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EXPERIMENTAL INVESTIGATION OF THREE-DIMENSIONAL TURBULENT JETS ISSUING FROM A NOZZLE WITH A RECTANGULAR OUTPUT SECTION

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A detailed analysis of average dynamic characteristics of flow in a nozzle with a rectangular output section in relation to the nozzle aspect ratio parameter and Reynolds number has been carried out and its results have been generalized. It has been established that the flow velocity profile on the jet axis in the nozzle is determined by the parameter of its aspect ratio and by the jet initial velocity. A semiempirical formula that describes well the change in the maximum flow velocity in the main section of a three-dimensional jet is suggested.

Keywords: *rectangular nozzle, aspect ratio parameter, axisymmetric jet, three-dimensional turbulent jet, coherent structure.*

In works [1–7] devoted to an experimental investigation of three-dimensional turbulent jets issuing from nozzles with a rectangular output section, a number of interesting features have been revealed, such as the deformation of the cross section of a jet, its anisotropy, and the presence, in such jets, of three regions of their axial velocity attenuation (the initial section with U_{ax} = const, transition section with $U_{ax} \sim x^{-0.5}$, and the main section with $U_{ax} \sim x^{-1}$). These distinctive features of the development of three-dimensional jets manifest themselves differently with change in the nozzle aspect ratio $\lambda = a/b$, where a and b are the dimensions of the long and short sides of the nozzle, respectively. The indicated features of a three-dimensional turbulent jet in a nozzle with a rectangular output section are mainly explained by the development of coherent flow structures in it [2, 8, 9], which is an important subject of research. It is also important to continue investigations of the averaged characteristics of flow in a nozzle of this kind.

The purpose of the present work is to analyze experimental data on the change of the averaged characteristics of flow in a nozzle with a rectangular output section depending on the Reynolds number and the nozzle aspect ratio parameter λ, with the remaining flow parameters kept intact.

Experimental investigations were carried out on a setup consisting of a fan, a vibration-quenching transition section, a plenum chamber, and a nozzle with the output section of rectangular shape. Changeable nozzles were used to form three-dimensional jets. In the experiments we used nozzles whose aspect ratios were λ = 1, 2.66, 5.07, 7.61, 11, 16, and 25.25, as well as a circular nozzle. The nozzles profiled according to Witoszynski′s formula have the same length of $90 \cdot 10^{-3}$ m and contraction close to 10, with the areas of all the nozzle outputs being approximately the same and equal to the area of the circular nozzle of diameter $d_{cir} = 22.57 \cdot 10^{-3}$ m. In this connection, the effective diameter of each rectangular nozzle d_{ef} was approximately the same as the diameter of the circular nozzle. The pressure and velocity distributions at the outputs of all the nozzles were uniform.

Main measurements were made at the flow rates at the nozzle output U_0 = 20 and 40 m /s, which corresponded to the Reynolds numbers $3.2 \cdot 10^4$ and $6.5 \cdot 10^4$ based on the effective nozzle diameter $\mathrm{Re} = U_0 \dfrac{d_{ef}}{\nu}$. To measure the mean flow velocity in a nozzle, we used a Pitot tube and an MMN-240 microanemometer. The error involved in measuring this velocity was mainly connected with the accuracy of microanemometer readings. The microanemometer makes it possible to measure even low velocities with an accuracy of up to 3%. The intensity of the flow turbulence at the nozzle output, estimated from the fluctuations of its longitudinal velocity, amounted to 0.025–0.27%.

