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EFFECT OF INITIAL CONDITIONS ON THE CHARACTERISTICS OF FREE JETS EXITING FROM CURVILINEAR CHANNELS

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Results are presented from an experimental study of the effect of centrifugal forces in a toroidal channel on the characteristics of a jet escaping therefrom.

The study of the principles of motion of free jets escaping from channels of various geometries is of great practical importance in many branches of industry and power production [1]. Study of the characteristics of such jet flows contributes to the development of that little-studied area of hydrodynamics concerned with mixing of turbulent jets with a nonsymmetric initial velocity and static pressure distribution. It should be noted that technological applications require calculation of the cutoff angle, i.e., the spatial position of the channel output section plane. Such a problem was considered as long ago as the 1930s in the theory of steam turbines. However, the unique features of escape of a jet from toroidal channels with an oblique mouth have yet to be sufficiently studied.

In the present study special attentiaon will be given to clarification of the effect of centrifugal forces upon the characteristics of a jet existing a toroidal curvilinear channel (Fig. 1c). The internal diameter of the channel d = 12 mm. The ratio between radius of curvature of the channel axis R_ω and the diameter d is: $R_\omega = 2.914d$. The mouth was oriented at an angle of 45° to the center of curvature. The entrance to the curvilinear segment was preceded by a cylindrical channel 50d in length. For comparison, jet flows from a cylindrical channel with straight (Fig. 1a) and oblique (45° angle) (Fig. 1b) mouths were also studied. Figure 2 shows shadow photographs of a jet of cooled air with initial velocity 10 m/sec. An IZK-463 viewer with 800-mm field of view permitted visual observation of jet propagation at quite significant distances (50 diameters). The visualizing knife was installed both along and across the jet. Exposure time for photography was $2\cdot10^{-3}$ sec.

It is well known that initial conditions at the nozzle mouth exert a definite effect on flow within a jet [2]. Initial boundary layers or an initial nonuniformity of the velocity profile, as a rule, is accompanied by an increased level of turbulence and turbulent viscosity, which leads to a more intense mixing of the jet as compared to the case of a uniform initial velocity profile. It is known [3] that the maximum value of turbulent viscosity in a turbulent boundary layer is determined by the dynamic viscosity u* and the thickness of the boundary layer δ:

$$E_{\max} \simeq 0{,}07u^*\delta, \qquad (1)$$

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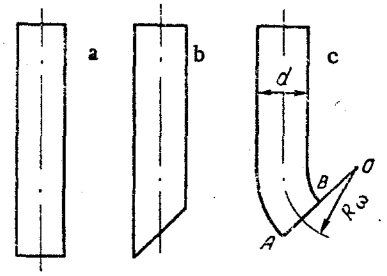

Fig. 1. Diagrams of channels studied: a) cylindrical channel with straight mouth; b) cylindrical channel with oblique mouth (at 45° angle); c) cylindrical channel with toroidal section, rotation through 45°.

