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EXPERIMENTAL INVESTIGATION OF THE PROPAGATION OF THE THREE-DIMENSIONAL TURBULENT JETS OUTFLOWING FROM RECTANGULAR NOZZLES

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An experimental investigation of the averaged parameters of the flow in the three-dimensional jets outflowing from rectangular nozzles with extension parameters varying within a wide range has been performed. The coherent turbulence structure of such a jet was determined.

Keywords: *rectangular nozzle, extension parameter, three-dimensional turbulent jet, large-scale vortex.*

The three-dimensional turbulent jets outflowing from nozzles with a rectangular cross section and from rectangular slots (the so-called rectangular turbulent jets) have been investigated both experimentally and theoretically during the last 50 years. Results of such investigations are presented in many scientific articles [1–11].

According to experimental investigations, the three-dimensional turbulent discharging jets outflowing from rectangular nozzles have a number of features.

First, in the three-dimensional jet outflowing from a nozzle with a rectangular output cross section there are three regions of decreasing axial flow velocity: 1) the initial region between the inner boundaries of the mixing layer with a potential core, in which the velocity of the flow along the axis of the jet is constant ($U_{max} \sim$ const) and close to the velocity of the jet at the output cross section of the nozzle; 2) the transient region where the axial flow velocity decreases substantially depending on the initial conditions of outflow of the jet and changes by the law $U_{max} \sim x^{-0.5}$ at a fairly large extension parameter of the nozzle; 3) the axisymmetric region where the flow as a whole is near-axisymmetric in character and its axial velocity changes by the law $U_{max} \sim x^{-1}$ independently of the initial conditions of outflow of the jet. At a large distance downstream from the nozzle there is the fourth region of completely developed axisymmetric flow.

Second, the development of the three-dimensional jet out flowing from a rectangular nozzle is accompanied by the deformation of its cross section, i.e., the short side of the rectangle in the direction of flow increases and its long side decreases. To put it differently, the deformation of the jet passes through the stage of inversion of the short and long sides of its cross section. At any distance from the nozzle exit section, the cross section of the three-dimensional jet becomes close to a circle. However, as the distance from the nozzle further increases, the short and long sides of the cross section of the jet change places.

Third, it is reasonably to suggest that, in all the cases, at the last stage of outflow of the three-dimensional jet from a rectangular nozzle the axial velocity of the jet decreases by the law corresponding to the axisymmetric case; to put otherwise, the jet tends to the axial symmetry.

To date there is no agreement among scientists regarding the laws of distribution of the velocities of the flows in the mutually perpendicular symmetry planes *xy* and *xz* of a three-dimensional discharging jet, which is explained evidently by the deficit of experimental data on the three-dimensional jets outflowing from nozzles different in the extension parameter λ. In this connection, the aim of the present work is analysis of experimental data on the flow velocity profiles in the symmetry planes *xy* and *xz* in the three-dimensional jets outflowing from nozzles with extension parameters varying within a wide range.

The experiments were carried out on a setup comprising a ventilator, a vibration-damping adapter, a plenum chamber, and a nozzle with a rectangular output cross section. Three-dimensional jets were formed with the use of changeable nozzles shaped by the Vitoshinskii formula. The nozzles had a length of $90 \cdot 10^{-3}$ m and a discharge coefficient close to 10. The areas of the exit sections of all the nozzles were approximately equal to the area of a circular nozzle with a diameter $d = 22.57 \cdot 10^{-3}$ m. Therefore, the effective diameter of each rectangular nozzle d_{eff} was approximately equal to the diameter

