OSCILLATORY TURBULENT FLOW IN A CYLINDRICAL CHANNEL

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UDC 532.526.4

Results are presented from a study of an unsteady turbulent boundary layer in a cylinder with different flow conditions.

Tests were conducted on a special unit depicted schematically in Fig. 1. The unit included an open-type aerodynamic loop, the necessary diagnostic equipment, and an automated data-measurement system.

Air was supplied by a high-pressure VVD-160 M blower 5 with a capacity of 150 g/sec. The velocity was changed in accordance with the law

$$\langle u_{01} \rangle = \bar{u}_{01}(1 + A\sin(2\pi ft + \varphi_u))$$

by means of a disk baffle 7 with D_y = 100 mm. The disk was rotated by electric motor 2 through an F-1 speed regulator 6. The drive system made it possible to smoothly regulate the frequency of rotation of the baffle in the range 0.3-100 Hz. The relative amplitude of the velocity fluctuations A could be varied within the range 0.1-0.7 by means of slide valves 3 and 9. The velocity $\bar{u}_{01}$ was regulated within the range 5-60 m/sec with slide valve 1.

A prechamber 10 and a Vitoshinskii nozzle 11 were installed to ensure a uniform velocity field in front of the inlet of the test section 15. The ratio of the area of the outlet section of the nozzle to the cross sectional area of the prechamber was 1:250, while the difference between the values $\langle u_{01} \rangle$ and

$$u_m(t) = \frac{2}{R^2}\int_0^R \langle u_1(r,\ t)\rangle\, rdr$$

at different phases of the period of velocity oscillation was no greater than 1%. To keep undesirable vibrations from developing during operation of the blower, the unit and the blower were connected by a flexible rubber tube 4.

Instantaneous values of velocity were measured with constant-temperature hot-wire anemometers 14 and 18. The output signals of the anemometers were collected and analyzed by a 3-channel measuring-computing complex (MCC) constructed on the basis of a microcomputer 19. The equipment linking the object 16 and the MCC includes three analog-digital converters (ATsP-F7077/1). We examined the possibility of operating with 2- and 3-wire transducers for the anemometers. When averaged over 100 periods, the error of the measurement of $\langle u \rangle$ was no more than 4% thanks to preliminary normalization of the anemometer signals with normalizing amplifiers 12 and the high resolution of the ATsP. The value of ε_u was determined with an error of 14%.

The data readout for all measurement channels was synchronized with a special marker 8 connected to the butterfly valve. The number of points for a period and the interval between them were assigned by the data collection program. Measurements were made at 20 points during the period 2π in our tests. We experimentally selected the optimum number of samplings in each period phase n = 100; a further increase in n did not lead to any appreciable increase in the accuracy of ε_u.

The tests were conducted with oscillations of the velocity of the medium which correspond to the natural frequency of the through channel of the wind tunnel. Velocity oscillations which were nearly sinusoidal were obtained at this frequency at the inlet of the working

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Kazan Chemical-Engineering Institute. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 50, No. 6, pp. 908-912, June, 1986. Original article submitted April 18, 1985.

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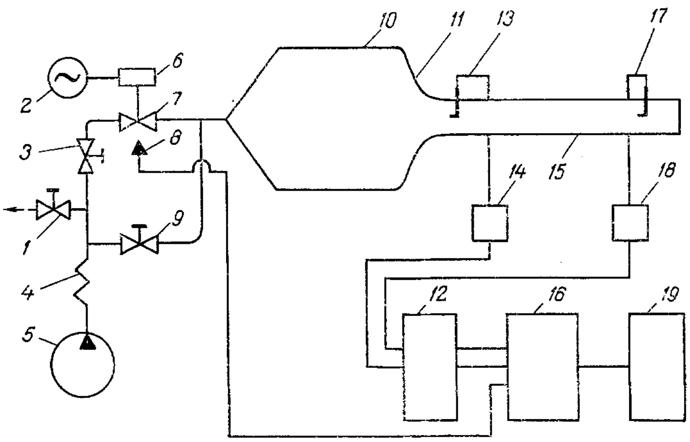

Fig. 1. Diagram of experimental unit.