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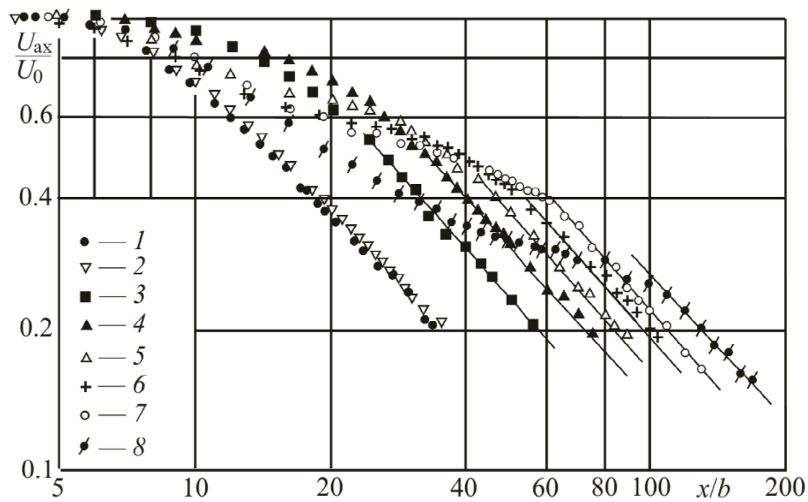

Fig. 1. Regularities in the change of the axial velocity of an axisymmetric jet issuing from a circular nozzle (1) and of three-dimensional jet issuing from rectangular nozzles with $\lambda = 1$ (2), 2.66 (3), 5.07 (4), 7.61 (5), 11 (6), 16 (7), and 25.25 (8); solid lines, calculation by Eq. (1); points, experiment.

Figure 1 presents the results of measurements of the axial velocity U_{ax} in the jets issuing from nozzles with a different value of λ at the flow rate $U_0 = 20$ m/s (from the comparison of the tip areas of the circular and square nozzles, the axial coordinate for an axisymmetric jet is taken in the form of $\frac{x}{b} = 1.33\frac{x}{d_{cir}}$, where $\frac{x}{b}$ and $\frac{x}{d_{cir}}$ are the relative coordinates (caliber)). An analysis of the data presented in this figure shows that the lengths of the initial and transition portions of the flow change gradually with increase in λ. As λ increases, the flow region where the decrease in the flow velocity slows down and thereafter increases again stands out more clearly. This region is located between the section where the flow velocity changes as in a plane jet ($U_{ax}/U_0 \sim x^{-0.5}$) and the section over which the flow velocity decreases as in an axisymmetric jet ($U_{ax}/U_0 \sim x^{-1}$). An empirical relation has been derived for calculating the axial flow velocity over the main portion of a three-dimensional jet for $2 \le \lambda \le 25$:

$$\frac{U_{ax}}{U_0} = \frac{8.07\lambda^{1/3}}{\frac{x}{b} - 2.85\sqrt{\lambda - 1}}. \quad (1)$$

If we represent the results of measurements presented in Fig. 1 in the form of the relation $x/b = f(x)$ at $U_{ax}/U_0 = 0.99$, as shown in Fig. 2, we can see that the length of the section with the selected velocity level U_{ax} has a maximum value at a certain value of λ. It has been established that the length of the initial portion x_{in}/b of the jet increases from 4.2 to 7 with variation of the aspect ratio parameter within the range $1 \le \lambda \le 3$ and decreases again to its initial value $x_{in}/b \approx 4.2$ at $\lambda > 3$, whereas at $\lambda = 10$ and $\lambda > 10$ it remains unchanged. It should be noted that if we relate the length of the initial section to the effective diameter of a circle with area equal to the output section area of a rectangular nozzle, the value of the parameter $x_{in}/d_{ef} \approx 4$ is retained up to $\lambda = 3$.

Figure 3 presents the results of a comparison between the experimental data on the attenuation of the axial flow velocity in a three-dimensional jet in a nozzle with a rectangular output section and the data for an axisymmetric jet in the form of the dependence of the dimensionless flow velocity at the jet axis on the ratio of the current distance from the tip of the nozzle to its effective diameter d_{ef}. It is seen that over the entire length of the nozzle, the distribution of the axial flow velocity within the range $1 \le \lambda \le 3$ is close to the flow velocity distribution in an axisymmetric jet. With transition to $\lambda = 5$, the reduction in the length of the initial section of the jet is observed (it is well illustrated in Fig. 2 with respect to the ratio x_{in}/d_{ef}), as well as the increase in the rate of the flow velocity decrease in its transition region, but when this happens, the law of the axial flow velocity decrease over the main section is the same as in the previous case.

