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EXPERIMENTAL INVESTIGATION OF A DEVELOPING FLOW IN A ROUND TUBE AT DIFFERENT LEVELS OF TURBULENCE. 1. EXPERIMENTAL SETUP AND MEASURING PROCEDURE

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An experimental rig is described used for measuring the averaged pulsational integral characteristics of a turbulent boundary layer on the starting portion of a round tube with different levels of turbulence. Measurements were made in the automatic regime with the use of a thermoanemometric probe and TSI apparatus. A procedure is given for calculating the spectral density of fluctuations of the longitudinal velocity from the measured coefficients of autocorrelations.

Up to the present time one of the most complex problems is the problem of a turbulent boundary layer. Of practical importance is the problem of a developing turbulent boundary layer in tubes or channels at different levels of turbulence at the inlet. Therefore the problem of theoretical and experimental investigation of structural characteristics is of current interest. The present paper is devoted to experimental studies of flow in the initial region of the tube at an elevated turbulence level.

Description of the Test Section of the Experimental Facility. Experimental investigation of the developing turbulent boundary layer structure in a round tube at different turbulence levels was conducted on a subsonic open-type wind tunnel. A schematic diagram of the facility is shown in Fig. 1. Air from the room is pumped into the test section by a centrifugal fan DV-1KM (1) whose capacity was varied by adjusting the VU-70B rectifier output voltage supplied to the electric motors of the fans. This allowed us to vary the flow velocity from 3 to 20 m/sec. Before entering into the test channel, air passes through filters (2) and a flexible connecting hose (3) into a receiver container (4) and then into a preliminary section of flow preparation (10) consisting of a wind straightener (5), a set of screens (6, 7, 9) with cells of dimensions 0.4 × 0.4 mm made from a 0.25 mm-diameter wire, and a honeycomb (8). The honeycomb consists of 22-mm-long and 2-mm-diameter pipes having a wall thickness of 0.1 mm. Upon leaving the preliminary section, air enters into a contracting nozzle (11) made to fit the Vitoshinskii profile with a contraction ratio of 9.

The test section (16) is a round stainless steel tube with a diameter of 72 × 80 mm. To measure turbulent characteristics, openings (14) were made on the upper side of the tube along the test channel length at different distances from the tube entry section. To vary the flow turbulence level, disk agitators were used made of carbon steel of different thickness in keeping with recommendations of [1]. Different levels of turbulence were achieved by varying the flow area and the agitator thickness, with the diameter of holes remaining intact (5 mm). During the experiments the agitators (13) were positioned in section (12) located between the nozzle exit and tube inlet sections. Such a design made it possible to vary the position of the agitator as well as to install wind straighteners together with agitators and in a relatively short period of time. The probe was displaced with the aid of an automatic positioning device (15) controlled by a computer and a block of measuring instruments (17). The number of points of measurement over the boundary layer thickness was varied. The minimum step of probe displacement amounted to 10 μm.

Procedure of Measuring Overall and Local Characteristics. The principal feature of measurements in the boundary layer is that a substantial change in all the characteristics takes place in a small wall region, the so-called