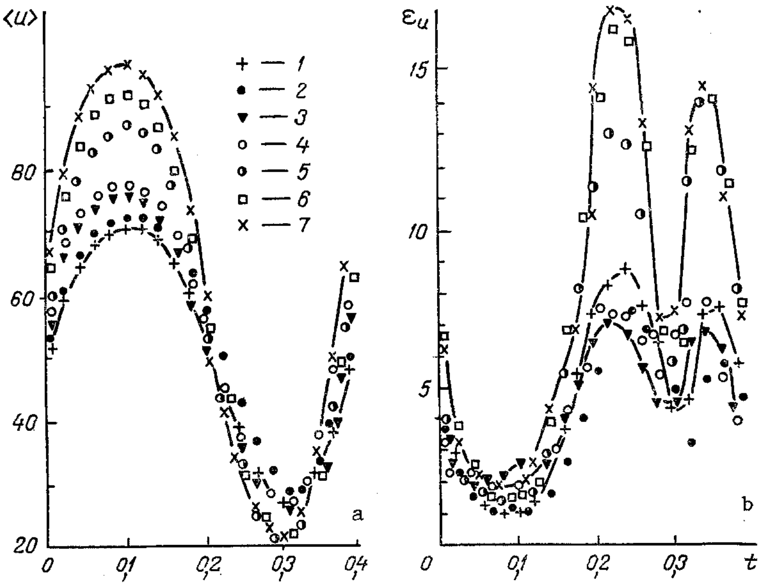

Fig. 2. Averaged profiles of velocity and intensity of turbulent pulsations for variant a: 1) x/D = 0; 2) 5; 3) 11; 4) 17 and variant b: 5) x/D = 0; 6) 7; 7) 13. $\langle u \rangle$ [m/sec]; ε_u [%]; t [sec].

channel. Values of the velocity u were measured during the tests with the aid of thermoanemometric instrumentation with wire-type transducers. One transducer 13 was secured in the central part of the measurement cross section of the flowmeter nozzle, while the second transducer 17 was moved perpendicular to the channel axis in the corresponding control section by means of special traversing equipment. The test section was an axisymmetric cylinder 0.825 m long and of the diameter D = 0.05 m. A conical diffuser 0.250 m long with a flare-angle tangent tan α = 0.05 was connected to the outlet of the cylindrical channel to obtain different flow conditions. All of the tests were conducted for two variants: a) a cylinder without a diffuser; b) a cylinder with a diffuser, but with the transducers located in the cylinder in both cases. The measurements were obtained in sections x/D = 0, 5, 11, and 17 for variant a and x/D = 0, 7, and 13 for variant b.

The instantaneous velocities were represented in the form of the following sum [1]:

$$u = \bar{u} + \tilde{u} + u' = \langle u \rangle + u'.$$

The velocities $\langle u \rangle$, averaged over the phase for each ensemble of samples n = 100, are

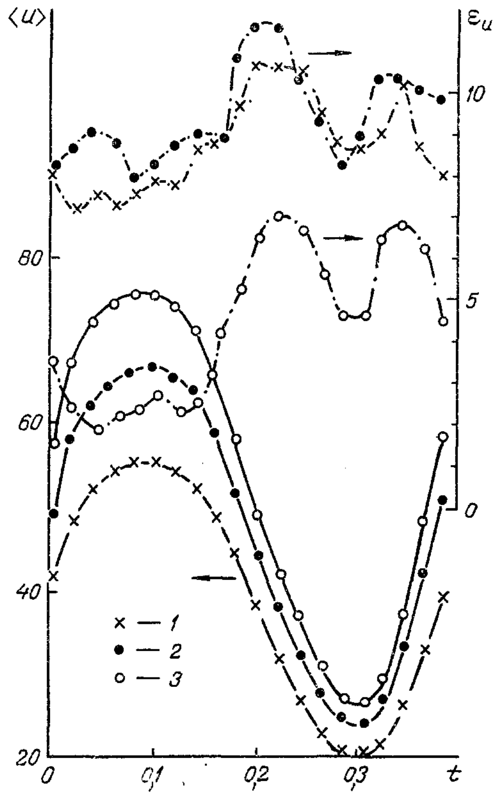

Fig. 3. Change in the parameters <u> and ε_u over the period T in the section x/D = 11 at y = 0.15 m (1); 2.2 m (2); 25 m (3).

