EXPERIMENTAL INVESTIGATION OF ISOTHERMAL TURBULENT FLOW IN A RECTANGULAR CHANNEL WITH BLOWING

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The profiles of longitudinal averaged velocities in a rectangular channel with two-way uniform blowing are measured. A method is proposed for the calculation of the velocities based on the obtained empirical relations. The normal components of the velocity and the shear stresses in the flow are computed.

In recent years a considerable number of investigations of turbulent flows of a gas with transverse flow of matter have been carried out. In most cases the boundary layer forming on a permeable plate has been studied. However, in technology, turbulent flows inside permeable channels are often realized. In this case the flow has a number of peculiarities compared to the boundary layer in the conditions of the exterior problem and has been little investigated so far. In [1, 2] the averaged characteristics of the flow in porous circular tubes have been determined experimentally and in [3, 4] simplified equations of motion are analyzed for this case.

The present work is devoted to the experimental investigation of isothermal flow of air in a rectangular channel with air blown across two opposite walls. The dimensions of the cross section of the channel are 35 × 31 mm. The experiments are conducted for Reynolds numbers determined according to the equivalent diameter (Re = $1.6 \cdot 10^4 - 6.5 \cdot 10^4$ and for intensities of blowing at the entrance $m_0 = \rho_a v_a / \rho_0 \bar{u}_0 = 5.70 \cdot 10^{-2}$, where ρ_a, v_a are respectively the density and the normal component of air at the surface of the porous wall and ρ_0, $\bar{u}_0$ are the density and discharge rate of air in the main flow at the entrance into the permeable parts.

The permeable walls (the top and bottom walls of the operating section) are plates of dimensions 210 × 35 × 5 mm made of bronze 50-60% porosity with the average size of the pores roughly equal to 50 μ. The two side walls of the operating section are made of plastic. A preinserted nonpermeable segment of 1600 mm length is provided for the hydrodynamic stabilization of the flow.

The main air flow is produced by a blower (standard ventilator of diesel motors with output of 300 nm^3/h); the blown air passes through a reducer from the piston compressor with an accumulating capacity of 6 m^3. The discharge of air in the main flow is measured by gas counters RS-100 and is further regulated by a normal diaphragm. Immediately behind the gas counter the static pressure is measured by a U-shaped mercury manometer and the temperature at the center of the flow is measured by a copper–constantan thermocouple with KP-59 potentiometer of class 0.05. The discharge of the blown air is determined with a precalibrated measuring disk.

A series of measurements of the profiles of the longitudinal velocities were carried out for different intensities of blowing in four cross sections of the operating section at relative distances x/b = 1.49, 2.78, 4.17, 6.19 from the start of the porous segment; here x is the longitudinal coordinate and b is the height of the channel. The air velocity u was measured by a total-thrust microtube made of an injection needle

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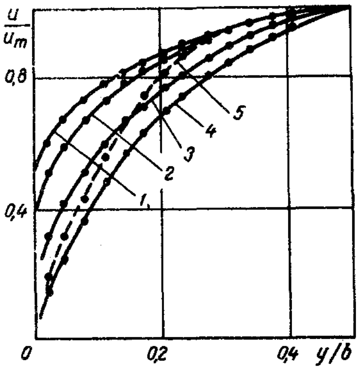

Fig. 1

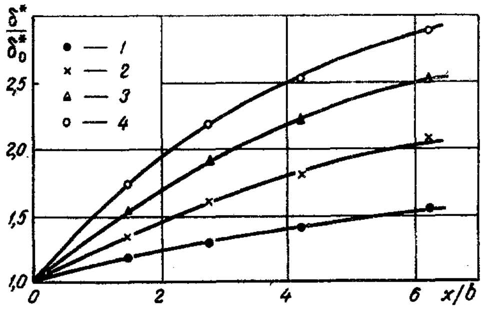

Fig. 2

Fig. 1. Profiles of longitudinal velocities: 1) m_0 = 0, x/b = 0; 2) m_0 = 0.0037, x/b = 6.19; 3) m_0 = 0.0162, x/b = 6.19; 4) m_0 = 0.0480, x/b = 6.19; 5) m_0 = 0.0480, x/b = 1.49.

Fig. 2. Dependence of displacement thickness δ^*/δ_0^* on the longitudinal coordinate x/b for different values of the parameter m: 1) m = 0.01; 2) m = 0.02; 3) m = 0.03; 4) m = 0.04.

having 1 mm external diameter and 0.5 mm internal diameter. The measuring tube was introduced into the flow through a slit in the side wall and was displaced along the vertical with the use of a coordinate device permitting the reading of the y coordinate with an accuracy up to 0.05 mm. The start of the reading was taken from the presence of electrical contact between the tube and the porous wall.

The static pressure P was measured at the center of the flow with a Prandtl tube.

