ON THE DISTRIBUTION OF THE TURBULENT VISCOSITY COEFFICIENT IN A RECTANGULAR CHANNEL WITH A FREE SURFACE

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To solve the Reynolds equations within the framework of the semi-empirical theory it is necessary to know the regularity of the vertical distribution of the turbulent friction $\tau=-\rho\overline{u'w'}$ or the coefficient of turbulent viscosity $K=\tau\Big/\frac{du}{dz}$ in the investigated liquid stream.

In the case of a plane-parallel flow near a wall (outside the viscous interval), the assumption that K(z) is proportional to the distance from the boundary leads to fair results and yields a logarithmic velocity distribution [1]

$$u(z)=\frac{u_\varkappa}{\varkappa}\ln\frac{z_0+z}{z_0}.$$

Here ρ is the density of the medium, u' and w' are the pulsations of the longitudinal and vertical velocity components, u is the velocity of motion of the water, the z axis is directed vertically across the motion of the stream, $u_\varkappa=\sqrt{\frac{\tau}{\rho}}$ is the dynamic velocity, z_0 is the dynamic roughness, and $\varkappa$ is the Karman constant.

However, this representation of the distribution of K(z) is valid up to relative heights $\eta=\frac{z}{H}\leqslant 0{,}2$ above the wall. According to the data in [2], K(z) increases linearly with increasing distance from the boundary up to $\eta\cong 0{,}2$, and then the character of the distribution changes and K(z) reaches its maximum value at $\eta=0{,}3$. Flow in pipes is characterized by two maxima of the turbulent viscosity at a distance 0.5 R from the axis [1,3].

For a flow in rectangular channels with a free upper boundary, a characteristic feature is the presence of a maximum of K(z) at a relative height η = 0.3 above the bottom [4,5]. When the distance from the bottom is increased, K(z) decreases monotonically and the exchange coefficient on the surface, according to the data of [4,6], is zero.

It should be noted that in the definition of K(z) it is usually assumed that the flow is logarithmically distributed over the entire thickness of the stream, i.e., the maximum value of the velocity is on the free surface of the liquid. Careful measurements, however, performed [7] in a channel with a free upper boundary, have shown that in the near-surface layer the average velocity does not fit the main logarithmic profile. At a relative height $\eta \geq 0.9$, the velocity gradient reverses sign, i.e., the flow velocity decreases in the direction towards the interface between the water and the air (see Fig. 2 and [7]).

One of the possible causes of the decrease of the flow velocity in the near-surface layer is the dynamic action of the water surface on the adjacent air layer. As a result of this interaction, the moving liquid stream drags the boundary layers of air, giving up thereby a fraction of its energy, thus leading to a decrease of the flow velocity and consequently to a reversal of the sign of the velocity gradient in the near-surface layer. In this case, either the turbulent friction should also reverse sign, or else the coefficient of turbulent viscosity in the near-surface layer must be negative, i.e., negative viscosity should be observed. This conclusion was arrived at by Nikitin, who compared the negative values of τ in the region $\eta\geqslant 0{,}91$ with the positive values of du/dz [8].

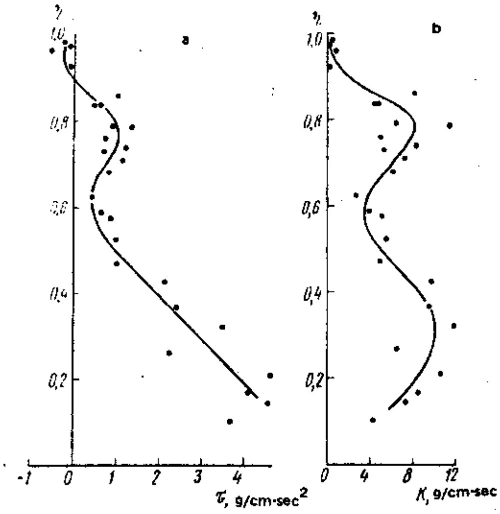

Fig. 1

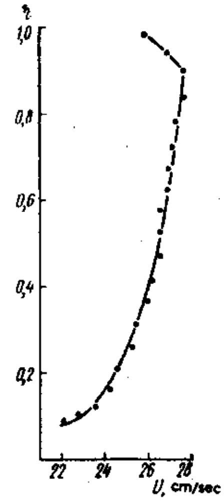

Fig. 2

Fig. 1. Vertical distribution of turbulent friction $\tau(z)$ (a) and vertical distribution of the coefficient of turbulent viscosity K(z) (b).

