TURBULENT BOUNDARY LAYER ON A PERMEABLE SURFACE WITH INTENSIVE BLOWING

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Results of an experimental investigation of the structure and integrated characteristics of a turbulent boundary layer on a permeable plate in a broad range of blowing intensities $\bar{j}$ = 0.005-0.04 are presented.

Porous cooling is one of the prospective methods of heat shielding. This can apparently explain the current interest in investigations of the turbulent boundary-layer structure on a permeable surface [5-9, 12]. The domain of comparatively low blowing intensities is investigated most completely, since the authors directed their attention mainly towards obtaining reliable dependences of the magnitude of the friction and heat-exchange coefficients on the permeability parameter. Interest in using strong blowings grew recently in connection with attempts to use porous and screen cooling for shields of gas-turbine buckets, of walls of powerful MHD generators, etc., since they permit essential diminution of the convective heat flux in the wall. Under these conditions there are much fewer experimental investigations and their results do not always agree.

Detailed measurements of the turbulent boundary-layer structure and integrated characteristics are performed in this paper on a porous plate around which a gradient-free subsonic stream flows in a broad range of blowing intensities $\bar{j}$ = 0.005-0.040.

The experiments were conducted in the continuous subsonic wind tunnel of the Moscow State University Institute of Mechanics. The air came from the cylinder station through a pressure regulator and to a system of cleansing filters in the prechamber. Two honeycombs, a set of turbulizing grids, and a nozzle with high precompression (1 : 15.5) permitted obtaining a sufficiently low degree of turbulence 0.2-0.3%. The working section is a rectangular channel with 0.07 × 0.075 m cross section and 0.6 m length. The model was the upper wall, the lower wall was flexible and permitted varying the height of the working section as a function of the blowing intensity so that the static pressure always remained constant over the length. The stress parameters did not vary and were as follows: velocity 50 m/sec, temperature 290-300°K, and Reynolds number per meter $3.6 \cdot 10^6$.

A measuring model (Fig. 1) of 0.16 m length consisting of four equal sections having a separate gas supply was fabricated by sintering a batch of stainless steel rods. To diminish the lateral and longitudinal heat overflow to the plate, slots were made in which Textolite heat-insulating inserts were glued. As measurements showed, such a honeycomb separation of the model does not affect the uniformity of the permeability. The temperatures of the porous wall and the blown-in air under the plate were measured during the investigation by means of Chromel–Copel thermocouples with cold junctions. The diagram for their mounting is shown in Fig. 1. Measurements were carried out by using an electronic digital voltmeter with a printout after all parts of the model emerged into the stationary thermal mode. Air came to the model from a high-pressure grid ($2 \cdot 10^7$ N/m^2) through a reducer, a critical measuring washer, and an electrical heater. A more detailed description of the model and the injected air delivery system is presented in [14]. A traversing gear, permitting displacement of the probes with $\pm 10^{-5}$ m accuracy vertically and $\pm 10^{-3}$ m accuracy horizontally, was mounted on guide rails in the working section. An IAB-451 shadowgraph with spark illuminator was used for flow visualization. The velocity and temperature profiles, as well as the distributions of their pulsating components, were measured by a total pressure tube and a thermoanemometer of the 55M system of the firm "DISA-Electronics." Standard, single-filament wire sensors F 31 or F 35 were used.

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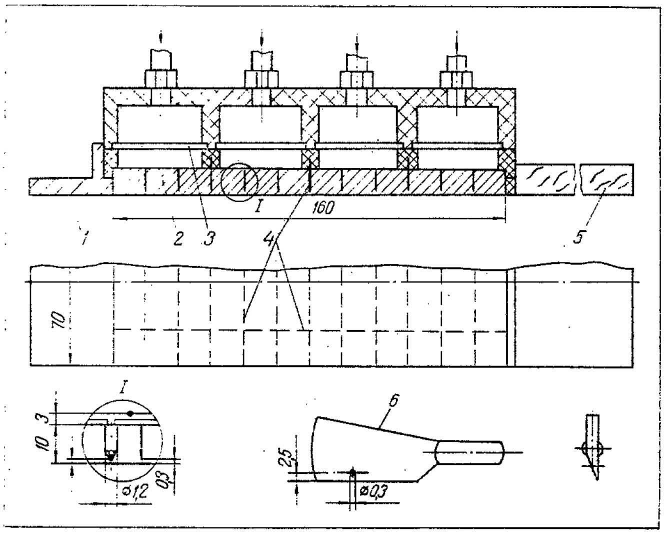


Fig. 1. Experimental model and static pressure probes: 1) nose; 2) porous plate; 3) filter; 4) heat-insulating inserts; 5) impermeable plate; 6) static pressure probe.