The existence of a fully developed turbulent flow at the entrance into the operating section in the entire investigated range of Reynolds numbers was established by preliminary measurements of the velocity profiles and the static pressure in the flow without blowing. No readjustment of the velocity profile along the length of the operating section was noticed.

The transverse injection of matter changes the form of the flow structure appreciably. A typical family of measured velocity profiles u/u_m, where u_m is the velocity of air at the center of the channel, is shown in Fig. 1. The blown gas, not having any momentum in the longitudinal direction, causes a retardation of the main flow near the wall. This in turn leads to an increase of the velocity in the central part of the channel above the natural increase of velocity due to the addition of the mass of blown gas to the main flow. The velocity profiles become less filled and the deformation of the profiles is more noticeable for more intense blowing and larger longitudinal coordinate x. The most "rapid" change of the form of the velocity profiles occurs at the beginning of the permeable segment. In the sections displaced from the beginning there is a tendency toward the stabilization of the flow and the establishment of "self-similar" profiles, i.e., profiles whose form no longer depends on the longitudinal coordinate x and is a function of the conditions of blowing only. The present experiments were conducted on a relatively short porous segment ($x/b \le 6.2$), which did not permit the determination of the distances necessary for the establishment of the "self-similarity." Almost complete stabilization of the flow occurred only for small intensities of blowing ($m_0 \le 0.3 \cdot 10^{-2}$).

The analysis of the experimental data showed that all measured velocity profiles can be described sufficiently accurately by a relationship of the form $u/u_m = (2y/b)^n$, where u_m and n are functions of the coordinate x and the conditions of blowing.

However, it should be taken into consideration that this dependence, as all such kind of power laws of velocities, does not correspond to the real nature of the profile at the center of the channel, where the derivative $\partial u/\partial y$ must tend to zero for $y \to b/2$.

For the generalization of the experimental data it was found convenient to introduce an integral quantity, the thickness of displacement

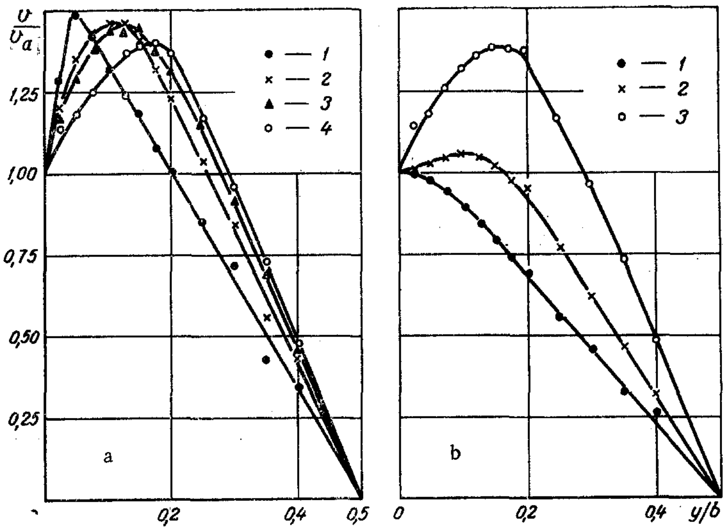

Fig. 3. Profiles of normal components of velocity for x/b = 0.75 (a) and for m_0 = 0.054 and different values of x/b (b): a: 1) m_0 = 0.0037; 2) 0.0194; 3) 0.0296; 4) 0.0540; b: 1) x/b = 5.0; 2) 2.0; 3) 0.75.

$$\delta^* = \int_0^{b/2} \left(1 - \frac{u}{u_m} \right) dy. \tag{1}$$

Substituting (1) into the above expression of the velocity profile we can find the relation between the power exponent n and the displacement thickness δ^*:

$$n = \frac{2\delta^*}{b - 2\delta^*}. \tag{2}$$

The magnitude of the longitudinal velocity at the center of the channel can also be expressed in terms of δ^*. From the law of conservation of mass we can write

$$\bar{u}_0 \frac{b}{2} + v_a x = \int_0^{b/2} u dy. \tag{3}$$

On the other hand from the definition of the displacement thickness it follows that

$$u_m (b/2 - \delta^*) = \int_0^{b/2} u dy. \tag{4}$$

A comparison of Eqs. (3) and (4) leads to the following expression for the velocity at the center of the flow:

$$u_m = \bar{u}_0 \frac{1 + 2m_0 \frac{x}{b}}{1 - \frac{2\delta^*}{b}}. \tag{5}$$

