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EXPERIMENTAL INVESTIGATION OF A FLOW DEVELOPING IN A CIRCULAR TUBE AT VARIOUS LEVELS OF TURBULENCE.
2. ANALYSIS OF EXPERIMENTAL RESULTS

A. V. Medvedev, S. Ya. Raisikh, and
É. D. Sergievskii

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Experiments on a boundary layer developing in a circular tube were carried out at low (0–1.5%) and high (4–17%) levels of turbulence. New data were obtained on such characteristics as the distribution of the autocorrelation coefficients, spectral densities of longitudinal velocity fluctuations, and the distribution of the form parameter, momentum flux, blockage factor, and skin friction coefficient.

Analysis of Averaged and Pulsational Characteristics. In [1], an experimental setup and methods of measuring integral and local averaged and pulsational, as well as spectral, characteristics are described.

Experiments on a boundary layer developing in a circular tube were carried out at low (0–1.5%) and high (4–17%) levels of turbulence.

A low turbulence level (0.3%) was attained by using a Vitoshinskii nozzle with contraction ratio 9 and rectifying grids and a honeycomb in a preinserted segment. Measurements were made in seven cross sections of the tube. A higher turbulence level (1.5%) was produced by installing a grid with a wire diameter of 1.5 mm and a mesh size of 2 × 2 mm at the nozzle exit. Analysis of the results obtained has shown that velocity fluctuations remain almost intact near the tube wall, whereas in the logarithmic layer and the flow core they increase substantially. The distribution of velocity fluctuations in universal coordinates shows that as the distance increases, the maximum of the fluctuations grows, whereas its position remains invariant at the coordinate $Y^+ = 13$. The profiles of velocity fluctuations along the channel length are similar to those obtained in [2]. The distribution of fluctuations is similar qualitatively, but quantitatively discrepancies are observed. The behavior of the velocity and the fluctuations at $Tu = 1.5\%$ points to a more rapid development of the flow than in the case of a low initial level of turbulence.

A high level of turbulence was produced by disk turbulizers with various numbers of holes of identical diameter. Let us consider the results obtained at the turbulence levels 4, 9, 12, and 17%. Analysis of the results on the distribution of velocity and velocity fluctuations in both conventional and universal coordinates over an entire tube cross section and near the wall showed that in the first cross section the fluctuations attain their maximum values, but then, as the turbulized stream moves further, these values decrease. Moreover, higher values of fluctuations in universal coordinates correspond to higher values in conventional coordinates. The velocity profile usually corresponds to a logarithmic law with small deviations to one side or the other. However, in conventional coordinates the fullness of velocity profile changes differently; for example, with the use of turbulizer No. 3 the profile becomes flatter and with the use of turbulizers Nos. 4 and 5 it becomes more peaked, which seems to be attributable to the different initial velocity profile. It is noteworthy that velocity fluctuations near the wall are relatively insensitive to the effect of the turbulence level. Thus, for example, whereas fluctuations in the flow core in the first section attain 17%, on the wall they rise insignificantly, i.e., up to 14%.

This fact does not agree with the experimental data of [3], where the turbulence intensity on the wall always exceeded that on the axis and attained values of the order of 30–50%. At the same time the character of

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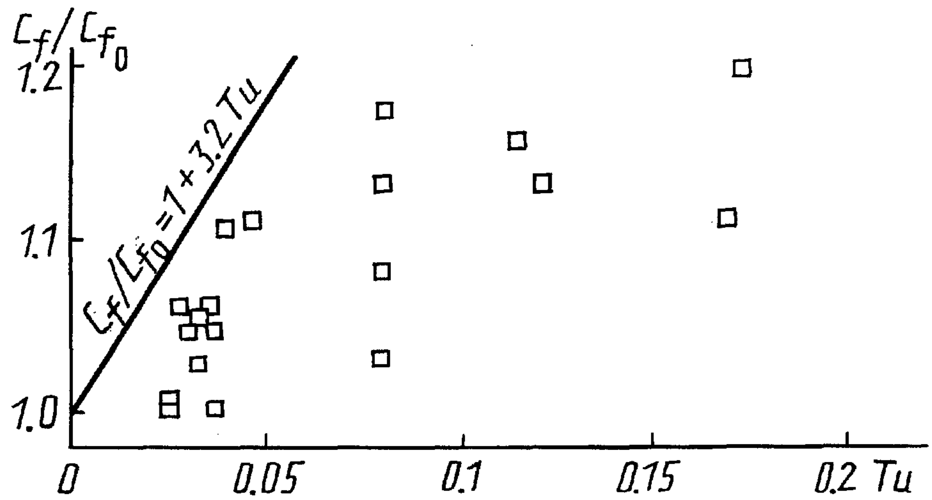

