ENERGY SPECTRA OF VELOCITY PULSATIONS IN A TURBULENT BOUNDARY LAYER ON A PENETRABLE PLATE

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UDC 532.526.4.001.5

Results of measurements of the pulsation characteristics of a turbulent boundary layer on a flat penetrable plate, in a range of variation of the parameters of in-blow from 0 to 20, are presented. It is shown that for supercritical in-blows close to the surface there exists a zone in which the energy spectra of velocity pulsations do not vary as the distance from the surface increases, and they differ from the spectra in the core of the boundary layer.

In [1-4] it is experimentally shown that in the case of strong in-blows that exceed the critical in-blows a characteristic "drive-back layer" arises on a penetrable surface. In this layer the gradients of the longitudinal velocity, temperature, and concentration, with respect to the normal to the surface, are practically zero. Velocity pulsations in this layer are considerably less than in the remaining portion of the boundary layer. It is of interest to examine under these conditions the variation, along the normal to the surface, of other characteristics of the surface layer, in particular, the energy spectrum of velocity pulsations.

The experiments were carried out on a subsonic aerodynamic tube of the open type working in suction (Fig. 1). The velocity range in the working chamber was 2-70 m/sec with intensity of turbulence of the flow $\varepsilon \approx 0.1\%$. The comparatively low degree of intensity of turbulence of the flow was achieved thanks to the presence of a profiled nozzle 1, prechamber 2 with smoothing grids 3 (grid dimension 2×2 mm^2), and a tenfold compression of the flow in constrictor 4. The length of the prechamber was 1500 mm, and the section was 680×680 mm^2. The working chamber had a length of 1400 mm, a width of 200 mm; its height could be varied from 100 to 300 mm, thanks to a flexible upper wall 5. The working section 6, on which the boundary layer was investigated, constituted a flat clear plastic plate of length 1010 mm, width 154 mm, and thickness 22 mm. The front and back edges had a streamlined shape. The plate was fixed to the lower wall of the working chamber by six supports 7 which had a good streamlined shape of the cross section. The height of the supports was 53 mm. Three porous plates of dimension $278 \times 120 \times 8$ mm^3 were placed on the upper plane of the working section. Under each plate there was an isolated cavity. The in-blown air reached each cavity via a separate air duct. The porous plates were baked from the powder of polymethylmethacrylate L-1 with a diameter of particles 0.1 mm. The technology of baking was as follows: the powder was poured into a copper mould, heated up to the temperature 160-180°C, kept for 2 h at this temperature, after which its compression by means of the lid of the mould was carried out until the required degree porosity was obtained. The uniformity of penetrability of the plates was checked by the method described in [5].

After the working chamber the flow passed a diffuser 8 of length 2700 mm with a small opening angle and went into a receiver having a volume of 140 m^3. From the receiver the air was drawn off by a centrifugal fan driven by a direct-current electric motor. The receiver is separated from the diffuser by a silencer in order to prevent the penetration of the acoustic noise, excited by the fan and the motor, into the working chamber.

All measurements were carried out at a distance of 730 mm from the front edge of the working section. The measurements of the profiles of the mean velocity, intensity of turbulence, and energy spectra of velocity pulsations were carried out by means of a thermo-anemometer of constant resistance in the

Novosibirsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 3, pp. 115-119, May-June, 1973. Original article submitted August 2, 1972.

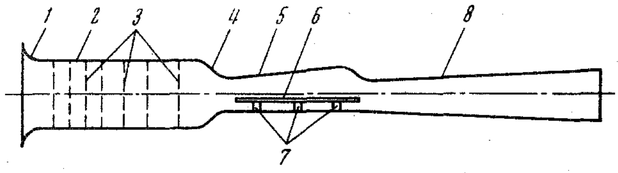

Fig. 1

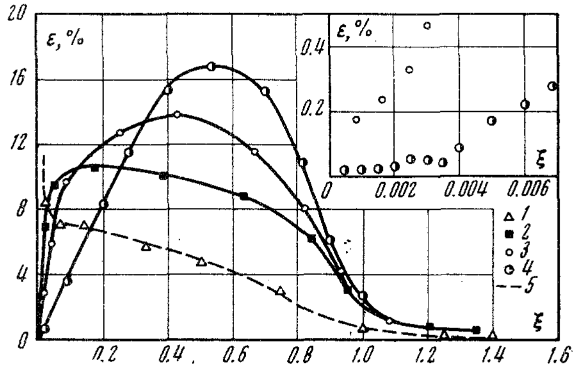

Fig. 2

band 10-3000 Hz. As the transducer of the thermoanemometer, a gilded tungsten filament of diameter 0.008 mm, length 2 mm, was used; it was placed parallel to the penetrable wall and perpendicular to the basic stream. The distance of the transducer filament from the pentrable surface was measured by means of a KM-6 cathetometer with an accuracy of 0.005 mm. The mean velocity of the stream was registered by a dc voltmeter, while the pulsating constituent of the velocity vector was measured by a mean-square voltmeter. A spectrum analyzer was connected parallel with the latter.