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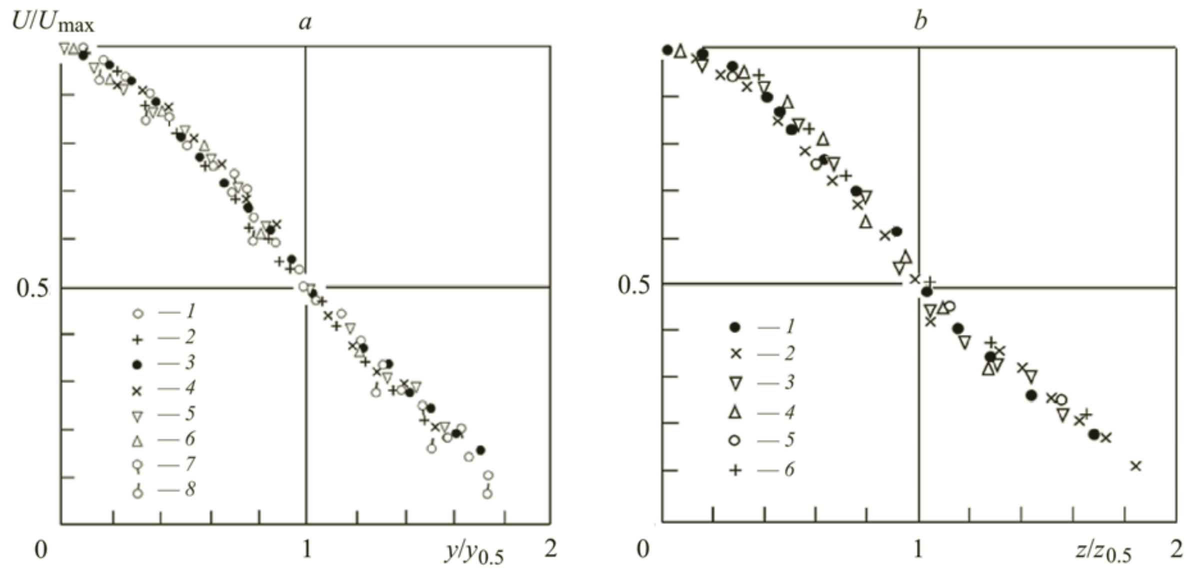

Fig. 1. Dimensionless velocity profiles of the three-dimensional jets $U/U_{max} = f(y/y_{0.5})$ at $U_0 = 20$ m/s, $\lambda = 3$ and $x/b = 7$ (1), 13 (2), 19 (3), 25 (4), 35 (5), and 45 (6), $\lambda = 12.4$ and $x/b = 50$ [3] (7), and $\lambda = 12.4$ and $x/b = 90$ [3] (8) (a) and $U/U_{max} = f(z/z_{0.5})$ at $U_0 = 20$ m/s, $\lambda = 3$ and $x/b = 19$ (1), 25 (2), 35 (3), and 45 (4), $\lambda = 5.2$ and $x/b = 20$ [3] (5), and $\lambda = 5.2$ and $x/b = 50$ [3] (6) (b).

of the indicated circular nozzle. The pressure and velocity distributions at the exit sections of all the nozzles were uniform. The average velocity of the flow in a nozzle was measured with the use of a Pitot tube and a MMN-240 micromanometer. The error in measuring this velocity was determined mainly with an accuracy corresponding to the accuracy of indications of the micromanometer. The micromanometer made it possible to measure even small velocities with an accuracy as high as 3%. The turbulence intensity of the flow at the output of a nozzle ε_0, estimated by the pulsations of its longitudinal velocity, was 0.025–0.27%. The root part of a jet was in the working part of an IAB-451 shadow apparatus equipped so that one could observe the instantaneous shadow pattern of the flow. With the use of a three-dimensional traverse gear, the Pitot tube and the transducers were moved along the three symmetry axes of the nozzle. In the experiments, nozzles with ratios between their sides $\lambda = 3$, 11, 16, and 25.25 were used. The main measurements were performed with jets outflowing from the nozzles with a velocity $U_0 = 20$ m/s, which corresponded to the Reynolds number $3.25 \cdot 10^4$ calculated by the effective diameter of a nozzle: $\mathrm{Re} = U_0 d_{eff}/\nu$. To determine the influence of the extension parameter of a nozzle λ on the aerodynamics of the three-dimensional jet outflowing from it, we measured the profiles of the average velocities of the flows in the mutually perpendicular symmetry planes of the jet at different its cross sections. Results of measurements of the velocity profiles along the jet axes parallel to the long side z and short side y of the output cross section of a nozzle are presented in Figs. 1–4.