Fig. 1. Distribution of the relative friction coefficient along the tube length vs the level of turbulence.

fluctuations correlates with the behavior of the friction coefficient if we assume that the latter is associated with the level of maximum fluctuations in the layer. Actually, the friction coefficient is expressed as follows:

$$C_f = 2\tau_w/\rho U_m . \tag{1}$$

Next we assume that $C_1 = \sqrt{U'^2_{max}}/U_m$ and $C_2 = \sqrt{U'^2_{max}}/U_\tau$; this permits us to rewrite formula (1) as

$$C_f = 2\,(C_1/C_2)^2 . \tag{2}$$

Now, we may make use of experimental results and consider the relative increase in the resistance coefficient, having previously determined $\sqrt{U'^2}/U_m$. This yields

$$C_f/C_{f_0} = (C_1/C_2)^2/(C_1/C_2)_0^2 . \tag{3}$$

For a high-turbulence regime $C_1 = 0.16$ and $C_2 = 3$ and for a low-turbulence regime $C_1 = 0.12$ and $C_2 = 0.25$. Then

$$C_f/C_{f_0} = (0.16/3)^2/(0.12/2.5)_0^2 = 1.23 .$$

The above result agrees well with that obtained in the case of direct determination of C_f (Fig. 1). In [3] distributions of velocity fluctuations in a circular tube are given in the absence of a turbulizer, and velocity fluctuations on the wall attain much higher values than in the present work and in [2]. The overstated values of fluctuations in [3] seem to be due to errors introduced by the measuring equipment and to the use of a mouthpiece.

The results on the variation in the turbulence level along the channel showed that at high initial values of Tu a decrease in the turbulence level is observed up to the coordinate $x/d = 25$, where the turbulence level for all of the turbulizers equalizes and amounts to 2.5–3.5%. At low turbulence levels a different picture is observed. Thus, at $Tu = 0.3\%$ the turbulence level grows slightly up to $x/d = 10$ and then increases sharply and continues to grow up to $x/d = 40$. The jump in the turbulence level after $x/d = 10$ seems to be due to the merging of boundary layers at this place. At $Tu = 1.5\%$, starting from the entrance, the turbulence level first falls until $x/d = 10$ is reached and then begins to rise smoothly up to $x/d = 40$. We may assume that in this case the boundary layers merged earlier than in the previous case, as indicated by the growth in the level of turbulence after the attainment of a minimum at the coordinate $x/d = 7$.

Processing of the results on the distribution of the turbulence level along the channel length at high values of Tu gives the following expression:

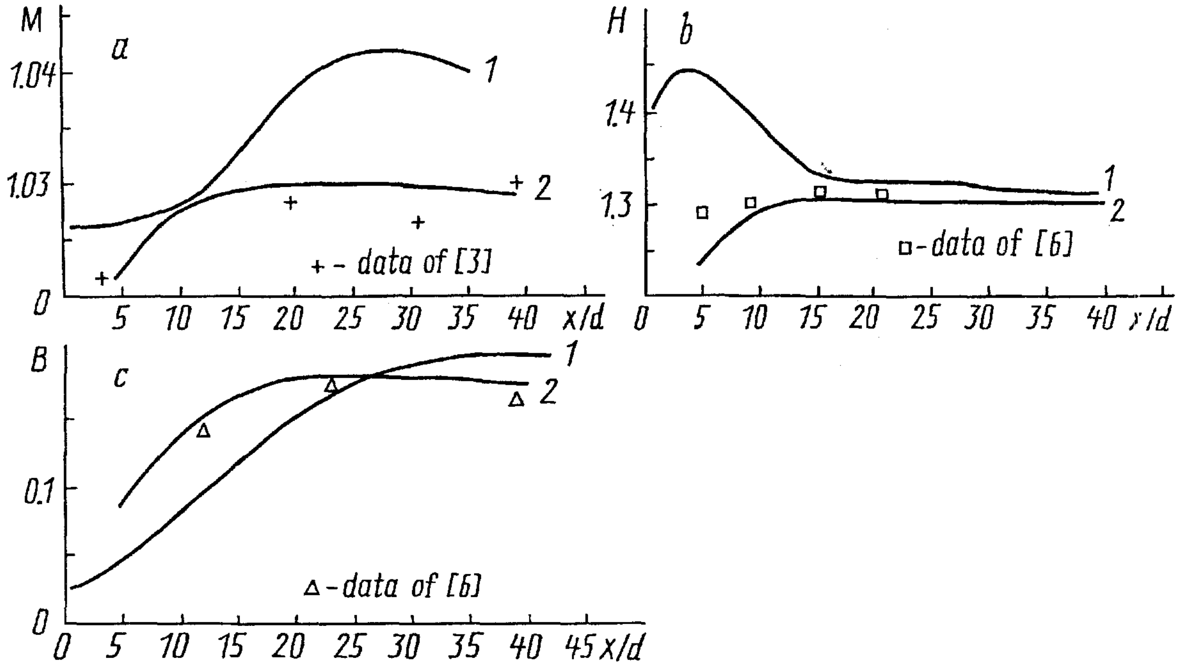

Fig. 2. Distribution of the momentum flux (a), form parameter (b), and blockage factor (c) along the tube length at different levels of turbulence: 1, $Tu = 0.3\%$; 2, 1.5.

$$Tu = [1.11\,(x/d + 4.44) + \exp\,(-\,24.67 Tu_{0_{\mathrm{in}}} + 4)\,]^{-1}\,. \tag{4}$$

The error in this formula does not exceed 10%.

Analysis of Integral Characteristics. In this section attention is given in the main to such integral characteristics as the form parameter H, momentum flux M, blockage factor B, and skin friction coefficient C_f. The blockage factor was introduced by Sorvan and Klomp [4]. It characterizes the degree of flow development and is defined as the ratio of the axisymmetric boundary layer displacement thickness to the tube radius or as the ratio of the velocity on the tube axis U_0 to the velocity averaged over the cross section U_{m}:

$$B = 2 * \delta_*/R = 1 - U_0/U_{\mathrm{m}}\,, \tag{5}$$

where

$$\delta_*/R = \int_0^1 (1 - U/U_0)\, r/R d\,(r/R)\,. \tag{6}$$

In according with Kline's recommendations [5], in the present work the blockage factor was defined in terms of velocity ratio.

In Fig. 2c the distribution of the blockage factor along the tube is compared with the data of Sprenger at low initial turbulence levels – 0.3–1.5%. We see good agreement of the present results with those given by Sprenger in [6]. As is evident from Fig. 2c, in this case a small increase in the turbulence level up to 1.5% leads to more rapid development of the flow, as evidenced by higher values of the blockage factor than in the data of Sprenger and also by the presence of a maximum at the distance $x/d = 22$.

The results on the distribution of the form parameter in Fig. 2b also indicate more rapid development of the flow. As is seen from the figure, the distribution of the form parameter likewise has a maximum at the distance $x/d = 15$. After a length of 20 diameters, the value of H remains constant and equal to 1.3, which corresponds to a developed turbulent flow. The distribution of the form parameter in the case of natural development of a flow with a low turbulence level is quite different (curve 1, Fig. 2b). Up to the cross section $x/d < 3$, the values of the