Thus the problem of generalization of the experimental data on longitudinal velocities reduces to the determination of a generalized dependence of the quantity δ^*. The experimental values of this quantity were obtained by graphical integration of the measured velocity profiles. The values of δ^* are given in Fig. 2 in the form of a function of the relative longitudinal coordinate x/b. The local intensity of blowing m, calculated from the value of the discharge rate in the corresponding cross section, is used as a parameter in the graph. The local intensity of blowing m is related to the intensity of blowing at the entrance m_0 through the relation

$$m = \frac{m_0}{1 + 2m_0 \frac{x}{b}}. \tag{6}$$

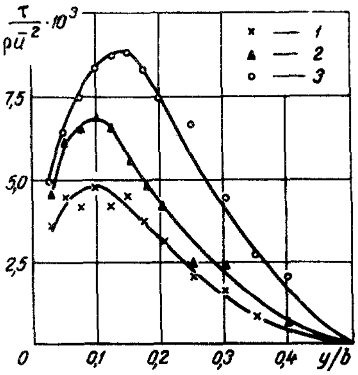

Fig. 4. Profiles of shear stresses at x/b = 5.0; 1) m_0 = 0.0194; 2) m_0 = 0.0296; 3) m_0 = 0.054.

As shown in [1], the choice of m as a parameter defining the intensity of transverse feed of mass is more justified in comparison with m_0, since at a certain distance from the start of the porous segment down the flow, input effects must disappear and the nature of the flow will be completely determined by the local conditions.

On the basis of the experimental data we obtain the following empirical relationship

$$\delta^* = \delta_0^* \left[1 + 14.3 \left(\frac{x}{b}\right)^{0.7} m \right], \tag{7}$$

which is valid for $1 \le x/b \le 6.2$ and $0 \le m \le 0.04$. The quantity δ_0^* corresponds to zero intensity of blowing and is equal to the displacement thickness at the entrance to the porous segment.

The profiles of the normal components of the velocity v and shear stresses τ are computed from the measured profiles of the longitudinal velocities and the values of the static pressure. The integration of the continuity equations leads to the following equation determining the local value of the normal component of the velocity:

$$v = -\frac{\partial}{\partial x} \int_0^y u dy + v_a \tag{8}$$

or

$$\frac{v}{v_a} = 1 - \frac{\partial}{\partial (x/b)} \left[\frac{u_m}{v_a} \int_0^{y/b} \frac{u}{u_m} d(y/b) \right]. \tag{8'}$$

The integration of the profiles in the limits from 0 to y/b was done graphically. From the values of the quantities in the square brackest, obtained in five different cross sections (including the cross section x/b = 0), an approximate analytic expression was found by the least-squares method, which was used for computing the derivative with respect to x/b.

The local values of the tangential stresses were obtained by integration of the momentum equation

$$\tau = \tau_w + \frac{\partial}{\partial x} \int_0^y \rho u^2 dy + \rho u v + \frac{\partial P}{\partial x} y \tag{9}$$

or

$$\tau = -\frac{\partial}{\partial (x/b)} \rho u_m^2 \int_{y/b}^{0.5} \left(\frac{u}{u_m}\right)^2 d(y/b) + \rho u v - \frac{\partial P}{\partial x} \left(\frac{b}{2} - y\right). \tag{9'}$$

The integral term in Eq. (9) was evaluated by a method similar to that used in the case of Eq. (8).

The profiles of the normal components of the velocity are shown in Fig. 3 (a and b). For small values of x/b near the wall an increase of v is observed right up to a certain maximum value v_m, which can be appreciably larger than the velocity v_a at the exit from the porous wall. The value of the ratio v_m/v_a and also of the coordinate corresponding to the maximum of the profile for a fixed x/b depends on the intensity of blowing. An increase in m_0 causes the displacement of the maximum of the profile toward the center of the channel and the maxima themselves become more "flat." The zone from the wall to the point where the velocity v again becomes equal to v_a, corresponds to the part of the flow experiencing retardation under the action of the injected mass. As was to be expected, this zone is larger for larger intensity of blowing.

As the axial distance x/b from the beginning of the porous segment increases, the increase of v near the wall slows down and at a certain value of x/b, which depends on the condition of blowing, there is no increase (Fig. 3b). At x/b = 5.0 the normal component of the velocity approximates to a linear function of the relative coordinate y in the entire investigated range of intensities of blowing, decreasing from v_a at the wall to zero at the center of the flow.

The distribution of the shear stresses, normalized to $\rho \bar{u}^2$, is shown in Fig. 4; here $\bar{u}$ is the local discharge rate in the given cross section. These profiles are significantly different from usual linear profiles in channels with nonpermeable walls. The transverse injection of matter causes a decrease of the shear stresses at the wall. The value of τ increases with the distance from the wall and at a certain distance y/b it attains its maximum value which generally exceeds the shear stress at the wall in the absence of blowing. The maximum value τ_m increases with the intensity of blowing and the position of the maximum shifts toward the center of the flow.

The shear stresses and the normal components of the velocity obtained from the computations are in qualitative agreement with the corresponding values given in [1] for the case of air flow in a porous circular tube.

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