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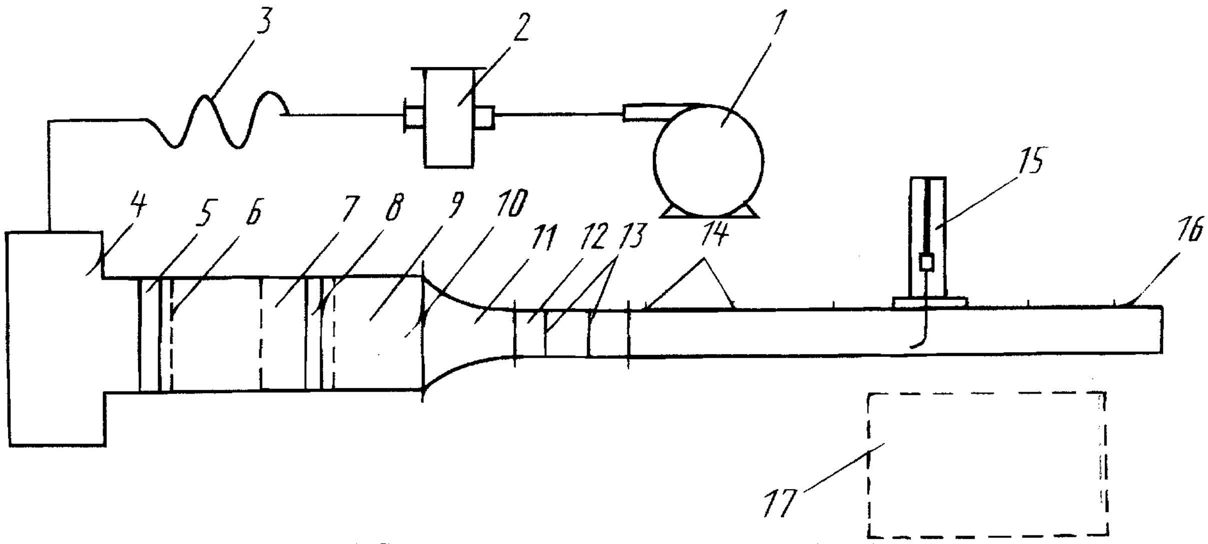


Fig. 1. Schematic diagram of an experimental facility.

zone of the viscous sublayer. In this case the measuring apparatus should introduce minimal disturbances into the flow, ensure rather close access to the surface and have a fast response.

In the present work we conducted measurement of averaged and pulsational characteristics of a turbulent boundary layer with use of the TSI complex of multichannel thermoanemometric apparatus in the mode of constant temperature, which made it possible to exclude the effect of the thermal inertia of the thread, for frequencies of turbulent fluctuations not exceeding 30 kHz, which is more than sufficient for most of the turbulence studies. The principle of thermoanemometer operation and the procedure of measurements of the main turbulent flow characteristics are described in detail in [2-4]. Preliminary calibration of a single-filament probe was made in a TSI calibrator when the flow velocity at the exit from the calibrating nozzle varied from 1 to 40 m/sec.

When measurements are made in the immediate vicinity of the surface, the thermoanemometer readings become overestimated because of additional cooling of the filament by the surface immersed in flow. In [5] a correction for the thermoanemometer readings was suggested based on the fact that there is a linear distribution of velocity in the viscous-sublayer region in nongradient flow, as indicated by numerous velocity measurements by diversified methods of visualization and Pitot tubes. For isothermal conditions the true velocity values are found from the formula

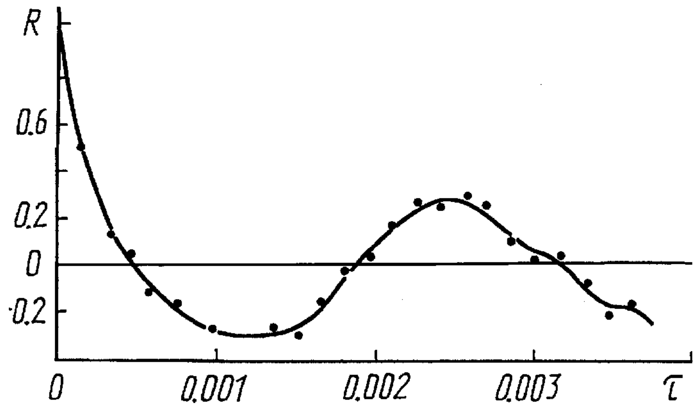
$$U_{\text{true}} = \left[U_{\text{meas}} - \frac{1{,}26\,(\Lambda - 1)^2}{\sqrt{y/\nu}\,(1 + 2E - 4B^{3/2})\,(1 + 0{,}065 R_{\text{true}})^2\,(1 + \Lambda)^2} \right]^2, \tag{1}$$

where U_{meas} is the mean velocity; $\Lambda=\lambda_w/\lambda_{gas}$ gas is the ratio of thermal conductivities of the wall and the gas; $B = y/r$ is the ratio of the transverse coordinate to the filament radius; $Re_{true} = U_{meas}d/\nu$ is the Reynolds number based on the filament radius.

