toward the chamber periphery, and that at the borderline with the near-end boundary layers directed toward its center.

On the radius of the circumferential velocity minimum, i.e., at the beginning of the zone of quasipotential flow, the wall layers link up virtually completely. Thus, from the minimum zone the gas radial velocity was directed toward the chamber axis. The formation of closed toroidal vortex zones at the periphery of the swirl chamber can be explained by the same imbalance of forces that took place in the redistribution of the flow rate over the chamber height at radii close to the discharge [2].

Near the cross-section of mean height over the swirl chamber at the boundary of the jet zone, centrifugal forces prevail over the forces caused by the radial pressure gradient. This causes the inflow of some gas from the

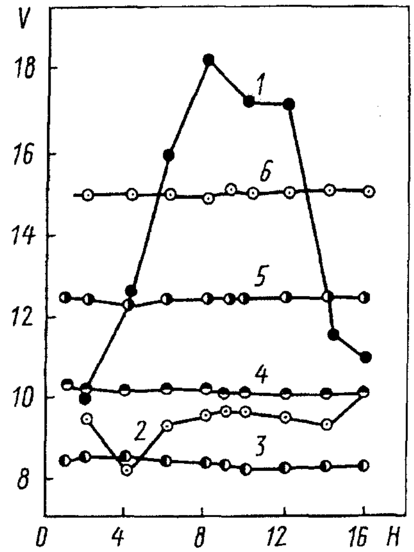

Fig. 2. Profiles of circumferential velocity over the chamber height with four intake openings ∅ = 3 μμ, Δ_0 = 90 μμ, δ0 = 16 μμ, H = 18 μμ, Γ = 0.75 γ/σεχ: 1, ρ = 44; 2, 39; 3, 30; 4, 19; 5, 14; 6, 11 μμ. H, μμ.

swirl chamber depth, thus stimulating the main flow rate to leave the jet zone for the wall layers. As the radius decreases the wall layers thicken until they completely link-up in the zone of the circumferential velocity minimum.

Thus, the formation of closed toroidal vortex zones at the periphery of a short swirl chamber is one more of its specific features that should be taken into account during design and utilization since it leads to a substantial change in the fields of the tangential velocities.

The results of the experiments in chambers with an air flow rate of 0.5–4 g/sec and within the limits of variation of their geometry mentioned above were processed by the parameter A^* obtained in [4]. This parameter characterizes the portion of the bulk mass flow rate through the near-end boundary layers

$$A^* = \frac{0.27 V_0 R_0}{\mathrm{Re}^{0.2} U_0 H}. \tag{1}$$

On processing the results of the experimental studies it was transformed to a form more convenient for calculation

$$A = \frac{0.42\varepsilon^{0.8} D_0^2}{\mathrm{Re}^{0.2} F}. \tag{2}$$

The coefficient of velocity conservation $\varepsilon = V_0/V_{\mathrm{in}}$ is determined by the relation [5]:

$$\varepsilon = 20\,(F/2\pi R_0 H)^{0.68}. \tag{3}$$

As the studies showed, at $F/2\pi R_0 H > 1.2\cdot 10^{-2}$ the velocity at the boundary between the jet zone and the flow core is approximaely equal to the inlet velocity, i.e., $\varepsilon \simeq 1$. The Reynolds number Re was determined by the inlet velocity, which was calculated from the equation for the flow rate, and by the radius R_0.

The flow character in a short swirl chamber can be judged from the value of the parameter A. For swirl chambers with $A \le 3$ the increase in the circumferential velocity starts virtually from the boundary of the jet zone and obeys the quasipotential law of flow $Vr^n = \mathrm{const}$. If $A > 3$, then the radius of the beginning of the quasipotential flow zone R_p can be calculated, with an accuracy of ±15%, by the empirical relation

$$\bar{R}_p = \frac{R_p}{R_0} = \frac{1.16}{A - 1.2} + 0.36. \tag{4}$$

It should be noted that within the range of $3 \le A \le 4$ on the radial profile of circumferential velocity there is a velocity "platform" ($V = \text{const}$) from the jet zone to the zone of quasipotential flow. In this case the dimensionless velocity $\overline{V} = V_p/\varepsilon V_{in}$ is about equal to unity. For $A > 4$ the dimensionless velocity is $\overline{V}_p < 1$ and with an accuracy of ±15% it can be calculated by the empirical relation

$$\overline{V}_p = \frac{V_p}{\varepsilon V_{in}} = \frac{4.69}{A + 1.08} + 0.08 . \tag{5}$$

In processing of the experiments, R_p and V_p were determined as the coordinates of the point of intersection of the tangential line at the minimum on the radial profile of the circumferential velocity and the inclined line drawn through the points in the zone of quasipotential flow in logarithmic coordinates. The angle of inclination in the zone of quasipotential flow gives the power index in the expression $Vr^n = \text{const}$.

In practically all the experiments in chambers with flow-specific features at the periphery, n has a constant value of from the radius of the circumferential velocity minimum to the discharge opening. For chambers where there are no flow-specific features at the periphery and the circumferential velocity begins to grow directly from the jet zone, in logarithmic coordinates the velocity profiles are also linear and well filled over the chamber height.