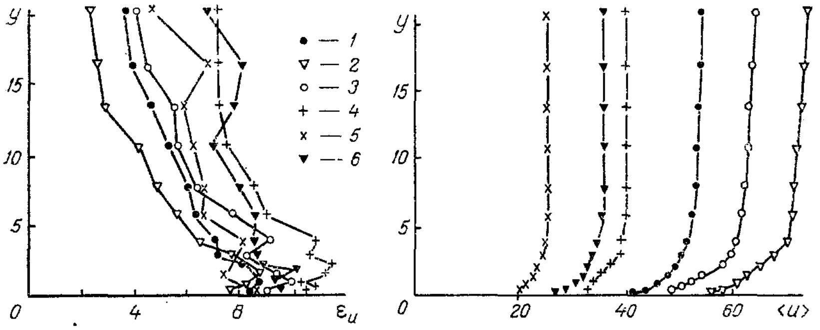

Fig. 4. Intensity of turbulent pulsations and profiles of mean velocity for variant a: 1) t = 0; 2) 2/5π; 3) 4/5π; 4) 11/10π; 5) 6/4π; 6) 17/10π. y [mm].

$$\langle u \rangle = \sum_{i=1}^{n} u(t + iT)/n.$$

The mean value over time was found by integration:

$$\bar{u} = \int_0^T \langle u \rangle \, dt/T.$$

We then calculated the turbulent fluctuations $u' = u - \langle u \rangle$ and determined the intensity of the turbulent pulsations

$$\varepsilon_u = \sqrt{\sum_{i=1}^{n} u'^2(t + iT)/n} / \langle u \rangle \cdot 100\% .$$

Figure 2a shows phase-averaged velocities $\langle u \rangle$ on the cylinder axis.

The value of $\langle u \rangle$ typically increases along the cylinder, which is connected with acceleration of the flow in the core due to boundary layer development. We should point out the increase in velocity for variant b with unaltered conditions of blower operation. Connection of the diffuser to the cylinder makes it possible to significantly increase the mass velocity of the air.

The change in $\langle u \rangle$ in all of the sections remains sinusoidal. A more exact correspondence to a sinusoidal distribution could be obtained by means of harmonic analysis.

Figure 2b shows the intensities of turbulent pulsations ε_u for the same sections and coordinates of the transducers. Analysis of the graphs shows first that the change in ε_u is opposite in phase to the change in $\langle u \rangle$ for variants a and b. Second, connection of the diffuser to the cylinder increases the intensity of the turbulent velocity pulsations. The value of ε_u is nearly identical for both variants for the first half-period. In the second half-period, the velocity oscillations ε_u are twice as great for variant b as for variant a. In the second half-period there are also two peaks in the distribution of turbulent pulsations in the ranges from π to $7/5\pi$ and from $8/5\pi$ to $9/5\pi$, although there is a substantial decrease in the value of ε_u in the phase $3/4\pi$ and in its vicinity.

Figure 3 shows data for variant a which characterizes the changes in the parameters $\langle u \rangle$ and ε_u over the period T in section $x/D = 11$ at three different points over the radius. With the development of the boundary layer, there is an appreciable increase in velocity from the wall to the axial zone of the cylinder. The minimum values of ε_u for the period correspond to the phases of the greatest values of the parameters $\langle u \rangle$. The distribution of ε_u remains qualitatively the same as on the cylinder axis.

Figure 4 shows profiles of $\langle u \rangle$ and ε_u for six fixed phases of the period of velocity change measured in the section $x/D = 11$. Analogously to the steady flows, the maximums of the distributions $\varepsilon_u(y)$ are located in the wall region.