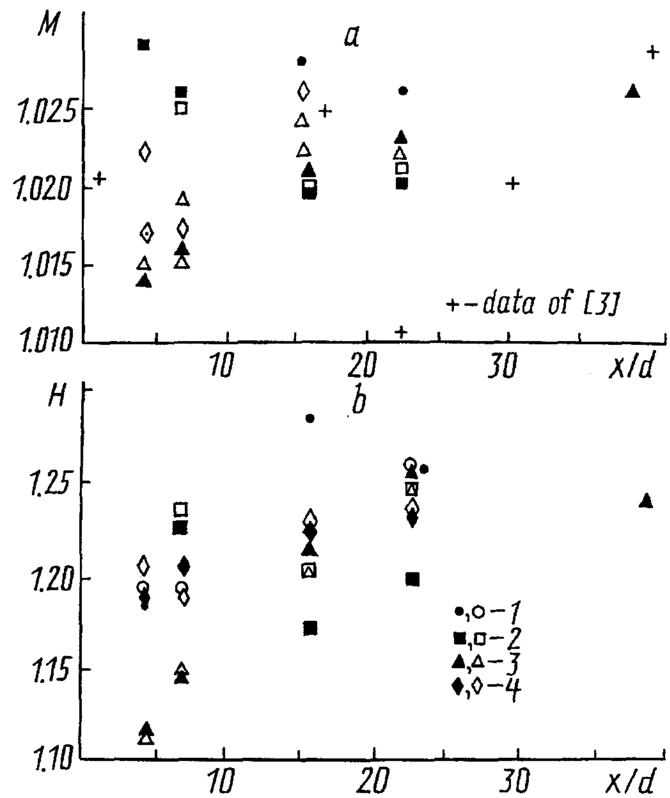

Fig. 3. Distribution of the momentum flux (a) and the form parameter (b) along the tube length at high levels of turbulence (Tu = 4–17%): 1, Tu = 4%; 2, 17; 3, 12; 4, 9%; dark and light points, first and second series of the experiment.

form parameter exceed 1.3, which probably corresponds to the transition regime. This is followed by a rapid fall in the values in the region $3 < x/d < 10$ and a further smooth decrease to 1.3.

In the present work we use still another quantity that characterizes the degree of flow development, namely, the momentum flux M, which is defined as

$$M = \int_0^1 (U/U_m)\, d\,(r/R)^2 . \tag{7}$$

In the case of a low initial turbulence, the momentum flux at the beginning of the tube is almost constant, but beyond a length equal to 10 diameters it increases rapidly and then falls, attaining the value 1.04 (Fig. 2a). It seems that here too the rapid growth is due to merging of the layers. The behavior of this quantity with installation of a grid at the entrance to the tube is similar to that of the form parameter and differs from the case considered above: the momentum flux attains a maximum at a distance of 15 diameters and acquires the value 1.03 at a distance of 40 diameters. The distribution of the form parameter and the momentum flux in the case of high turbulence levels is presented in Fig. 3. Here too we can see a qualitative resemblance in the behavior of these two characteristics. At a distance of 20–40 diameters the values of these quantities are smaller than those corresponding to low turbulence levels. This is natural since the velocity profile is, as a rule, fuller. Another characteristic feature of the considered case of a high turbulence level is the absence of jumps in the distribution, indicating much earlier merging of boundary layers than in the case of weak flow turbulization.

The dependence of the friction coefficient on the turbulence level is presented in Fig. 1. This dependence was obtained by processing the results on the distribution of the relative coefficient of friction along the tube length. The graph shows clearly that with an increase in the level of turbulence the relative coefficient of friction increases. Here, for comparison we give Bradshaw's correlation for a flat plate. We can see that our data lie below the curve.

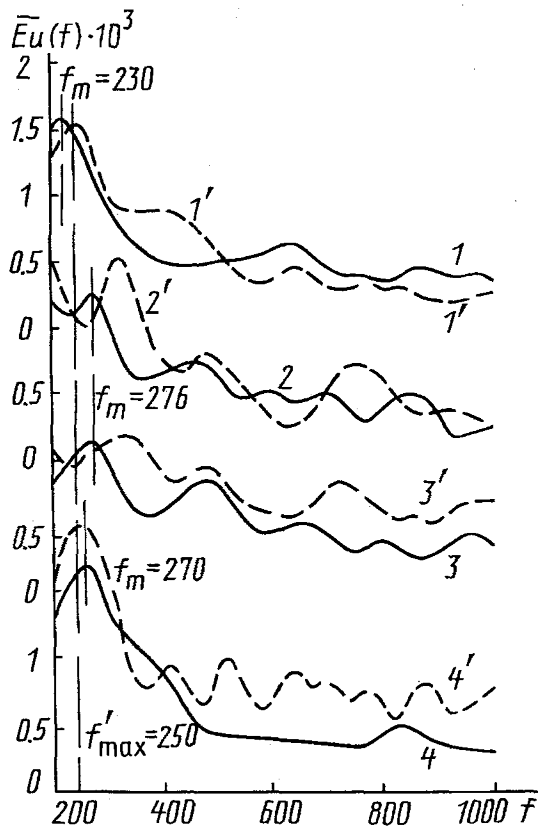

Fig. 4. Distribution of the spectral density of the longitudinal velocity: 1, 2, 3, 4, Tu = 1.5%; 1', 2', 3', 4', Tu = 12%; 1, x/d = 4.5; 2, 7; 3, 15; 4, x/d = 21. f, Hz.

presented. This can be explained by the fact that the negative pressure gradient arising in the tube flow suppresses the turbulence.