Analysis of the results obtained shows that, for nozzles with different extensions, the similarity between their velocity profiles along the jet axis parallel to the short side of the nozzle output cross section is established at $x/b \geq 7$ independently of the parameter λ, and the velocity profiles along the jet axis parallel to the long side of the nozzle output cross section become similar to the velocity profile characteristic of an axisymmetric jet at $\lambda = 3$ and $x/b \geq 20$, $\lambda = 11$ and $x/b \geq 50$, $\lambda = 16$ and $x/b \geq 70$, and $\lambda = 25.25$ and $x/b \geq 100$. In the velocity profile along the larger axis of the jet outflowing from the nozzle with $\lambda = 11$, there is a transient saddle-shaped region. An increase in the nozzle-extension parameter leads to an increase in the number of maxima in the velocity profiles along the indicated axis. For example, the number of these maxima is 3 at $\lambda = 16$ and 5 at $\lambda = 25$. It should be noted that, in all cases, the flow velocity distributions become monotonous at the point corresponding to the beginning of the region where the axial flow velocity decreases by the law for an axisymmetric jet in which the velocity profiles along the y and z axes are similar, which correlates well with the data of [11]. The situation described is illustrated in Fig. 5. Figures 1 and 5 show the dimensionless velocity profiles of the flows in the transient and main regions of three-dimensional jets obtained in [1, 3]. It is seen from these figures that the results of our experiments are in good agreement with the data of other authors.