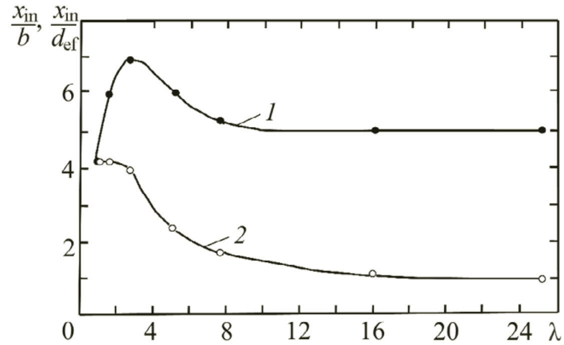

Fig. 2. Length of the initial portion of the jet vs. the nozzle aspect ratio at U_0 = 20 m/s: 1) x_{in}/b; 2) x_{in}/d_{ef}.

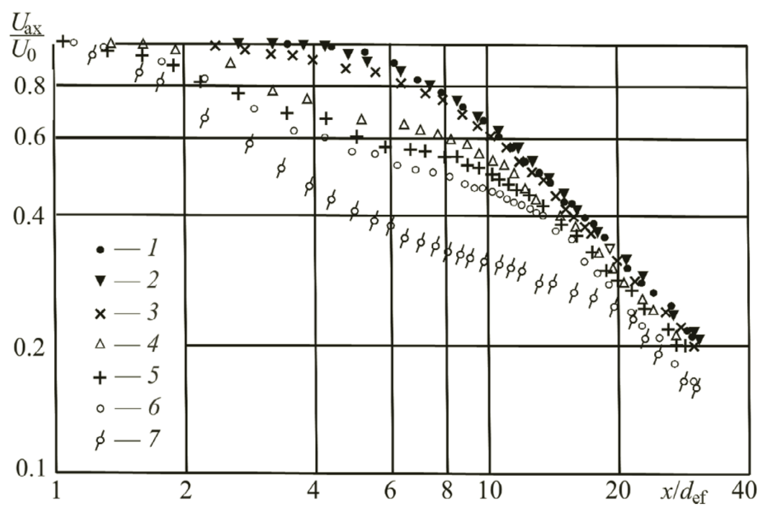

Fig. 3. Comparison of experimental data on the change in the flow velocity along the axes of the three-dimensional and axisymmetric jets at U_0 = 20 m/s: 1) circular nozzle; 2) λ = 2.66; 3) 5.07; 4) 7.61; 5) 11; 6) 16; 7) 25.25.

In the range λ = 7–25, the length of the initial portion of the jet is reduced sharply and flows are observed in its transition portion that differ in the character of their axial velocity distribution, but starting from a certain distance from the nozzle tip, they all start to obey the same law depending on λ. It is also seen from Fig. 3 that with increase in the parameter λ the beginning of the region in which the rate of velocity decrease is proportional to x^{-1} shifts downstream. The jet propagates in this region as an axisymmetric one, but beginning from $x = 7$ at the same values of x/d_{ef} the velocity in these jets is lower than in the axisymmetric jet.

Further investigation has shown that an increase in the flow velocity up to 40 m/s (Fig. 4) leads to the straightening (smoothing) of the form of the curve (U_0 = 20 m/s) that corresponds to the flow region where the rate of decrease in its velocity slows down and afterwards increases again. Here it can be stated with certainty that the laws governing the axial velocity attenuation depart clearly from the law $U_{ax}/U_0 \sim x^{-0.5}$ typical of a plane jet to the law $U_{ax}/U_0 \sim x^{-1}$ typical of an axisymmetric jet. This is confirmed by the data of both experimental and theoretical investigations carried out by many researchers.

