A TURBULENT JET IN A CONCURRENT STREAM AT A PERMEABLE SURFACE

A. N. Boiko, L. N. Dymant,
V. M. Eroshenko, and V. M. Spanovskii

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The average and pulsation velocity profiles are measured in a rectangular channel during combined pore-slot blowing. Universal functions are proposed which generalize the experimental data obtained in different cross sections and in a wide range of intensities of pore blowing.

In a number of industrial devices (MHD generators, prospective power installations, instruments of plasma-chemical production) the preferred and sometimes the only possible means of controlling the processes of mass and heat exchange in the boundary layer is the combined pore-slot blowing of the working media, when a slot curtain near the wall is organized in addition to the transversely distributed blowing through the permeable wall. The flow realized in such a case can be considered as a semiconfined turbulent jet at a permeable surface in a concurrent stream.

This flow is characterized by a number of specific properties in comparison with purely pore or purely slot blowing. At the same time, combined pore-slot blowing has been studied little in the literature. One can mention only [1, 2], where a boundary jet without a concurrent stream at a permeable surface at low blowing intensities was studied, and [3], which considered a curtain in a burning graphite channel.

The present study was conducted on an apparatus with a working section consisting of a channel of rectangular cross section 31 × 35 mm in size. The tangential boundary jet was formed in a rectangular slot with an exit cross section of 3 × 35 mm. The transverse blowing of gas into the boundary layer was carried out through a plate of porous nickel mounted flush with the lower wall of the channel at a distance of 6 mm from the cut of the slot. The dimensions of the working section of the plate were 235 × 35 mm. The main gas stream arrived at the experimental channel after a section of aerodynamic preparation, as a result of which the longitudinal velocity profile at the entrance to the model was close to rectangular — the relative thickness δ^*/δ of displacement was 0.01 and the intensity of longitudinal pulsations at the center of the stream did not exceed 0.015.

All the measurements were conducted with an ATA-1 thermoanemometric instrument. The head was calibrated against a micro-Pitot tube at the middle of the channel at the beginning and end of each series of experiments. The flow-rate parameters for the gas components were recorded from the pressure drop at the measuring disks.

The preliminary qualifying measurements in a boundary jet without blowing in a concurrent stream gave satisfactory agreement with the well-known generalizations for flows of this type [4]. The flow rates of the incoming, slot, and pore gas supplies were varied in the course of the experiments. With a main stream velocity of $u_{i_0} = 8$ m/sec three slot blowing velocities were established: $u_0 = 4$, 8, and 16 m/sec. With a main stream velocity of $u_{i_0} = 20$ m/sec only slot blowing with $u_0 = 20$ m/sec was examined. For each mode four values of the pore blowing intensity were achieved: $m = 0.05$, 0.03, 0.01, and 0. The thermoanemometric measurements were made in five cross sections along the length of the working section with the following dimensionless longitudinal coordinates: $\bar{x} = x/h = 5.3$, 22.0, 38.7, 55.3, and 72.0. The distributions of the average and pulsation longitudinal velocities were measured in each cross section.

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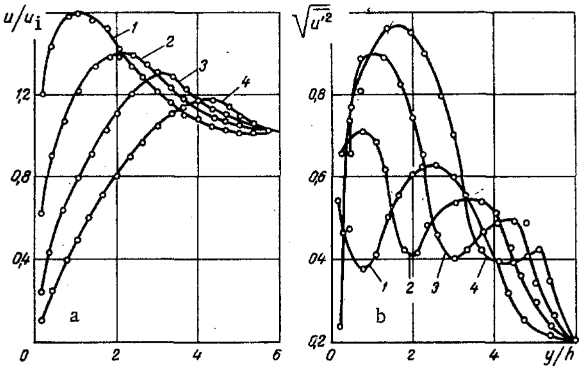

Fig. 1. Profiles of average (a) and pulsation (b) longitudinal velocities in cross section $\bar{x} = 55.3$ at $r = 0.5$: 1) $m = 0$; 2) 0.01; 3) 0.03; 4) 0.05. $\sqrt{\overline{u'^2}}$, m/sec.