The quality of experimental data, especially near the wall, is influenced by the design of the probe and its orientation in the flow. As noted in [6], the influence of probe orientation manifests itself differently depending on the conditions of measurements. In the present work preference was given to probes of the TSI company with longitudinal orientation of the legs. The skin friction coefficient (C_f) was determined by the method of velocity profile differentiation and the Clauser method. To ensure good accuracy of the first method, from 4 to 10 measured velocity values were located in the viscous-sublayer zone. According to the Clauser method [7], the measured velocity profile is compared with the universal logarithmic law

$$U/U_\tau = 1/k \ln (U_\tau y/\nu) + c, \tag{2}$$

to obtain the unknown dynamic velocity.



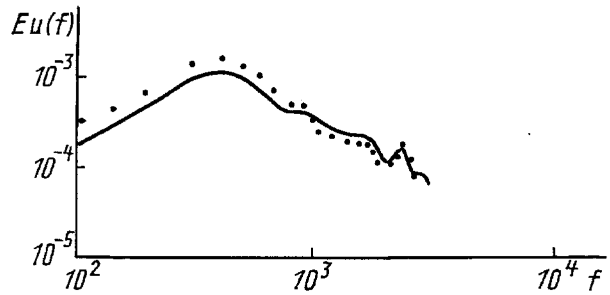


Fig. 2. Autocorrelation coefficient of longitudinal velocity fluctuation according to [9].

Fig. 3. Comparison between spectral density predictions in [9] and in the present paper.

Procedure of Calculating the Spectral Characteristics. It has been ascertained from the accumulated results of visual investigation [8] that a certain cyclic process arises in turbulent shear flows. Liquid particles occurring in the vicinity of the wall and possessing a small momentum start to move in the direction from the wall. This motion promotes thickening of the viscous sublayer and culminates in an explosion of chaotic turbulence followed by vigorous motion to the wall of liquid particles with a high momentum, and the viscous sublayer thins down again [2]. It is precisely this phenomenon which basically determines the process of heat removal from the surface. This in turn lends importance to investigations aimed at the study of laws governing the explosive process in a viscous sublayer.

It has been found in [9, 10] that the period of turbulence explosion can be determined from the autocorrelational-function distribution near the wall when the autocorrelation coefficient attains the first maxima. Thus, in order to study the cyclicity of the process of turbulence explosion in a viscous sublayer, it is necessary to measure the autocorrelation coefficient of longitudinal fluctuation. It is determined from the formula

$$Ru(\tau) = \overline{U'(\tau')\,U(\tau+\tau')}/\overline{U'^2}. \tag{3}$$

The results were processed by the procedure expounded in [11, 12]. To find the spectral density from N known discrete values of the autocorrelation coefficient, the following expression is used [12]:

$$\bar{G}xx(f) = 2t\,[Rxx(0) + 2\sum_{K=1}^{L-1} Rxx(k)\,W(k)\cos 2\pi fkt] \tag{4}$$

in the frequency range $0 < f < 1/2t$, where t is the interval of reckoning. Equation (4) is an analog of the well-known relation

$$Gxx(f) = 4\int_0^\infty Rxx(\tau)\cos 2\pi f\tau\, d\tau. \tag{5}$$

The function W(k), entering into Eq. (4), is called the time window. It is introduced to lower the error of spectral-density calculation from the discrete values of the autocorrelation coefficient. At the present time, spectral analysis makes wide use of rectangular, Bartlett, Tukey, and Parzen time windows. When calculating the spectral density, we used the Tukey window, which, as test calculations showed, has an advantage over the other spectral windows.