Fig. 2. Vertical profile of the flow velocity in an open rectangular channel.

To clarify this question and to obtain detailed profiles of τ and K, we measured the average velocity of the stream and obtained synchronous records of the longitudinal and vertical components of the velocity in the layer of a flowing liquid. The measurements were made in the axial part of the channel. The stream depth H was 20 cm. The experimental data and the formulas indicated above were used to calculate the vertical distributions of τ and K.

Figure 1a shows a plot of the vertical profile of the turbulent friction in the region $0{,}1 \leqslant \eta \leqslant 0{,}98$. As seen from this diagram, τ has a maximum at $\eta \cong 0{,}8$. In the surface layer itself in the region $\eta \geqslant 0{,}92$ the turbulent friction is negative, although the absolute value of τ is small here and lies within the limits of the measurement error.

The results of the calculation of the coefficient of turbulent viscosity are shown in Fig. 1b, from which it is seen that K in the region $0{,}1 \leqslant \eta \leqslant 0{,}98$ is positive and is characterized by the presence of two maxima in the stream regions near the bottom and near the surface.

Figure 2 shows a pattern of the velocity, which shows that in the region of relative heights $\eta \cong 0{,}92$ above the bottom, the sign of the flow velocity gradient is reversed. It should be noted that the reversal of the sign of both du/dz and τ occurs in the region of the same values of η, from which it follows that the coefficient of turbulent viscosity in the entire region of the stream is positive.

The character of the distribution of $u(z)$, $\tau(z)$, $K(z)$ attests to an interaction between the moving liquid and the adjacent layers of air, and makes it possible to assume arbitrarily that the upper boundary of the stream is quasi-rigid. This, in turn, makes it possible to present a somewhat more detailed kinematic structure of the stream. According to [10], the entire bed of the turbulent stream is filled with a hierarchy of rotating vortices, the largest of which are commensurate with the stream as a whole. This scheme reflects real processes that occur in a turbulent stream in the presence of one solid boundary. In those cases when the friction forces on the upper boundary can no longer be neglected (i.e., when the flow velocity in the near-surface layer decreases), it is necessary to modify somewhat the scheme of the kinematic structure of the stream. Indeed, in the region where the gradient of the average velocity reverses sign one should observe a decrease in the angular velocity, whereas according to the proposed scheme in [9] it increases (it is assumed that the maximum stream velocity occurs on the surface).

However, the experimental data (see Fig. 2 and [7]) offer evidence of a reversal of the sign of the velocity gradient in the region $\eta \geq 0.9$. According to [10], on the other hand, when the "turbulent vortex with positive tangential stress penetrates into the zone of the negative velocity gradient, the generation of turbulence energy becomes negative and the vortex attenuates rapidly." Therefore, starting from the foregoing, we propose to supplement the existing scheme of the stream kinematics (for the case when the friction against the upper boundary cannot be neglected) by the presence of a chain of rotating vortices also in the surface layer.

The dimensions of the regions enclosed in the vortices in the near-bottom and near-top parts of the stream, as well as the positions of the maxima in the distributions of τ and K, offer evidence that the stream boundaries have different properties and exert different forces on the moving liquid. The increase of the friction on the upper (free) boundary probably leads to a propagation of the near-surface flow velocity profile with negative value of du/dz over larger regions of the flux and to a shift of the maxima of τ and K into the region of lower values of η. That is to say, in this case the motion of the liquid can be regarded as some analog of motion between two parallel walls.

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