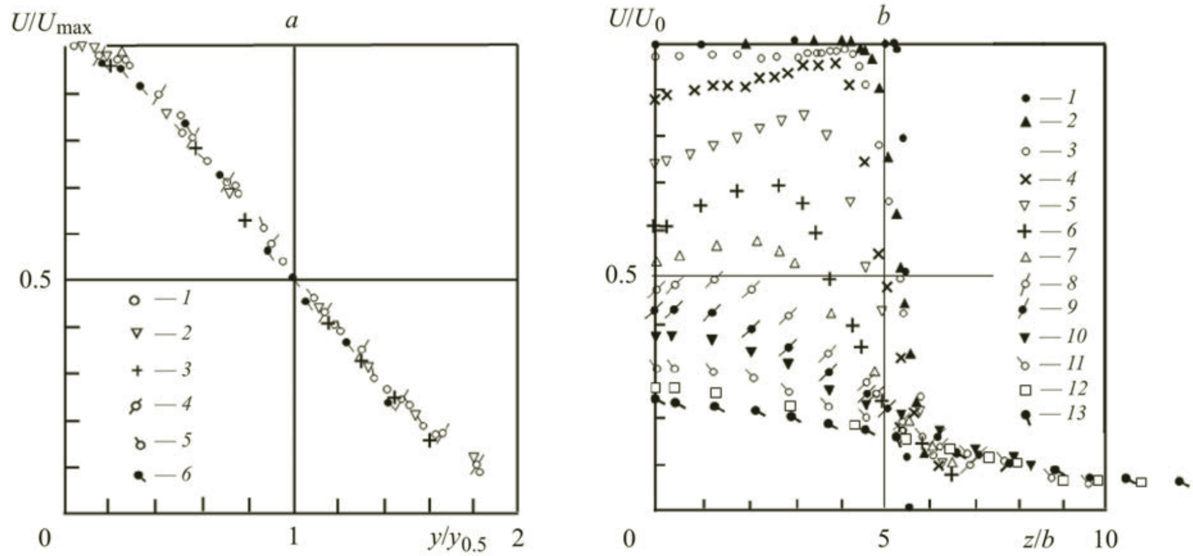

Fig. 2. Dimensionless velocity profiles $U/U_{max} = f(y/y_{0.5})$ (a) and $U/U_0 = f(z/b)$ (b) in the three-dimensional jets at $\lambda = 11$, $U_0 = 20$ m/s, and $x/b = 6$ (1), 12 (2), 20 (3), 40 (4), 70 (5), and 90 (6) (a) and $x/b = 0$ (1), 4 (2), 6 (3), 8 (4), 12 (5), 20 (6), 30 (7), 40 (8), 50 (9), 60 (10), 70 (11), 80 (12), and 90 (13) (b).

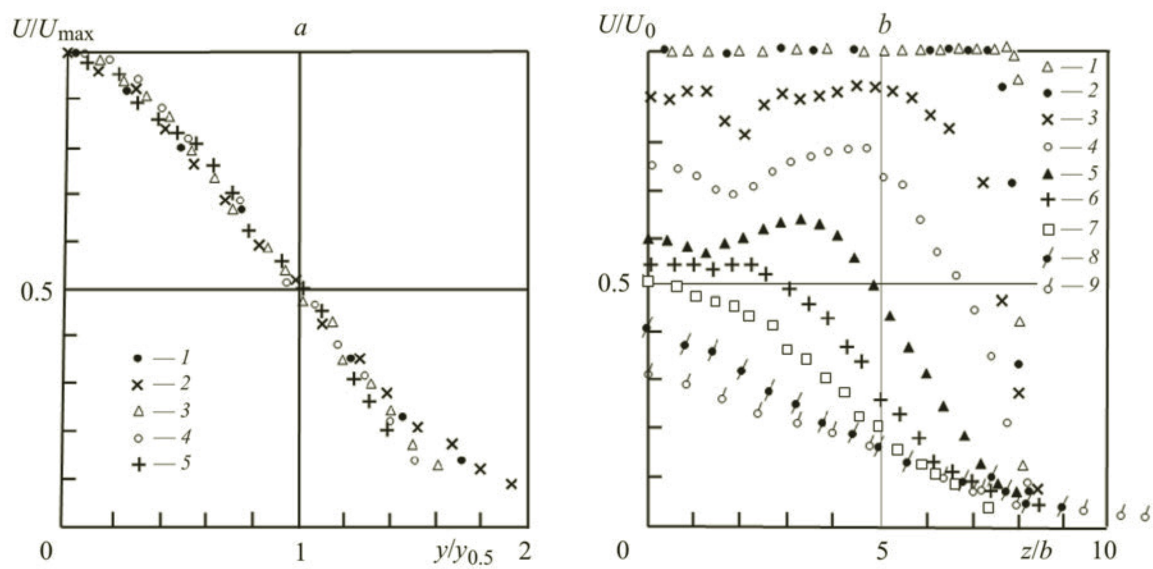

Fig. 3. Dimensionless velocity profiles $U/U_{max} = f(y/y_{0.5})$ (a) and $U/U_0 = f(z/b)$ (b) in the three-dimensional jets at $\lambda = 16$, $U_0 = 20$ m/s, and $x/b = 8$ (1), 12 (2), 30 (3), 40 (4), and 60 (5) (a) and $x/b = 2$ (1), 4 (2), 8 (3), 12 (4), 20 (5), 30 (6), 40 (7), 60 (8), and 80 (9) (b).