In the initial stage of the measurements, the velocity and temperature profiles, as well as their pulsating components in the boundary layer, were measured in the experimental section. Characteristic results were obtained for turbulent boundary-layer development in the absence of blowing. The point of transition from the laminar to the turbulent flow mode was 20-30 mm upstream from the leading edge of the porous plate. For a low blowing intensity $\bar{j} = 0.005$ the dimensionless velocity and temperature profiles verify the limit velocity and temperature profiles well [1] (Fig. 2):

$$\vartheta = \left(1 - \frac{b}{b_{cr}}\right)\vartheta_0 + \frac{b}{b_{cr}}\vartheta_0^2, \quad \omega = \left(1 - \frac{b}{b_{cr}}\right)\omega_0 + \frac{b}{b_{cr}}\omega_0^2, \tag{1}$$

where $\vartheta_0 = \xi^{1/7}$; $\omega_0 = \xi^{1/7}$; $b_t = 5.3$ is determined taking account of the finiteness of the Reynolds number [1].

Analogous results in the similarity of the velocity and temperature profiles have been obtained in [12].

The magnitude of the energy (δ_t^{**}) and momentum (δ^{**}) losses obtained by integrating the profiles corresponded well to the results of a computation using the formula

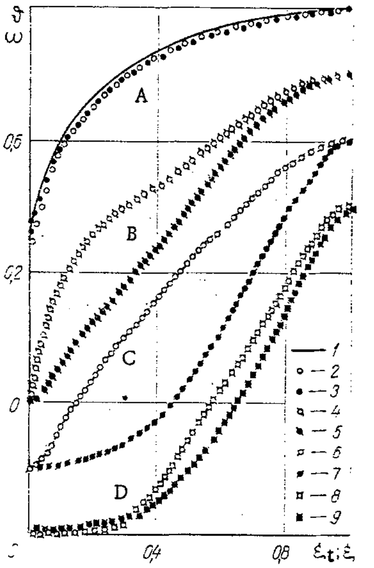
$$\delta_t^{**} = \int_0^x (\mathrm{St} + \bar{j})\, dx, \quad \delta^{**} = \int_0^x \left(\frac{c_f}{2} + \bar{j}\right) dx, \tag{2}$$

which also agrees with the deductions in [12].

The limit law of heat exchange on a permeable plate [1] is compared with the authors' experimental results in Fig. 3, where

$$\Psi_{sx} = \left(\frac{\mathrm{St}}{\mathrm{St}_0}\right)_{\mathrm{Re}_x} = \frac{(1 - b/b_{cr})^2}{(1 + b/b_{cr})^{0.2}},$$
$$b_{tx} = \frac{\bar{j}}{\mathrm{St}_{0x}} = \frac{b}{(1 + b/b_{cr})^{0.2}}. \tag{3}$$

Represented in this same graph is a dependence by which the authors of [5] approximated the results of their measurements. The discrepancy from the data in this paper is observed only in the range of high blowing parameters, where the latter exhibit a complete forcing back of the thermal boundary layer. An essential distinction in the conditions of conducting the tests can be noted. Results of measurements on a long permeable plate (2.5 m) are described in [5], but the maximum blowing intensity did not exceed 0.005. Large values of the parameter b_{tx} were obtained because of the low values of St_{0x}. In this paper the measurements were conducted on a relatively short permeable plate and the increase in the permeability parameter is related mainly to the increase in $\bar{j}$. The quantities $\bar{j} = 0.20$–0.030 correspond to the values $b_{tx} = 5$–6. It is shown in Fig. 2 how the shapes of the temperature and velocity profiles change as the blowing intensity increases from 0.005 to



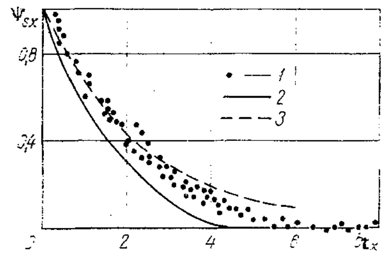


Fig. 2 Fig. 3

Fig. 2. Influence of blowing intensity on the temperature and velocity profiles for x = 0.14 m [A) $\bar{j}$ = 0.005; B) 0.01; C) 0.02; D) 0.04]: 1) computation using (1); 2, 4, 6, 8) temperature profiles $\vartheta = f(\xi_t)$; 3, 5, 7, 9) velocity profiles $\omega = f(\xi)$.

Fig. 3. Influence of blowing on the heat-elimination coefficient on a permeable plate: 1) $\bar{j}$ = 0.001-0.03; 2) computation using (3); 3) [5].