Figure 4 compares the experimental data of other authors and the theoretical curves for the axial velocity of a plane and axisymmetric jet of work [3] obtained respectively by the formulas

$$\frac{U_{ax}}{U_0} = \frac{2.56}{\sqrt{\frac{x}{b} - 2}}, \tag{2}$$

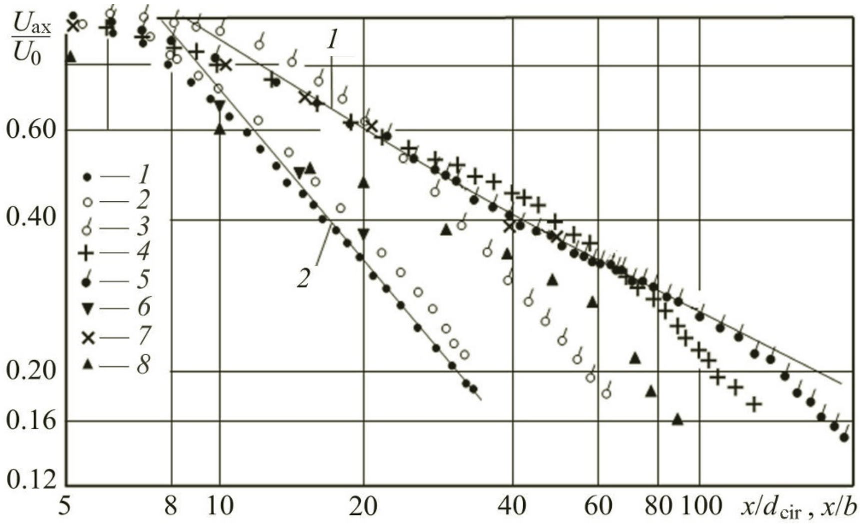

Fig. 4. Regularities in the change of the axial velocity of the three-dimensional jet at U_0 = 40 m/s calculated by Eqs. (2) (top line) and (3) (bottom line): circular nozzle; 2) λ = 1; 3) 2.66; 4) 11; 5) 25.25; 6) 1 [10]; 7) 10 [10]; 8) 12.4 (slit orifice [4]).

$$\frac{U_{ax}}{U_0} = \frac{5.78}{\frac{x}{d} - 2} , \tag{3}$$

with our experimental data. It was considered in these formulas that the pole of the main section inside a nozzle lies for a plane jet at the distance

$$\frac{ax_0}{b_0} = \frac{a(x - S)}{b_0} = 0.41$$

and for an axisymmetric jet, at the distance

$$\frac{ax_0}{r_0} = \frac{a(x - S)}{r_0} = 0.29 ,$$

where x is the distance from the pole of the jet, S is the distance from the nozzle tip, x_0 is the distance from the pole to the nozzle tip, b_0 and r_0 are the halfwidth and radius of the nozzle tip, respectively, and a is an empirical constant that characterizes the jet structure: $a = 0.11$ for the plane jet and $a = 0.083$ for the axisymmetric one. As is seen from Fig. 4, good agreement between experimental and theoretical values for the axial velocity is observed for the given polar distances for the cases where a jet propagates from a profiled nozzle.

As mentioned earlier and as shown by the results presented in Fig. 4, our experimental data and the data of other researchers for the transition section obey the law $U_{ax}/U_0 \sim x^{-0.5}$ typical of a plane jet. This seems to be the reason why no mention was made in other works [4, 5] about the presence of a portion with a slow rate of flow velocity decrease (at $U_0 \leq 20$ m/s), since the experiments in those works were carried out at flow velocities from 40 to 100 m/s.

If we compare the above-given results (U_0 = 20 m/s) with the data for an axisymmetric jet in the form of the dependence U_{ax}/U_0 on x/d_{ef}, then, as seen from Fig. 5, the differences in the levels of the flow velocity at constant x/d_{ef} for the region where the jet propagates as an axisymmetric one will be smaller than those when the flow velocity is equal to U_0 = 20 m/s. This seems to be explained by the decrease in the thickness of the near-wall boundary layers on increase of Re and respective decrease in the scale of the appearing vortices contributing to the increase in the jet range.