It was established in the experimental investigations performed in [1, 2] that the velocity and temperature profiles in the transient regions of the jets outflowing from a rectangular nozzle with a large extension and from a slot with sharp edges are very nonuniform (saddle-shaped) even in the case where the velocity and temperatures profiles of the flows at their output are uniform. In [1], this phenomenon was explained by the formation of a system of closed circular vortices in a jet. Further investigations [12] have shown that the indicated nonuniformities are due to the large-scale vortices developed in the initial region of a jet. In [13], The three-dimensional turbulent jets outflowing from a rectangular nozzle and a rectangular slot with sharp edges cut in a thin plane were investigated from the standpoint of formation of large-scale structures in the mixing layer near the nozzle and the slot. Visual investigations of the outflow of a heated jet from a rectangular nozzle, performed with the

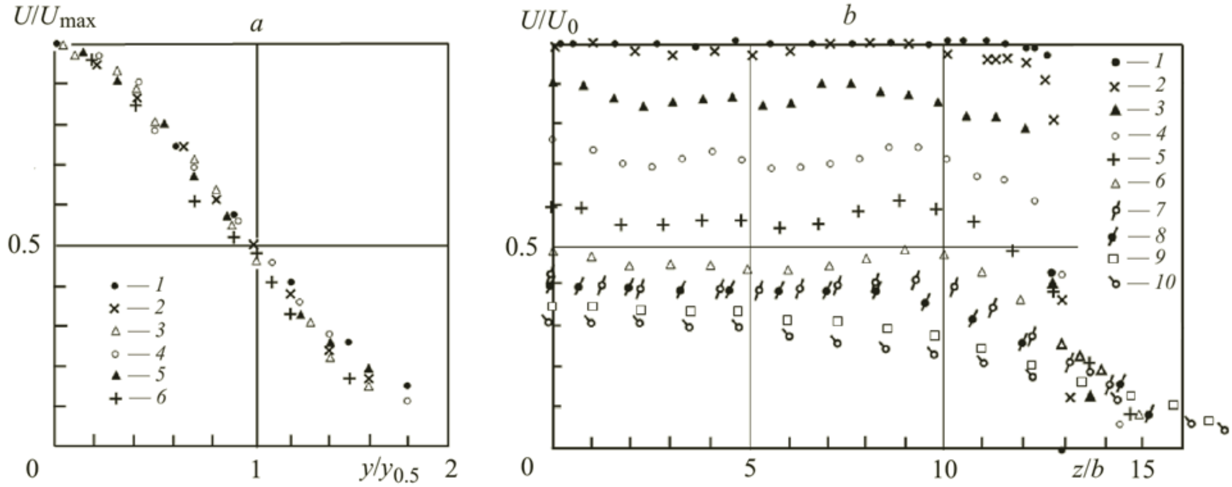

Fig. 4. Dimensionless velocity profiles $U/U_{max} = f(y/y_{0.5})$ (a) and $U/U_0 = f(z/b)$ (b) in the three-dimensional jets at $\lambda = 25.25$, $U_0 = 20$ m/s and $x/b = 8$ (1), 12 (2), 20 (3), 30 (4), 40 (5), and 60 (6) (a) and $x/b = 2$ (1), 4 (2), 8 (3), 12 (4), 20 (5), 30 (6), 40 (7), 60 (8), 80 (9), and 100 (10) (b).

use of optical devices, have shown that in the mixing zone of the turbulent jet there arise periodic large-scale vortices that are continuously deformed with distance away from the nozzle exit section. On the basis of consideration of the spatial behavior of such large-scale vortices, we have performed qualitative analysis of the above-presented data.

The visualization of the flow patterns in the three-dimensional jets outflowing from rectangular nozzles with different ratios between their sides and the measurements of the velocity and temperature profiles in these jets made it possible to determine several possible variants of the development of large-scale vortices in the initial and transients region of a discharging three-dimensional jet. In the case where $1 \le \lambda \le 3$, the large-scale vortices formed in the initial region of a jet are closed by themselves in the form of a torus. In this case, the vortices have no substantial influence on the profiles of the average velocities of the flows along the y and z axes. The velocity distributions of the flows along the y and z axes in the jet outflowing from the nozzle with $\lambda = 3$ at different distances from the nozzle are shown in Fig. 1. It is seen that, in this case, the velocity profiles are monotonous. In the case where $\lambda \ge 10$, the movement of long vortex cords formed along the edges of a jet becomes unstable, and with distance away from the nozzle they can divide into several vortex rings positioned along the z axis (the length of the nozzle). In this case, with distance away from the nozzle, in the velocity profile of the flow in the transient region of the jet along the z axis there arise several maxima and minima.

