DISTRIBUTION OF STATISTICAL DYNAMIC CHARACTERISTICS IN JETS FLOWING OUT OF PLANE CURVILINEAR CHANNELS

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Results are presented of an experimental investigation of the influence of centrifugal forces in a plane curvilinear channel on the characteristics of a jet flowing out.

Investigation of the regularities of propagation of jets flowing out of channels of different geometry is of practical value for many branches of industry and energetics. The characteristics of jet flows with nonsymmetric initial velocity distribution and static pressure are also of scientific interest [1, 2].

We investigated the influence of centrifugal forces on the characteristics of a jet flowing out of a plane curvilinear channel with a width-to-height ratio of $a/h = 10$, where h is parallel to the radius of curvature (Fig. 1) and $h = 10^{-2}$ m. The channel axis radius of curvature is $R_\omega = 2.9 \cdot 10^{-2}$ m. A 40h long rectilinear plane channel preceded the entrance to the curvilinear part. An important feature of the flow in the curvilinear section is the origination of secondary flows of the second kind due to the presence of centrifugal forces. Taylor—Goertler vortices [3] that have alternating left and right rotation and whose axes coincide with the main stream direction are formed in the boundary layer around a concave surface. The angle between the plane of the exit and the plane of the initial section of the channel curvilinear part was 90°, consequently, it can be asserted that the secondary flows had a sufficiently developed shape. The purpose of this paper is to clarify whether Taylor—Goertler vortices are conserved in a free jet flowing out of such a channel and what influence do they exert on the statistical dynamical turbulence characteristics.

An IZK-463 device with a 800 mm field of view that permitted observation of the jet propagation process at sufficiently significant distances from the channel exit (50 calibers) was used for flow visualization. The exposure time for the photographing was $2 \cdot 10^{-3}$ sec. Because of the presence of centrifugal forces the static pressure is distributed nonuniformly in fluid flow in a curvilinear channel [3]. The presence of a static pressure gradient at the exit results in rotation of the direction of jet propagation toward the concave wall of the channel by an angle $\alpha \approx 15°$ as compared with a jet flowing out of a rectilinear channel. Taken as the propagation direction is the middle of the jet visible in the direction A (Fig. 1). Consequently, the velocity characteristics were measured in planes perpendicular to the propagation direction and a plane rotated through an angle α relative to the exit plane was taken as initial section. It should be noted that the angle of rotation remained practically constant as the jet outflow velocity varied in 5-15 m/sec limits. A Cartesian OXYZ coordinate system (Fig. 1) is later used for the description, where the OY and OZ axes are in the plane of the initial section while the OX axis coincides with the propagation direction. Moreover, the plane passing through the OX and OY axes will be called the central plane of the jet. A constant temperature thermoanemometer of the firm "Decca Electronics" of the type 55A01 was used to measure the average velocity and the rms values of the velocity fluctuations. The necessary sensor displacements were realized by using a special traverse gear and were checked by observation on a shadow pattern.

Distributions of the average velocity and the rms values of the velocity fluctuations $\langle U \rangle$, $\langle u^2 \rangle^{1/2}$ are represented in Fig. 2 for different values of the coordinates z and x. For $z = -5$, i.e., at a 5-mm distance from the central plane of the jet toward the concave wall, the average velocity profile along the y coordinate for $x/h = 2$ has a wavey shape similar to the isotachs obtained in [4] near the concave surface while for $z = +5$, i.e., at a 5-mm

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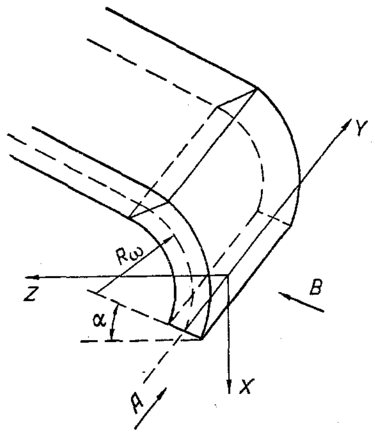

Fig. 1

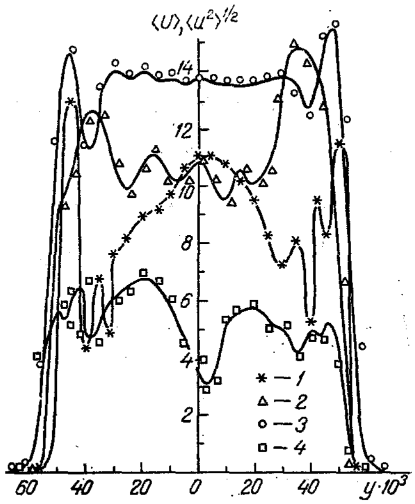

Fig. 2

Fig. 1. Diagram of a plane curvilinear channel geometry.

Fig. 2. Profiles of averaged velocity ⟨U⟩ and rms values of the velocity fluctuations $\langle u^2 \rangle^{1/2}$ along the coordinate y: 1) ⟨U⟩, x = 2 h; z = 0.5 h; 2) ⟨U⟩, x = 2 h, z = −0.5 h; 3) ⟨U⟩, x = 5 h, z = 0; 4) $\langle u^2 \rangle^{1/2}$, x = 5 h, z = 0. ⟨U⟩, $\langle u^2 \rangle^{1/2}$, m/sec; y, m.

distance from the central plane toward the convex wall, the velocity distribution clearly has no regular periodicity, at least in the domain $30 \geq y \geq -30$. As regards the domain $-30 > y > 30$, here secondary flows of the first kind are felt whose formation near the plane walls of the curvilinear channel is described in [5]. Analysis of the average velocity distribution over the y coordinate in the $z < 0$ domain permits the conclusion that such a periodicity is possible only in case there are vortices with alternating left and right rotation and with axes coincident with the average velocity direction, where five velocity maximums correspond to the presence of these vortices.