The experimental results for the cross section $\bar{x} = 55.3$ and $r = 0.5$ are presented in Fig. 1. The graphs presented permit an estimate of the degree of influence of the pore blowing on the retardation of the jet. It is characteristic that along with considerable deformation of the velocity profiles the usual structure of a semiconfined jet with a maximum longitudinal velocity is retained during intense transverse blowing at considerable distances from the start of the jet (more than $\bar{x} = 72$ at $m = 0.05$). The blowing redistributes the thicknesses of the wall and jet boundary layers, with the total thickness of the jet remaining unchanged under the experimental conditions examined. The latter is connected with the effect of a negative pressure gradient which increases with an increase in the blowing and compensates for the forcing back of the jet by the transverse flow of material.

In the analysis of the velocity profiles presented in Fig. 1 it must be considered that the local velocities u are normalized with respect to the local velocity of the concurrent flow u_i which is not constant along the length of the jet ($u_i = 8.0$ m/sec for mode 1, 8.5 for 2, 9.8 for 3, and 11.4 m/sec for mode 4). Thus, the maximum velocity u_m under the present conditions in a fixed cross section first decreases, but then increases with the further increase in the blowing intensity and becomes greater than at first. This is explained by the fact that with light blowing the retardation of the jet dominates over its enhancement which is promoted by the supply of mass by the external stream, while with strong blowing the picture is reversed.

The lengths of the initial section of the jet are determined from the dependence of the maximum velocity excess $u_m - u_i / u_{m_0} - u_{i_0}$ on the longitudinal coordinate $\bar{x}$. It turned out that with an increase in blowing the initial section contracts, almost degenerating at the maximum blowing intensity $m = 0.05$ for

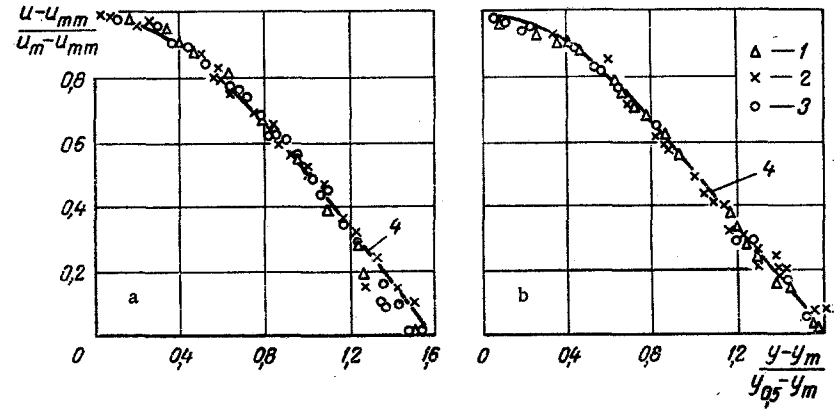

Fig. 2. Generalized dependence for average velocity in middle zone of a boundary jet with $r = 0.5$ (a) and with $r = 1$ and 2 (b): 1) $m = 0.01$; 2) 0.03; 3) 0.05; 4) from Eq. (1).

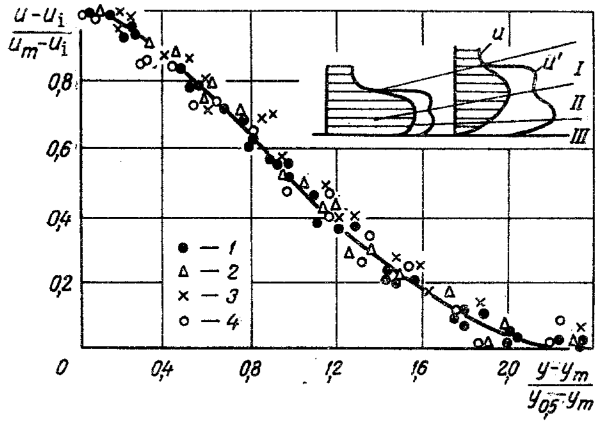

Fig. 3. Universal profile of average velocity for outer zone of boundary jet: 1) m = 0; 2) 0.01; 3) 0.03; 4) 0.05.

the present experiments. The variation along the jet of the relative coordinate of half velocity $y_{0.5}/h$, which characterizes the width of the jet, shows that in the presence of blowing, the outer zone of the boundary jet obeys the general rule for self-similar jet flows — straightness of the outer boundary [5]. The blowing affects, although not greatly, the location of the pole of the jet. With an increase in the blowing intensity the pole is shifted toward the start of the jet.