Thus, the experimental investigations of the aerodynamics of three-dimensional turbulent jets issuing from a nozzle with a rectangular output section at the initial velocity U_0 = 20–40 m/s have shown that up to the values of $\lambda \leq 3$ a three-dimensional jet behaves as an axisymmetric one following the law of axial velocity attenuation over the entire length of its propagation.

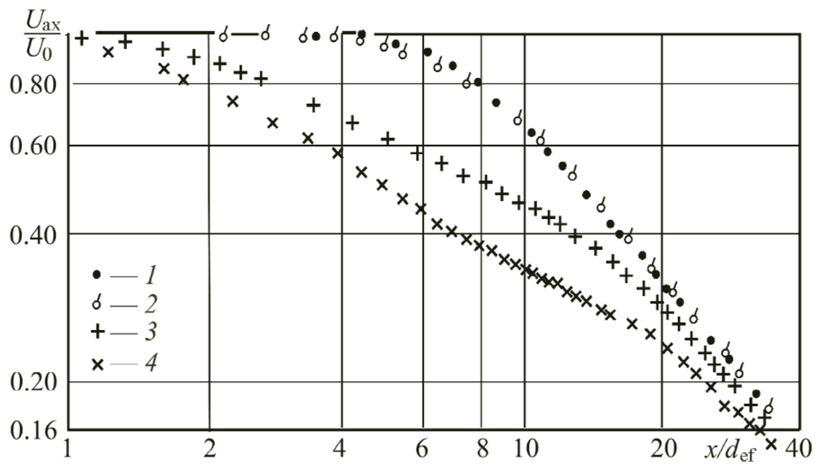

Fig. 5. Comparison of experimental data on attenuation of the axial velocity of the three-dimensional and axisymmetric jets at U_0 = 40 m/s: 1) circular nozzle; 2) λ = 2.66; 3) 11; 4) 25.25.

Starting from $x = 7$, another dynamics is observed. It has been established that in the range λ = 7–25 at a small initial velocity in the transition section a flow region stands out in which the rate of decrease in the axial velocity slows down and then increases again. This region is located between the sections in which the velocities of both the plane and axisymmetric jets undergo a change. With increase in the initial velocity of a jet up to values exceeding 20 m/s, the curve corresponding to the flow region, in which the rate of decrease in the flow velocity slowed down earlier, is straightened out gradually. A semiempirical formula is suggested for calculating the maximum flow velocity in the main portion of the three-dimensional jet in the range $2 \le \lambda \le 25$. It is shown that the length of the initial portion of the jet x_{in}/b increases from 4 to 7 in the range $1 \le \lambda \le 3$ and at $\lambda > 3$ decreases again to the primary value $x_{in}/b = 4$ at $\lambda = 10$, whereas at $\lambda > 10$ remains unchanged.

NOTATION

a, b, and $\lambda = a/b$, length, width, and the aspect ratio of the nozzle tip, m; $d_{ef} = 2\sqrt{ab/\pi}$, effective diameter of the circle of area equal to the output section area of a rectangular nozzle, m; d_{cir}, diameter of the output section of a circular nozzle, m; $\sqrt{\overline{U_0'^2}}$, longitudinal velocity pulsation at the nozzle tip, m/s; U_0, velocity in the output section of a nozzle, m/s; U_{ax}, velocity at the jet axis, m/s; x, coordinate axis along which the flow propagates, m; x/b, x/d_{ef}, relative coordinates (caliber); x_{in}, length of the initial portion of a jet, m; $\varepsilon_0 = \dfrac{\sqrt{\overline{U_0'^2}}}{U_0}$, turbulence intensity; ν, kinematic viscosity of a medium, m^2/s. Indices: cir, circular; in, initial; ef, effective; 0, value of the parameter at the nozzle edge; ax, axial.

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