Preliminary measurements of the velocity of the basic stream in horizontal sections at various heights above the porous plate showed the presence of a zone of width 50-60 mm, where the flow is two-dimensional even for such large in-blows when $b \approx 20$. Here b is the in-blow parameter

$$b = \rho_w w_w 2\ /\rho_0 w_0 c_{f0}$$

where ρ_0 and ρ_W are the densities of the material of the basic and in-blown streams, w_0 and w_W are the velocities of the stream, respectively, on the edge of the boundary layer and at the output from the porous plate, and c_{f_0} is the coefficient of friction under the standard conditions (on a plane nonpenetrable surface under isothermal conditions).

Measurements of the profiles of the mean velocity on a nonpenetrable plate confirmed the presence of a developed turbulent boundary layer in the section being considered. The velocity profiles measured on the penetrable plate in the case of subcritical in-blows satisfactorily coincide with a calculation carried out in accordance with [7], using an expression that is repeatedly being confirmed by experimental data

$$\omega = 1 - \sqrt{\Psi + b}\,(1 - \omega_0) + {}^1/_4\ b\ \ (1 - \omega_0)^2 \tag{1}$$

$$\Psi = (1 - b/b_*)^2 \tag{2}$$

$$b_* = 4\ \ [1 + 0.83/(\mathrm{Re}^{**})^{0.14}] \tag{3}$$

$$\omega_0 = \xi^{1/n} \tag{4}$$

where $\Psi = (c_f/c_{f_0})_{\mathrm{Re}^{**}}$ is the relative variation of the coefficient of friction in the case Re^{**} = idem, $\omega = w/w_0$ is the dimensionless velocity in the boundary layer on the penetrable plate, Re^{**} is the Reynolds number determined from the thickness of the impulse loss, ω_0 is the velocity profile on the nonpenetrable surface, $\xi = y/\delta$ is the dimensionless ordinate referred to the thickness δ of the boundary layer, and b_* is the critical blow parameter. For $b = b_*$ according to (2) $\Psi = 0$. For $b > b_*$ a drive-back layer arises on the surface subjected to the flow [1, 2, 4, 7]. For the experiments carried out, $n = 6$; this agrees with the estimates produced in [8].

The energy spectra of velocity pulsations were measured under the conditions of subsequent analysis by means of an S5-3 harmonic analyzer. In the case of measurements close to the wall and on the outer edge of the boundary layer, the contribution by the noise of the electrical circuit of the thermoanemometer grows sharply. Therefore, when processing the results, the amount of noise was subtracted from the measured signal. The intensity of this noise and its energy spectrum were measured in the case where the transducer of the thermoanemometer was placed in the medium at rest.

The intensity of turbulence was determined according to [6] from the following expression:

$$\varepsilon = \frac{4u_\varepsilon u}{u^2 - u_0^2}\,\omega \cdot 100\%$$

where u_ε is the voltage measured by the mean-square voltmeter, u is the voltage measured by the dc voltmeter, corresponding to the mean velocity at the point of measurement; u_0 is the voltage corresponding to the medium at rest.

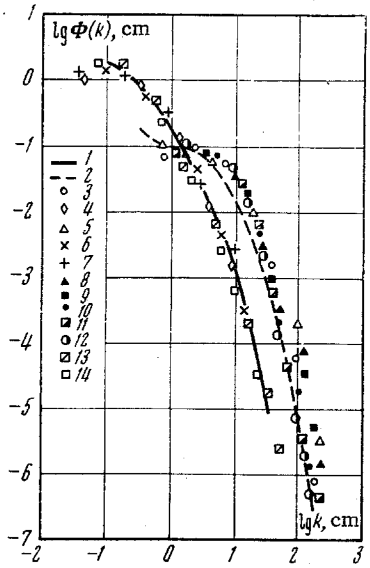

Fig. 3

The spectral function $\Phi(k)$ was calculated according to the expression

$$\Phi(k) = (w/2\pi\Delta f)\,(u_f^2/u_\varepsilon^2)$$

where $k=2\pi f/w$ is the wave number, u_f^2 is the square of the reading of the output instrument of the spectrum analyzer, which corresponds to the energy of the velocity pulsation at the frequency f; u_ε^2 is the energy of the signal entering the input of the analyzer, in the whole frequency range; Δf is the width of the pass band of the spectrum analyzer, and f is the frequency being investigated.