The velocity profiles in the jets outflowing from the nozzles with $\lambda = 11$, 16, and 25 are shown in Figs. 2–4. In all the cases, several closed toroidal vortices are formed in the initial region of a jet. As a result of the influence of these vortices on the flow in the jet, the velocity profile of the flow along the z axis becomes substantially nonuniform at a distance from the exit section of a nozzle x/b of several gauges even in the case where the velocity profile of the flow at the output of the nozzle is uniform. In the jet outflowing from the nozzle with $\lambda = 11$, there can arise two toroidal vortices at its cross section, with the result that a minimum appears at the center of the velocity profile along the z axis (Fig. 2) and two maxima appear at its edges. At $\lambda = 16$, in the initial region of the jet, instead of one long toroid, three toroidal vortices are formed along the z axis at one cross section of the jet, with the result that three maxima arise in the velocity profile along the z axis (Fig. 3). In the jet outflowing from the nozzle with $\lambda = 25$, five toroidal vortices can be formed and five maxima can appear in the velocity profile along the z axis (Fig. 4).

As shown in [12], on the basis of measurement of the spatial profile of the total pressure in the three-dimensional jet outflowing from a rectangular nozzle, examination of the shadow pattern of the flow in this jet, and comparison of the dimensionless profiles of its velocities and excess temperature, one can construct a simplified scheme of evolution of the shape and sizes of the vortices formed in the jet at different distances from the nozzle exit section and explain the appearance of nonuniformities in the flow-velocity and excess-temperature profiles in the jet. The reason for the appearance of nonuniformities in the velocity profiles along the z axis in a discharging three-dimensional jet in the case presented in Fig. 6 can be explained in just the same way. An analysis of the shadow pattern of the flow in the three-dimensional jet outflowing from a rectangular nozzle has shown that the vortices formed in this jet are deformed continuously, with the result