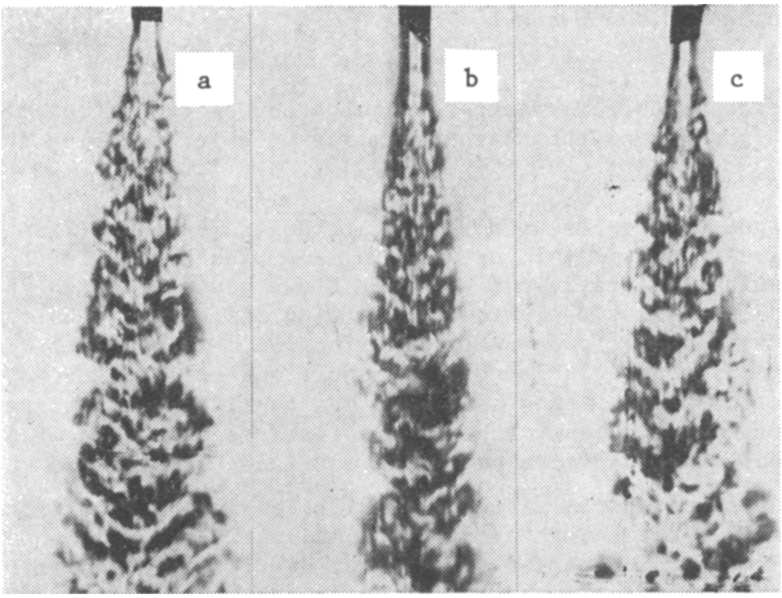

Fig. 2. Shadow photographs of free jets escaping from channels of various form, obtained with horizontal orientation of visualizing diaphragm (a, b, c as in Fig. 1).

while the width of the wake behind thin bodies is uniquely determined by the total momentum loss width $\delta_{\varepsilon}^{**}$ in the boundary layers:

$$b \simeq 1{,}76\sqrt{x\delta_{\varepsilon}^{**}}. \tag{2}$$

The character of liquid flow in a curvilinear channel is affected by the form, cross-sectional dimensions, and radius of curvature of the channel. Centrifugal forces which develop in curvilinear motion of a liquid lead to a change in the static pressure field. Because of nonuniformity of the axial velocity distribution, secondary flows develop in the form of peripheral overflows into the boundary layers. Readjustment of the axial velocity profile due to mass centrifugal forces is observed at a significantly shorter length than velocity stabilization in a straight channel, which occurs due to viscosity forces. Depending on the angle of flow rotation and the liquid flow regime, upon exit from the curvilinear channel the secondary flows may have a more or less developed form [4]. Due to the centrifugal forces rapid particles are forced from the center along the radius more intensely than slow ones. This

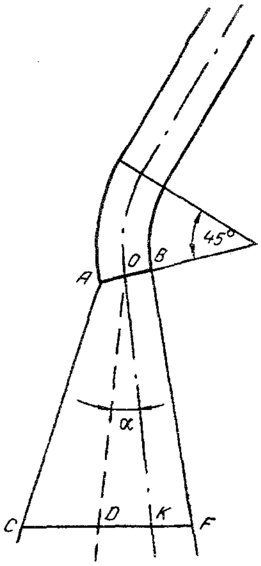

Fig. 3. Geometry of jet exiting a curvilinear channel: OK) tangent to channel axis; OD) geometric axis of jet; AC and BF) boundary jets; KF and KC) half-widths of mixing zones in vicinities of conves and concave walls, respectively.

leads to opposite effects on turbulent mixing along the convex and concave surfaces. For flows where the velocity increases with removal from the wall (boundary-layer flows) near the convex surface turbulent mixing is attenuated, while along the concave wall it is intensified as compared to mixing near a plane surface. Therefore, for other conditions the same, the thickness of the boundary layer on the convex surface will be less than on the concave [5].

On the basis of the above, and with considerations of Eqs. (1), (2), it can be expected that the intensity of increase in the width of the mixing zone (aperture angle) of a jet exiting a curvilinear channel (Fig. 1c) in the vicinity of the point A will be greater than in the vicinity of the point B. Figure 3 shows the geometry of the jet boundaries, where OK is the tangent to the channel axis and OD is the geometric axis of the jet in a plane coinciding with the plane of symmetry of the channel. The section CF is perpendicular to OK. The boundary jets AC and BF are equivalent to the boundaries of the corresponding shadow photograph, shown in Fig. 2. As follows from Figs. 2 and 3, at a distance of six diameters from the channel mouth the half-width of the mixing zone KC in the vicinity of the point A is approximately three times greater than the half-width of the mixing zone KF in the vicinity of the point B. It should be noted that the main cause of nonsymmetric mixing of the jet with the surrounding medium is nonuniformity of the pressure distribution over the section AB due to curvature of the channel. These geometric characteristics of the jet remain practically constant with increase in Reynolds number at initial escape velocities of 7-20 m/sec. The total widths of jets escaping from all channels shown in Fig. 1 are practically identical in corresponding sections, as illustrated by Fig. 2.