The following conclusion can be made. For constant conditions of blower operations the attachment of a diffuser to the cylinder significantly increases the mass velocity of the air and the intensity of turbulent pulsations.

The character of the change in the intensity of turbulent pulsations ε_u is qualitatively stable with regard to the period and channel length. All variants are characterized by coincidence of the sections of maximum values of the mean velocity $\langle u \rangle$ in the first half-period with minimum values of ε_u, maximum turbulence on the transitional section between the first and second half-periods, and a substantial reduction in turbulence at the end of the stagnation section of the second half-period. The occurrence of two maximums of turbulence intensity is typical of the second half-period. The appearance of two peaks in the distributions of turbulent pulsation intensity by period was also noted in [2]. However, the position of these peaks is changed quite a bit in the boundary layer, while peaks are generally absent outside the boundary layer.

NOTATION

f, frequency; A, amplitude; T, period; n, number of periods; D, diameter; R, radius; x, distance along channel axis; y, distance over channel radius, u, velocity in the direction x; φ, phase; t, time; r, radial coordinate; α, angle; ε, intensity of turbulent pulsations. The indices: u pertains to the velocity u; m pertains to a value averaged over the cross section; 1 denotes the coordinate x = 0; 0 denotes a value on the cylinder axis; $(\ )'$ denotes a pulsative quantity; the bar pertains to averaging over time; the wavy bar denotes a periodic quantity; $\langle\ \rangle$ denotes a value averaged over the ensemble.

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VELOCITY FIELD IN THE INITIAL SECTION OF A FILM FLOW

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UDC 532.526.7

The velocity field in the initial section of gravitational film flows has been investigated analytically and experimentally, and a relationship has been obtained for calculating the length of this section.

The increasingly wide use of gravity flows of thin liquid layers in technological plants has led to an increased interest in recent years in the structure of the flows in films, particularly under the conditions of stabilization of the film [1-10]. In the initial or entry section hydrodynamic stabilization leads to a transformation of the velocity profile from the initial profile which is determined by the conditions for the distribution of the liquid into the film to the fully developed velocity profile, which takes the form of a semiparabola for the single-phase flow of the liquid in the laminar or pseudolaminar regimes. The initial velocity profile depends on many factors: the type of the distributing device and the features of its construction, the inclination and shape of the wetted surface of the wall, the form and dimensions of the wall roughness elements, the properties of the liquid, etc. [7, 10]. In making calculations, it is necessary to isolate the initial section when its length is greater than or commensurate with the total length of the wetted surface. In theoretical investigations the accuracy of the determination of the length of this section is determined by the degree of approximation of the velocity pattern which is undergoing transformation to the fully developed, stabilized profile.

Analytical relationships are known which are either somewhat simplified, and do not take into account the features of the initial liquid distribution into the film, and are unsuitable for small path lengths (for example, the functions of N. A. Gasan or R. Khagen [9]), and which therefore give results which are in poor agreement with the experimental data [3-7], or which have a complicated and inconvenient form and imply only numerical methods of solution [8, 9].

A simplified analytical method of calculating the velocity profile in the initial section was proposed earlier [1, 2, 7] for laminar flow of a wetting film along a vertical surface. A solution of the nonlinear equations of motion in dimensionless form

$$\frac{\partial^2 w}{\partial y^{*2}} - w\frac{\partial w}{\partial x^*} = -g^* \tag{1}$$

for the velocity w was sought in the form of an exponential polynomial. The dimensionless parameters appearing in Eq. (1) are:

$$w = \frac{w_x}{\bar{w}_s};\quad y^* = \left(\frac{\bar{w}_s}{\nu S}\right)^{0,5} y;\quad x^* = \frac{x}{S};\quad g^* = \frac{gS}{\bar{w}_s^2}. \tag{2}$$

Kiev Polytechnic Institute. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 50, No. 6, pp. 913-917, June, 1986. Original article submitted April 9, 1985.