0.040. They have the typical s-shape [7, 8, 10] for strong blowings. Attention is turned to the essential dissimilarity in the ω and ϑ profiles, which is manifest for $\bar{j}$ close to 0.01. Investigations of the boundary-layer structure under these conditions showed that not only the intensity, but also the scale of the turbulent pulsations, increases significantly. Shadowgraphs show that a growth in vortex size is observed not only as the blowing intensity increases, but also during motion along the permeable section. Similar phenomena have been noted earlier in displacement layers and wakes behind poorly streamlined bodies [13]. By analyzing the results of measuring the temperature and the quantity v'T', Townsend [4] disclosed that heat transfer can depend on the displacement of relatively large masses of gas across the layer in contrast to the transfer of the axial momentum component, which is apparently due principally to gradient-type diffusion. Starting from this, the dissimilarity obtained in the ω and ϑ profiles can be explained by the origination of large-scale vortex transport in the boundary layer. The origination of discrete vortex configurations stretched out at an angle to the direction of motion, whose size is commensurate to the boundary-layer thickness, was observed for $\bar{j}$ = 0.03-0.04. It is curious to note that the velocity and temperature profiles in such a flow mode again converge.

All the measurements of the mean axial velocity component in the experiments were obtained by using a pitot tube, but not a thermoanemometer sensor. The static pressure was measured in the same transverse section of the working part, but outside the boundary-layer limits. The pulsating velocity components are very large in the near-wall region (as thermoanemometer measurements of the authors and in [6], as well as visual observations, show). The magnitudes of the pulsation intensities can reach 100% and more if they are referred to the local velocity at the measurement point. Under such conditions any thermoanemometer measurements of the mean values have a large error [2], since the assumption that the pulsating component is small compared to the mean value underlies the method. It is impossible to compute the error in determining the mean value in practice. This remark refers to temperature measurements to a much lesser degree, since the sensor operates in the resistance thermometer mode and the measured quantity is a scalar. At the same time, it has been shown in [3] that the error in the readings of a pitot tube with sharp edges does not exceed 10-20% under these conditions.

It is assumed at this time that the thickness of the momentum loss δ^{**} and the thickness of the energy loss δ_t^{**} of a turbulent boundary layer on a permeable surface can be computed for $b \geq b_{cr}$ by means of (2) by assuming that there is neither friction nor heat exchange on the wall or that they are sufficiently small. To verify this relationship under conditions of total repulsion of the boundary layer, measurements were carried out which showed that it is satisfied well only at the initial section of the plates, and then substantial discrepancies between the results of experiment and computation appear (Fig. 4), where the discrepancies will start

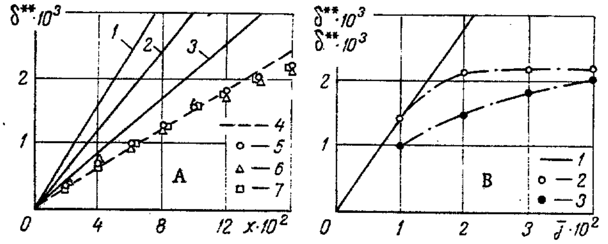


Fig. 4

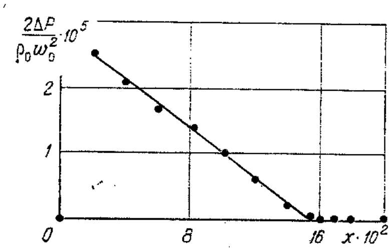


Fig. 5

Fig. 4. Dependence of the thicknesses of the momentum δ^{**} and energy δ_t^{**} losses on x and $\bar{j}$. For A: 1-3) computation by using (2) for $\bar{j}$ = 0.04, 0.03, and 0.02, respectively; 4) computation using (4); 5) $\bar{j}$ = 0.04; 6) 0.03; 7) 0.02. For B: 1) computation using (2); 2) δ^{**}; 3) δ_t^{**}. δ_t^{**}, m; x, m.

Fig. 5. Experimental points for $\bar{j}$ = 0.04; x, m.

more rapidly, the greater the blowing intensity. Moreover, δ^{**} does not equal δ_t^{**}, as results directly from the dissimilarity of the ω and ϑ profiles, which was mentioned above.