Results of Spectral Analysis. Figure 4 presents results of calculations of the spectral density from measured coefficients of autocorrelation in a viscous sublayer ($Y^+ = 5-8$) with the use of a procedure suggested in [6] for the cases of low and high levels of turbulence in various cross sections of a channel. In the case of a low turbulence level the maximum of the spectral density of velocity fluctuations or, in other words, the frequency of viscous sublayer separation, is virtually constant along the tube length beginning from the second cross section (x/d = 7) and is equal to 250 Hz (Tn = 4 msec). With an increase in the level of turbulence to 12% a similar pattern is observed, but the frequency of sublayer separation is somewhat higher and amounts to 270–280 Hz.

Analyzing the results of the calculation of the friction coefficient and the spectral density, we can easily see that the relative increase in the friction coefficient is of the same order as the relative increase in the frequency of sublayer renewal. This conclusion agrees with that made in the work of Kline [5], where the influence of the pressure gradient on the renewal period was noted. A positive pressure gradient reduces the period, while a negative gradient gives the reverse picture. It is known that in the case of a negative pressure gradient the dynamic velocity falls. If we compare this fact with the conclusion made by Kline, we can infer that flow laminarization leads to an increase in the period of viscous sublayer renewal and, as a consequence, to a decrease in the dynamic velocity. In our case, with increase in the flow turbulence the renewal frequency and the the dynamic velocity grow and, since the mean velocity over a tube cross section is constant, the friction coefficient grows.

CONCLUSIONS

1. An analysis of the results of measurement of the averaged velocity carried out using calculated mean integral characteristics, a namely, the blockage factor, form parameter, and momentum flux, showed that an

increase in the level of turbulence leads to more rapid development of the velocity profile than for the case of a low level of turbulence; this is especially evident in the case of moderate turbulence levels.

2. Velocity fluctuations near the wall are relatively insensitive to an increase in the level of turbulence. The distribution of fluctuations along the tube length at low turbulence levels differs from that observed at high levels. In the former case, a growth in fluctuations near the wall takes place when the flow develops along the tube, and in the latter case the reverse picture is observed, namely, velocity fluctuations near the wall usually attain their maximum values in the first cross section.

3. An increase in the initial level of turbulence leads to an increase in the relative coefficient of skin friction compared to the case of a low level of turbulence. This is especially evident in the first cross section. In subsequent cross sections the relative coefficient of friction decreases and approaches unity at a distance of 20–25 diameters.

4. The results of calculations of the spectral density of velocity fluctuations made it possible to determine the frequency (period) of viscous sublayer separation for the cases of low and high levels of turbulence along the length of the working section. It turned out that on the average the frequency of separation hardly changes along the tube length, but in the case of a high initial level of turbulence it is about 8–10% higher than for the case of a low level of turbulence and amounts to 270–280 Hz.

NOTATION

x, y, longitudinal and transverse coordinates; D, d, diameter of the tube; r, radius of the tube; U, U', longitudinal velocity and its fluctuation; U_τ, dynamic velocity; U^+, universal velocity; Y^+, universal coordinate; U_m, mean velocity over a tube cross section; U_0, velocity on the tube axis; τ_w, shear friction; C_f, friction coefficient; C_f/C_{f0}, relative friction coefficient; δ_*, displacement thickness; H, form parameter; Re, Reynolds number; Tu, level of turbulence; $Eu(f)$, one-dimensional spectral distribution density of velocity fluctuations; $E(f)$, energy spectrum of longitudinal velocity fluctuation; f, frequency; ρ, density; τ, retardation time. Subscripts: w, 0, conditions on the wall and on the tube axis.

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