To measure average velocity in the jets a "Disa Electronics" type 55A01 constant temperature thermoanemometer was used. The length of the heated sensor wire was 1.8 mm, with a resistance of 3.8 Ω. The sensor was moved by a special control system in a plane coinciding with the plane of symmetry of the channel. The direction of motion was perpendicular to the geometric axis of the jet, and was monitored by observing the shadow picture.

Measurement results are shown in Fig. 4. The solid and dashed lines denote average velocity profiles of jets exiting channels with forms shown in Fig. 1c and a, respectively. The lines R and (—R) denote the boundary of the channel, with R being the convex, and (—R),

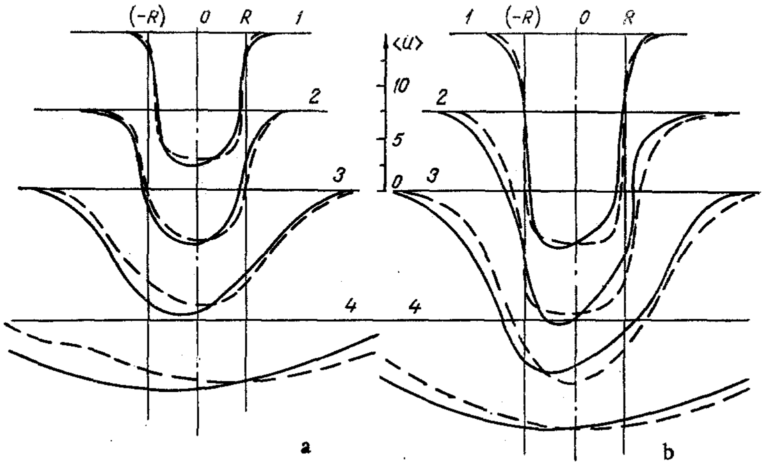

Fig. 4. Average velocity profiles of jets exiting cylindrical channel with straight mouth (dashed lines) and cylindrical channel with toroidal section, rotation by 45° (dashed lines) at $U_0 = 12$ m/sec (a) and $U_0 = 20$ m/sec (b) in sections: 1) 2 mm from mouth; 2) 10; 3) 60; 4) 200 mm. <u>, m/sec.

the concave wall. The asymmetry of the velocity profiles at even relatively small distances from the channel mouth confirm the hypothesis that the secondary flows are quite developed at the mouth of the curvilinear channel, as indicated by the shift in the axial velocity maximum toward the concave wall. With removal from the channel mouth the shift of the velocity maximum in this direction increases. This can be explained by rotation of the jet geometric axis relative to the tangent to the channel axis by a certain angle, as shown in Fig. 3. It follows from comparison of Fig. 4a and b that with growth in Reynolds number these effects intensity somewhat.

Average velocity profiles were also measured in various sections of a jet exiting from a cylindrical channel with oblique mouth (see Fig. 1b). However, no significant difference from the corresponding profiles of a jet exiting from the same channel with a straight mouth (Fig. 1a) were observed. Therefore, they will not be presented.

Thus, analysis of the results obtained show that the effect of centrifugal forces in a curvilinear channel section manifest themselves in a quite asymmetric distribution of hydrodynamic characteristics across the mouth, which leads to asymmetric mixing of the jet with the surrounding medium, and finally, to rotation of the jet's geometric axis to the side of the concave channel wall.

NOTATION

d, channel diameter; δ, boundary-layer thickness; δ_ε^{**}, total momentum loss thickness; R_ω, radius of curvature of toroidal channel section; E, turbulent viscosity; u_0, mean mass velocity at channel mouth; <u>, average velocity in various channel sections.

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