It should be noted that the experimental points for all the supercritical blowings are clustered around one dependence corresponding to the computation by means of (2) for the critical blowing, i.e.,

$$\delta^{**} = \bar{j}_{cr}\, x. \tag{4}$$

Under the conditions considered $\bar{j}_{cr}$ = 0.015. Still more unexpected results are obtained in constructing the experimental dependence $\delta^{**} = f(\bar{j})$ for a 0.14-m-long permeable section (Fig. 4). The measurements were made at a 0.02 m distance from the trailing edge of the porous plate. As $\bar{j}$ increases, the growth in thickness of the momentum loss in the near-wall layer practically ceases. A similar, but small deviation of the experimental results from the linear dependence was noted, albeit to a lesser degree, in [7], where it was explained by the influence of cessation of the blowing at the trailing edge. It is apparently impossible to consider this explanation sufficiently satisfactory, since measurements have shown that the quantities δ^{**} and δ_t^{**}, conversely, grow somewhat from the level shown in Fig. 4 in direct proximity to the edge.

Starting from the experimental results presented above, the following preliminary deductions can be made. Forcing back of the turbulent mixing zone from a porous plate surface starts as the blowing intensity approaches $\bar{j}$ = 0.015 during the blowing of a cooling gas into a turbulent boundary layer. A considerable inconsistency between the rate of gas delivery from the wall and the rate of growth in the momentum and energy loss thicknesses is manifest. The phenomenon indicates that not the whole cooling gas takes part in the mixing. Then a zone should form near the wall, in which a flow washing the "excess" gas downstream will develop. In order for such a flow to be realized, the presence of substantial longitudinal and transverse pressure gradients below the mixing layer is necessary. Measurements of the static pressure at the surface of the porous plate were conducted by a flat probe (see Fig. 1) at several cross sections of the working section at two points along the vertical: in the undisturbed stream and at a 2.5 mm distance from the porous plate, where the low pointed edge of the probe touched the wall. The measurement results are represented in Fig. 5. Despite the fact that there is no pressure gradient outside the mixing layer limits, its magnitude near the surface is sufficiently substantial. Its magnitude is small under the conditions investigated and diminishes practically to zero at the trailing edge. Unfortunately, confident results about the pressure gradient distribution in the direction from the wall to the stream were not obtained successfully, but it can apparently be asserted that dP/dy = 0 across the mixing layer. The profile shape for $\bar{j}$ = 0.04 (Fig. 2D) indeed shows that a longitudinal flow develops at the wall. A practically linear velocity distribution is conserved at the wall even for a quite strong blowing intensity. At the same time, the gas temperature in this region equals the gas temperature under the plate. Measurements of the pulsating components show that for $\bar{j}$ = 0.04 a zone exists at the wall in which the intensities of the velocity and temperature fluctuations are practically zero [11], where the zone of no temperature fluctuation is substantially greater than the zone of no velocity fluctuation. An analysis of the output signal oscillogram of a thermoanemometer bridge permits noticing the substantial miscibility taking place at the inner boundary of the mixing zone.

NOTATION

x, longitudinal coordinate from the leading edge of the permeable plate; δ, δ_t, thicknesses of the dynamic and thermal turbulent boundary layers; $\xi = y/\delta$; $\xi_t = y/\delta_t$ dimensionless thicknesses of the dynamic and thermal turbulent boundary layers; δ^{**}, δ_t^{**}, magnitude of the momentum and energy losses; ρ_0, w_0, T_0, density, velocity, and temperature at the outer boundary-layer limit; ρ_W, T_W, density and temperature on the permeable wall; w_W, velocity of injected gas delivery; $\bar{j} = \rho_W w_W / \rho_0 w_0$, blowing intensity; $\omega = w/w_0$; $\vartheta = (T_W - T)/(T_W - T_0)$, dimensionless velocity and temperature; w', T', velocity and temperature pulsations (fluctuations); Ψ_{SX}, relative heat-exchange coefficient; b_{tx}, permeability parameter; b_{cr}, critical permeability parameter; St_{0x}, Stanton number under standard conditions; ΔP, static pressure drop on the permeable wall and in the free stream; y, transverse coordinate; Re_x, Reynolds criterion; c_f, friction coefficient.

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STATIONARY TWO-DIMENSIONAL ROLLING WAVES ON A VERTICAL FILM OF FLUID

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The wave characteristics of two-dimensional stationary rolling waves on a vertical film of fluid are investigated experimentally using the electrodiffusion and shadow methods.

In order to calculate with sufficient accuracy the processes of heat and mass exchange during the drainage of thin films of fluid, it is important to be able to take into account the influence of wave formation, especially in the case in which the process rate is determined by mass exchange with respect to the gas [1].

In spite of the large number of theoretical papers written on this area of study [2-5], there is as yet no certainty that the theoreticians' predictions about the physics of wave formation on the surface of thin vertical layers of fluid are correct.

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