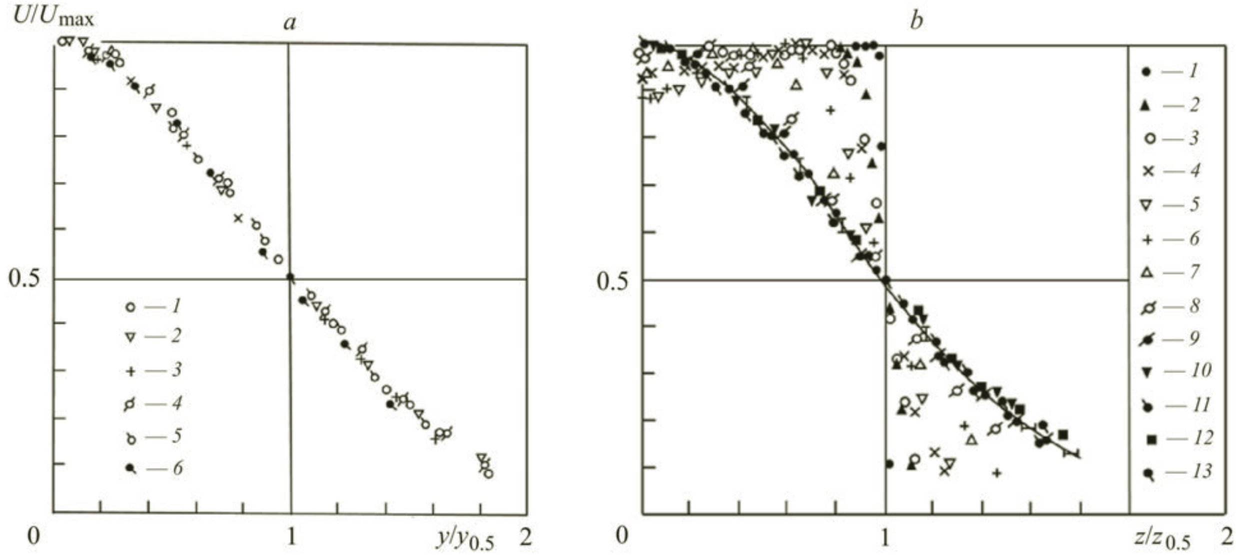

Fig. 5. Dimensionless velocity profiles $U/U_{max} = f(y/y_{0.5})$ (a) and $U/U_{max} = f(z/z_{0.5})$ (b) in the three-dimensional jets at $\lambda = 11$, $U_0 = 20$ m/s, and $x/b = 6$ (1), 12 (2), 20 (3), 40 (4), 70 (5), and 90 (6) (a) and $x/b = 0$ (1), 4 (2), 6 (3), 8 (4), 12 (5), 20 (6), 30 (7), 40 (8), 50 (9), 60 (10), 70 (11), 80 (12), and 90 (13) (b); full line) $\lambda = 10$ and 40 [1].

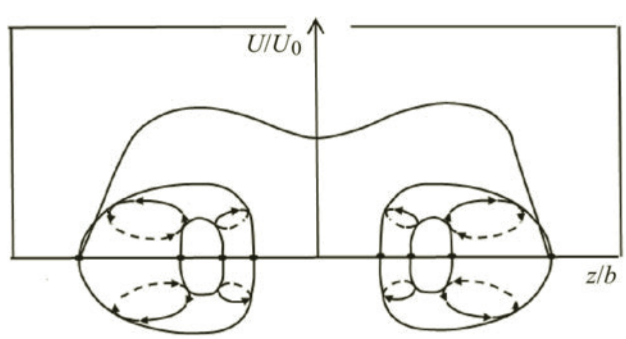

Fig. 6. Simplified scheme of an instantaneous pattern of large-scale vortices in the transient region of a three-dimensional jet and influence of these vortices on the flow-velocity distribution in the jet at $\lambda = 11$, $U_0 = 6$ m/s, and $x/b = 12$.

that the jet parts on the short and long sides of the nozzle approach each other by the complex trajectory. The existence of a minimum in the ratio U/U_0 (Fig. 6) is due to the formation of a local region in the jet, in which, after the completion of the bridging of the vortex cord near the jet axis and the formation of the final vortex torus, the linear velocity of the vortex is directed against the main flow (in Fig. 6, the large-scale vortices are positioned in the plane of the drawing for clarity; however, they are in fact in the *yz* plane perpendicular to the *x* axis). This explains the appearance of nonuniformities in the velocity field of the jet.

NOTATION

a and *b*, length and width of a rectangular nozzle, m; $d_{eff} = 2\sqrt{ab/\pi}$, effective diameter of a circle whose area is equal to the area of the output cross section of the nozzle, m; d_c, diameter of the output cross section of a circular nozzle, m; U_0, velocity of the jet at the output cross section of a nozzle, m/s; U, longitudinal velocity of a jet, m/s; U_{max}, maximum velocity of the flow along the axis of a jet, m/s; $\sqrt{\overline{U_0'^2}}$, longitudinal pulsation of the velocity of the jet at the nozzle exit section, m/s; x, longitudinal coordinate along the axis of a jet, m; x/b, relative coordinate, gauge; y and z, transverse coordinates, m; $y_{0.5}$ and $z_{0.5}$, transverse coordinates at which the flow velocity is equal to one-half of its maximum velocity, m;

$\varepsilon_0 = \sqrt{\overline{U_0'^2}} / U_0$, turbulence intensity; $\lambda = a/b$, extension of a nozzle; ν, kinematic viscosity of a medium, m^2/s. Subscripts: c, circular; in, initial; eff, effective; max, maximum; 0, value of a parameter at the edge of a nozzle.

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