In a jet with a parameter of concurrence r = 2 at a sufficient distance from the cut of the slot the velocity profiles are monotonic and it is difficult to fix the boundary between the region of mixing and the boundary layer near the wall on the basis of the usual concepts. The experimental data obtained at r = 2 show that the profiles of u/u_i are almost equidistant except for a relatively small region near the wall, and in contrast to the mode examined first the thickness of the jet increases with an increase in the blowing intensity, reaching values corresponding to r = 0.5 only at the highest m.

The pulsation characteristics are of considerable importance for the understanding of the structure of the complicated flow under consideration. The rms longitudinal-pulsation velocities are presented graphically in Fig. 1b. The presence of two maxima in the profiles is a characteristic property of the flow at r = 0.5. The first of the pulsation maxima is determined by the blowing and increases sharply with an increase in the rate of the pore supply, while the second maximum is a consequence of the development of the jet boundary layer and decreases with an increase in blowing. All this indicates the redistribution of turbulent energy between the wall and jet boundary layers of this jet under the effect of the transverse gas flow, as well as stabilization of the flow in the vicinity of the wall by the blowing.

The question of the location of the first maximum in the pulsations is important for the calculation of semiconfined jets of the type examined. This is connected with the fact that the velocity profile in its wall boundary layer taken for the calculation of the jet must allow for the transverse flow of material at the wall and it must be assigned specifically through relationships established for independently developing turbulent boundary layers at permeable surfaces. Many of the presently available methods of representing the velocity profiles in such boundary layers provide for the presence of two characteristic zones of flow (in the turbulent part of the layer). An individual velocity relationship is established for each of the zones, for example, all kinds of modifications of the "logarithmic wall function" for the inner zone and a "velocity defect" function for the outer zone of the layer [6]. The line of maximum shearing stresses or the line of maximum intensity of the turbulent pulsations is taken as the boundary between the zones. According to the experimental data the locations of the maximum pulsations and of the maximum in the shearing stresses correspond closely to one another [7].

It should be noted that the relationships established for the turbulent boundary layer at a permeable surface are limited as a rule to relatively low blowing intensities and the absence of a longitudinal pressure gradient. Except for solutions obtained on the basis of the theory of limiting transitions [8] and fully applicable to large Reynolds numbers there are no universal relationships in the literature for the boundary layer under consideration.

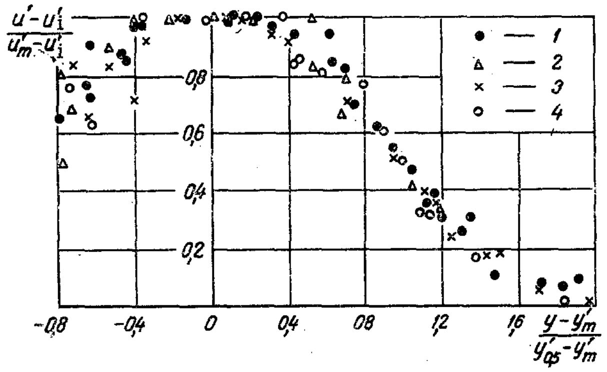

Fig. 4. Profile of rms pulsation velocity in outer zone of boundary jet: 1) m = 0; 2) 0.01; 3) 0.03; 4) 0.05