To check the reliability and validity of the data obtained with the aid of the procedure described above, we borrowed from [9] experimental values of the autocorrelational-function coefficients (Fig. 2) in a viscous sublayer

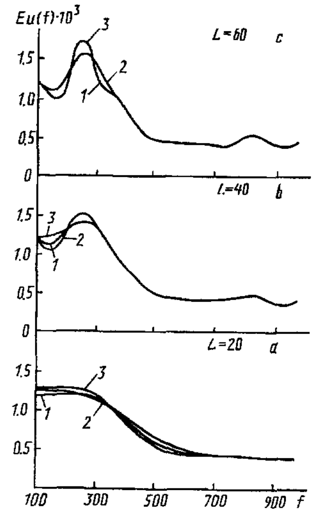


Fig. 4. Procedure of contraction and selection of the window shape: a: 1, 2, 3) Bartlett, Parzen, and Tukey windows, respectively; b: 1, 2, 3) Tukey, Bartlett, and Parzen windows, respectively; c: 1) Bartlett window; 2) Parzen and Tukey windows; 3) Bartlett and Tukey windows.

and then, following a program composed on the turbopascal language, we calculated the spectral density of velocity fluctuations. The results of calculations presented in Fig. 3 agree well both qualitatively and quantitatively with the data of [9]. The small discrepancy is due to an insufficient quantity of experimental points for the autocorrelation coefficient, Eq. (26), and to the error introduced when transferring the data from the plot given in [9]. The basic requirements imposed on the evaluation of spectra are high stability and a small degree of distortion. To meet these requirements, a method is used in practice which has been termed contraction of the window. The procedure of window contraction, as well as the effect of the window shape on the results of calculations can be seen in Fig. 4. Here, the spectral density was calculated with the use of the autocorrelation coefficient measured in a viscous sublayer ($y^+ = 7$) for the case of elevated turbulence. As is seen from the plots, the boundary of the cutoff point L substantially influences the behavior of the spectral-density function; thus, for example, at L = 20 and with the use of the Parzen and Tukey windows the maximum on the distribution curve is almost invisible, but as L increases from 20 to 60, it begins to appear and it attains its peak value at L = 60. It can easily be seen that at high L the calculations using the correlational Bartlett and Tukey windows give virtually identical results. The number of points necessary for calculating the spectral density with the use of the Parzen window is about 1.5 times higher than that with the use of the Bartlett and Tukey windows. Taking into account conclusions drawn in the course of test and preliminary calculations, the spectral density was subsequently calculated at different values of L (40-80) with use of the Tukey window. All the calculations were made on an IBM PC/AT computer and took 5-20 sec.

Qualification Investigations of the Experimental Characteristics of an Aerodynamic Setup and of the Method of Measurements. To secure the quality and reliability of experimental data for a developing turbulent boundary layer in a round tube at different levels of turbulence, we carried out measurements of a turbulent boundary layer in the sixth section of the test channel (x/d = 0.5-40). The results obtained were compared with the results of the works of Laufer [13], Hisida and Nagano [9], and Nikuradse [14]. Turbulent characteristics were measured in the automatic regime. Probe displacement control and acquisition of experimental information were made with the aid of a PC XT personal computer and a CAMAC interface. To carry out measurements across the boundary layer, a traverse mechanism was devised, which, owing to the rotation of a microscrew that was set in motion by a step motor, ensured probe displacement with the movement interval specified by the program. As a rule, the number of points of measurement across the boundary layer amounted to 45-60. In this case a minimum of 4-5 points lay in the viscous sublayer zone. Mean and root-mean-square voltages were read from 1076-model voltmeters. To measure the autocorrelational functions, Honeywell SAI-42A correlator was used. The experimental information obtained was processed according to the specially developed program EXPERIMENT written in the turbopascal language. In Fig. 5 the results of measurements of the velocity profile and velocity fluctuations in the sixth section are presented in