This distribution of the circumferential velocity over the radius and chamber height allows one to calculate the circumferential velocity by a power function. Generalization of experimental data made it possible to obtain a relation for determining the power index n [6]. Within the limits of $0.3 \le n \le 0.8$, with accuracy of ±15%, it can be calculated by the expression

$$n = 1.14 \left(\log \frac{G}{2\pi\mu H A} \right)^{-0.38} - 1 . \tag{6}$$

For chambers which have specific features for the flow at the periphery, n should be calculated by A^*, which is determined from the flow parameters on the radius R_p

$$A^* = \frac{0.27 V_p R_p}{\mathrm{Re}^{0.2} U_p H_p} . \tag{7}$$

Calculation of the power index n by the formulas from [7] and its comparison with the experimental data showed that the calculated values are in satisfactory agreement with the experimental ones. Even in the presence of specific features of the flow at the chamber periphery, the error in the determination of n did not exceed ±25%:

$$n = \frac{M}{0.01 + 0.56M} - 1 , \quad \text{where} \quad M = \frac{V_{in} F}{V_0 2\pi R_0 H} . \tag{8}$$

Thus, the relations obtained on the basis of the correlation of experimental data make it possible to determine the flow character in a short swirl chamber, without resorting to complex calculations, by finding only the parameter A. When $A < 3$ the chamber has no specific features of the flow at the periphery, and having determined the power index n, the distribution $V(r)$ can be calculated from $Vr^n = \text{const}$.

The distributions of $P(r)$ and $T(r)$ in the section $r_0 \le r \le R_0$ can be calculated using the results of [8]. In this paper the authors found the relation between the polytrope index n_1 and the power index n in the formula for calculating $V(r)$ in the zone of quasipotential flow.

$$n_1 = \frac{1}{1 - \dfrac{nR}{C_p}} , \tag{9}$$

and also obtained relations for calculating the distributions of $P(r)$ and $T(r)$:

$$1 - \frac{T}{T_0} = \frac{V_0^2}{2C_p T_0} \left[\left(\frac{R_0}{r} \right)^{2n} - 1 \right] , \tag{10}$$

$$1 - \left(\frac{P}{P_0}\right)^{\frac{n_1 - 1}{n_1}} = \frac{V_0^2}{2C_p T_0}\left[\left(\frac{R_0}{r}\right)^{2n} - 1\right]. \tag{11}$$

In the case of $A > 3$ it is necessary to find the radius of the beginning of the zone of quasipotential flow and the velocity in this section by relations (4) and (5), and the power index n by (6) or (8); further calculations should be performed starting from this radius using the same relations as for $A < 3$.

The distribution of static pressure over the swirl chamber radius was measured for all the studied models. The presence of specific features of the flow at the chamber periphery did not affect the pressure profiles. For chambers with flow-specific features and without them, the pressure decreased monotonically with the radius, changing slightly in value at the chamber periphery. Therefore, calculating the distribution of $P(r)$ for chambers with flow-specific features, the pressure at R_p can be taken as equal to the pressure at r_0.

Conclusions. The flow in a short swirl chamber working in air was studied by contactless methods. The existence of flow-specific features at the chamber periphery that manifest themselves in deviation from the quasipotential character of flow and in the origination of a zone of circumferential velocity decrease that is characterized by the range of the values of the special parameter A is established.

On the basis of the obtained results and also the data of [5, 7, 8] a technique is developed for calculating the distribution of parameters $V(r)$, $P(r)$, and $T(r)$ in the section $r_0 \le r \le R_0$ in the flow core of a short swirl chamber.

The technique indirectly takes into account, in terms of the power index n and the parameter A, the flow effect in the near-end boundary layers on the distribution of parameters in the flow core.

NOTATION

D_0, R_0, peripheral diameter and the swirl chamber diameter, m; d_0, r_0, diameter and radius of discharge opening of the swirl chamber, m; F, total area of intake channels, m^2; n, power index in the equation for circumferential velocity; V, U, W, circumferential, radial, and axial velocities, m/sec; V_0, U_0, circumferential and radial velocities at the boundary of the flow core, m/sec; V_{in}, mean-mass velocity in intake channels, m/sec; V_p, circumferential velocity at the boundary of the zone of quasipotential flow, m/sec; ε, coefficient of velocity conservation at the boundary of the flow core; G, mass flow rate of gas, kg/sec; P, static pressure, Pa; T, static temperature, K; n_1, polytrope index; μ, dynamic viscosity, N·sec/m^2; P_0, static pressure at the boundary of the flow core, Pa; T_0, static temperature at the boundary of the flow core, K; c_p, gas heat capacity, J/(kg·K); R, universal gas constant, J/(kg·K).

REFERENCES

1. E. P. Sukhovich, "Study of gas dynamics of swirl chambers," Deposited VINITI, No. 4457-72 Dep. (1972). Inzh.-Fiz. Zh., 23, No. 4, 762-763 (1972).
2. D. N. Wormley, Teor. Osnovy Inzh. Raschyotov, No. 2, 145-159 (1969).
3. N. A. Kostin, A. I. Sharakhovskii, and G. M. Yatskevich, Izv. AN BSSR, Ser. Fiz.-Énerg. Nauk, No. 3 88-93 (1981).
4. M. P. Rosenzweig, V. S. Lewellen, and D. G. Ross, Raketn. Tekhn. Kosmonavtika, No. 12, 94-103 (1964).
5. V. A. Rudnitskii, Efficiency of Thermal Engineering Processes, Issue 1, Vladivostok (1976), pp. 126-133.
6. N. A. Kostin, L. P. Podenok, and L. I. Sharakhovskii, Extended Abstracts of Papers Presented at IX All-Union Conference on Low-Temperature Plasma Generators, Frunze (1983), pp. 330-331.
7. V. A. Schwab, Inzh.-Fiz. Zh., 6, No. 2, 102-108 (1963).
8. J. P. Holman and G. D. Moore, Trans. ASME, D83, No. 4, 632-636 (1961).