In the present work an attempt is made to establish on the basis of the experimental data obtained general relationships suitable for the calculation of jets in a wide range of blowing intensities and longitudinal pressure gradients. The generalization applicable to the boundary layer of the jet is satisfied for its outer part, i.e., for the middle zone of the jet (zone II in Fig. 3). In comparison with the section near the wall, in which disturbing factors (blowing, the pressure gradient, roughness) affect the flow to a considerable extent, the middle zone is more conservative with respect to the disturbances enumerated because of the greater longitudinal momentum of the liquid, and in addition possesses the important property that in some structural characteristics and from a number of formal indications it is similar to turbulent boundary layers of mixing. On the basis of the latter, the data on the average velocities in the middle zone are analyzed in the coordinates $u-u_{mm}/u_m-u_{mm}$ and $y-y_m/y_{0.5}-y_m$, which are characteristic for jet flows. In the present case $y_{0.5}$ is the coordinate of the point where $u = 0.5\,(u_m + u_{mm})$. As seen from Fig. 2a, the data on the jet with $r = 0.5$ are outside of a dependence on the longitudinal pressure gradient for all the blowing intensities studied and the values of the longitudinal coordinate were generalized in the form of a single curve, for which the equation is

$$\frac{u-u_{mm}}{u_m-u_{mm}} = 1-0{,}5\left(\frac{y-y_m}{y_{0.5}-y_m}\right)^{3/2}. \tag{1}$$

The data for jets with $r = 1$ and 2 are presented in Fig. 2b in the same treatment. Since the velocity profiles here are monotonic, zones I and II (see Fig. 3) merge into a single zone. All the available data are also well generalized and, which is important, the curve fully corresponds to Eq. (1). The latter indicates the universality of Eq. (1). Through formal transformations one can obtain from (1) the relationship

$$\frac{u_m-u}{u_m-u_{mm}} = \left(\frac{y_m-y}{y_m-y_{mm}}\right)^{3/2}, \tag{2}$$

which is more suitable for use in calculations of jets.

The data were also generalized for the outer zone of the jet at $r = 0.5$. The analysis of the experimental data showed that the blowing and the longitudinal pressure gradient do not disturb the approximate self-similarity of the flow in this zone, i.e., for each fixed blowing parameter there is a single excess velocity profile in all the cross sections along the length of the jet: $u-u_i/u_m-u_i = f\,(y/y_{0.5})$. Moreover, differentiation of the self-similar profiles is observed with variation in the intensity of pore blowing. Assuming that the differentiation of the profiles is caused mainly by the shifting along the y axis of the line of maximum velocity u_m, the experimental data were treated in the coordinates $u-u_i/u_m-u_i$ and $y-y_m/y_{0.5}-y_m$. As seen from Fig. 3, all the experimental points were generalized in the entire range of blowing intensities studied, having formed a single profile of the relative velocity excess close to the profile for a free jet (the solid line on the graph is the Schlichting profile).

A similar approach was used in constructing the generalized dependence for the pulsation longitudinal velocities for the outer part of zone I. From Fig. 4, where experimental points obtained at different cross sections of the jet and at different blowing intensities are plotted, it is seen that universality of the profile of pulsation velocities is approximately observed in this part of the jet.

The flow in the wall zone of the jet (zone III) differs little from the flow in an ordinary boundary layer at a wall. Because of the relatively small thickness of this zone either one-dimensional solutions or other approaches allowing for the immediate proximity of the wall can be correct here with sufficient reliability.

NOTATION

$\bar{x} = h/x$: dimensionless longitudinal coordinate; y: transverse coordinate; h: height of slot; $y_{0.5}$: transverse coordinate of point where $u = 0.5\,(u_m + u_i)$ or $u = 0.5\,(u_m + u_{mm})$; u: average longitudinal velocity; u': rms longitudinal-pulsation velocity; v_w: velocity of transverse blowing; $m = v_w/u_i$: intensity of transverse blowing; u_0: velocity of slot supply; $r = u_i/u_0$: parameter of concurrence of jet; δ: thickness of boundary layer; δ*: displacement thickness. Subscripts: i: incoming flow; m: maximum; mm: at line of maximum shearing stresses; 0: at cut of slot.

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