A photograph of the shadow pattern (Fig. 3) is obtained for a CO_2 outflow velocity of 5 m/sec in the jet initial section and for visualization of the flow configuration in the direction B (Fig. 1). The carbon dioxide has a different refractive index from air and was used to magnify the contrast of the shadow pattern. As the outflow velocity increases, the contrast in the sense of determining the number of vortices was degraded because of magnification of the turbulence. However, the vortex configuration is quite definite even for a 15 m/sec outflow velocity. Qualitatively, this photograph is analogous to the photographs published in [6] on the detection of Taylor vortices in the gap between rotating coaxial cylinders. Clearly seen at distances up to x/h = 8 from the jet initial section are 5 vortex streets, i.e., we obtain agreement with the above-mentioned result of analyzing the periodic average velocity profile in the $z < 0$ domain.

The average velocity profile in the coordinate y has no strict periodicity for z = 0 and x/h = 5 (see Fig. 2). Therefore, the Taylor–Goertler vortices at distances up to x/h = 5 from the jet initial section are located in the $z < 0$ domain. However, for x/h = 10 and z = 0 a barely defined but clear periodicity was observed and it can be concluded that the vortex configuration reaches the central plane of the jet with removal from the initial jet section at $10 > x/h > 5$. The distribution of the rms values of the velocity fluctuations $\langle u^2 \rangle^{1/2}$ over the y coordinate is nonuniform and has a principal maximum near the point y = 0.

A certain nonsymmetry relative to the central jet plane is observed in the average velocity distribution (Fig. 4) in the plane passing through the OZ and OX coordinate axes, and the velocity maximum is shifted somewhat toward the channel concave wall with distance from the initial jet section. However, the distribution of the rms values of the velocity fluctuations $\langle u^2 \rangle^{1/2}$ is clearly nonsymmetric which can be explained by the different conditions for generation of turbulence in the area of this jet section [7].

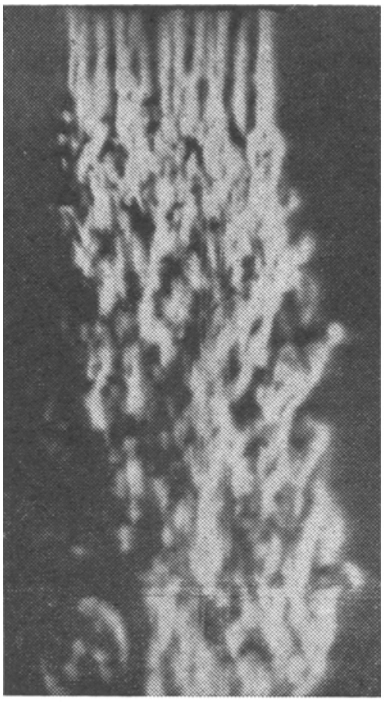

Fig. 3

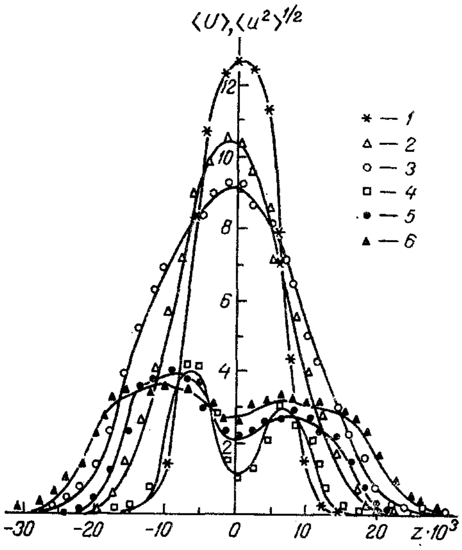

Fig. 4

Fig. 3. Photograph of the shadow pattern during visualization in the direction B (see Fig. 1) and outflow velocities in the initial jet section U_0 = 5 m/sec.

Fig. 4. Average velocity ⟨U⟩ and rms velocity fluctuation values distribution $\langle U^2\rangle^{1/2}$ along the z coordinate: 1) ⟨U⟩, x = 3 h; 2) U, x = 7 h; 3) U, x = 10 h; 4) $\langle u^2\rangle^{1/2}$, x = 3 h; 5) $\langle u^2\rangle^{1/2}$, x = 7 h; 6) $\langle u^2\rangle^{1/2}$, x = 10 h. z, m.

Therefore, available results of an experimental investigation permit the assertion that in jets flowing out of plane curvilinear channels, at least at distances to x/h = 10 from the initial jet section, Taylor–Goertler vortices are detected that are formed in the neighborhood of the concave wall in the channel because of the presence of centrifugal forces.

NOTATION

X, Y, Z, axes of a Cartesian coordinate system; a, channel width; h, channel height; R_ω, radius of channel axis curvature; α, angle of jet rotation; ⟨U⟩, average velocity in the longitudinal direction, m/sec; $\langle u^2\rangle^{1/2}$, rms value of the velocity fluctuations in the longitudinal direction, m/sec; U_0, the outflow velocity at the channel exit.

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