In Fig. 2 we have presented the experimental profiles of the intensity of turbulent pulsations of the modulus of the velocity vector on nonpenetrable and penetrable plates; 1) b=0, 2) 4.65, 3) 11.36, 4) 18.16, 5) b=0 [9].

As the in-blow parameter increases, the maximum of the profile of intensity of turbulence grows, and it is displaced toward the outer edge of the boundary layer. The intensity profile on the nonpenetrable surface satisfactorily agrees with the analogous measurements [9]. The profile of the intensity of the velocity pulsations on the penetrable surface qualitatively agrees with the data of [10, 11].

In [12] the longitudinal and transverse velocity pulsations were measured separately for small in-blows. The approach of the maximum intensity of the longitudinal velocity pulsations toward the wall was noted, when the in-blow parameter was increased in the range b=2.54–3.0. For b=3.8 the maximum began to move away from the wall. By summation of the longitudinal and transverse velocity pulsations according to these results, the distribution of the intensity of the modulus of the vector velocity along the normal to the surface was found. This distribution reveals a tendency of the maximum of pulsations to move away from the wall as the in-blow increases.

In Fig. 3 we have presented experimental energy spectra of pulsations on nonpenetrable surfaces. Curves 1 and 2 are the experiments [9], b=0, ξ =0.58, and 0.0011, respectively; 3 and 4 are for b=0, ξ =0.004 and 0.5, respectively; 5 is for b=5.33, ξ =0.006; 6 and 7 are for b=3.72, ξ =0.29 and 0.69, respectively; 8–14 are for b=18.16, ξ =0.0015, 0.003, 0.007, 0.01, 0.015, 0.316, 0.72 respectively. From these graphs we can see that on the nonpenetrable surfaces the energy spectra in a broad range of variation of ξ will agree with the known results [9].

In the immediate vicinity of the wall the spectra are located in the region of large wave numbers; they are displaced into the region of smaller wave numbers, if we move away from the wall. For the turbulent core of the boundary layer these spectra are practically unaltered. The same pattern is observed in the presence of a transverse flow of the medium in the range of variation of the in-blow parameter b from 0 to b_*. Furthermore, such a distribution of the spectra is preserved over the entire section of the boundary layer, with the exception of the region in the immediate vicinity of the wall, even for very large in-blows ($b \approx 20$). In the immediate vicinity of the wall the energy spectrum of velocity pulsations in the case of supercritical in-blows remains unaltered for the entire region.

From Fig. 3 we can see that for b=18.16 the extent of this region along the ordinate is ξ =0–0.015 (y=0–1.5 mm).

Also an interesting feature is noted which consists of the following. By introduction of additional perturbations into the in-blow stream, we can vary the energy spectrum of velocity pulsations close to the wall. In the case of supercritical in-blows, this new form of the energy spectrum close to the wall reveals a tendency to remain unaltered.

We consider in a greater detail the results of measurements of the intensity of turbulence and the energy spectra of velocity pulsations in the case of supercritical in-blows (b=18.16). From Fig. 2 we see that up to the height $\xi \approx 0.002$ the intensity of turbulence is small and only slightly varies. In addition, from the analysis of traces obtained by means of an oscillograph, it follows that the velocity oscillations in this region substantially differ in form from the turbulent pulsations in the boundary layer. These oscillations have a smoothed low-frequency character, while the turbulent pulsations in the outer portion of the boundary layer have the form of sharp high-frequency peaks. For the outer region of the boundary layer, the turbulent velocity pulsations exist in the frequency range 0-3000 Hz and higher. Near the wall the upper boundary of the frequency range corresponds to $\sim$500 Hz.

The results obtained here agree with the conclusions of [1] about the fact that in the case of large in-blows on a penetrable surface there exists a "drive-back layer." Use of energy spectra of velocity pulsations in the analysis of a turbulent boundary layer, in the case of supercritical in-blows, allows us to establish more confidently the variation of modes of flow under these conditions. Such an approach was found to be successful when studying the flow of two-phase liquids [13].

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