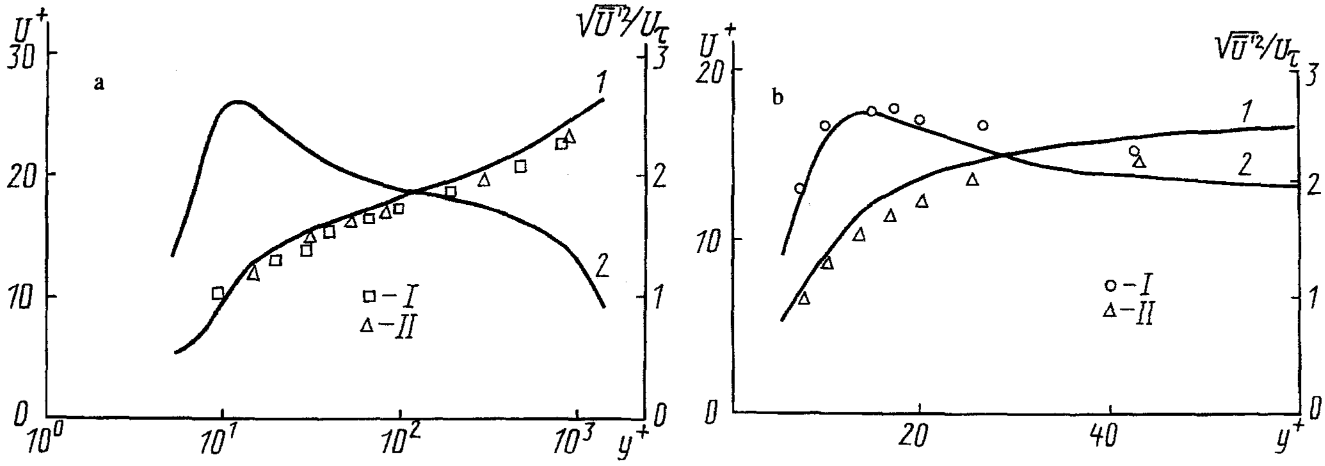


Fig. 5. Distribution of velocity (1) and velocity fluctuations (2): a) in universal coordinates: I) data of Hisida [9]; II) data of Nikuradse [14]; b) near the wall: I, II) data of Laufer [13].

comparison with experimental results of various authors. Figure 5a presents the profiles of the averaged velocity and velocity fluctuations over the entire tube section at Re = 73,000 in comparison with data of Hisida [9] and Nikuradse [14]; good coincidence of the data of the present work with those of Hisida and Nikuradze is seen. The small discrepancy between the data presented in Fig. 5b is due to the fact that in Laufer's experiment the measurement section was located at a distance of 50 diameters and the Reynolds number was smaller (50,000).

The created experimental setup and the application of the proposed procedures of measurements and processing made it possible to obtain data on the distribution of different characteristics of the turbulent boundary layer over the starting length of a round tube at different levels of turbulence the analysis of which will be presented in the next paper.

NOTATION

x, y, longitudinal and transverse coordinates; D, d, diameter of tube; r, radius of tube; U, U', longitudinal velocity and its fluctuation; U_τ, dynamic velocity; U^+, universal velocity; y^+, universal coordinate; U_m, mean velocity over tube cross section ; U_0, velocity at tube axis; $\tau_{w'}$, shearing friction; C_f, friction factor; C_f/C_{f0}, relative friction factor; δ^*, displacement thickness; H, form parameter; Re, Reynolds number; Tu, turbulence level; k, kinetic energy of turbulence; $Rxx(\tau)$), longitudinal-velocity autocorrelation coefficient; $\overline{E}u(f)$, one-dimensional spectral density of the distribution of velocity fluctuations; E(f), energy spectrum of longitudinal-velocity fluctuation; Φxx, spectral densities; f, frequency; ν, kinematic viscosity; ρ, density; τ, delay time. Subscripts: w, 0, conditions on the wall and the tube axis.

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