EXPERIMENTAL STUDY OF NON-STEADY-STATE TURBULENT FLOW IN AN AXISYMMETRIC DIFFUSOR

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Results of an experimental study of the structure of an oscillating flow in a conical diffusor are presented and evaluated.

Many important engineering applications (aerodynamics, hydraulics, etc.) must deal with non-steady-state turbulent flows, but this area of hydrodynamics has remained little studied up to the present. Only a few experimental studies have investigated oscillating turbulent flows [1-6]. There are also available numerical calculations of non-steady-state turbulent flows [7, 8] in which semiempirical models of turbulence used for calculation of steady-state turbulent flows were employed. However, the small number of available experimental studies where non-steady-state turbulent flow has been investigated with known initial and boundary conditions, so necessary for performance of numerical calculations, makes determination of the limits of applicability of "quasi-steady-state" turbulence models difficult.

The reason why non-steady-state turbulent flows have been studied so little lies in the difficulties which they present to investigators. In experimental studies of non-steady-state flows the same measurement equipment is used (thermoanemometers, etc.), but to analyze and decode the analog signals they produce special high-speed digital equipment must be used, capable of averaging sets of values at various fixed time intervals.

In order of increasing measurement complexity and difficulty, one can investigate the following quantities in non-steady-state flows: mean velocity profiles over time $\bar{u}$, mean velocity over phase $\langle u \rangle$, intensity of longitudinal components of turbulent pulsations $\langle u'^2 \rangle$, intensity of transverse pulsations $\langle v'^2 \rangle$, and turbulent tangent stresses $\langle u'v' \rangle$. At the present time, the most thorough studies performed are those of Cousteix and Hino. Aside from the quantities mentioned above, scholars have studied probability characteristics of turbulent fluctuations, fourth order central moments [1], while [4] performed a simplified balancing of the turbulence kinetic energy equation. In [1, 4, 5] an oscillating turbulent flow in a rectangular channel was studied, while [2, 9] considered flow on a plane plate with longitudinal pressure gradient. However, the experiments of [2, 9] were limited to the study of $\bar{u}$, $\langle u \rangle$. Oscillating flow in a conical diffusor was studied in [3], but no data on $\langle u'^2 \rangle$ were offered. Therefore the question of the effect of a positive pressure gradient on the intensity of turbulent velocity pulsations of an oscillating turbulent flow remains open. The present study is an effort to partially fill this gap in knowledge and to determine the mechanism by which $\langle u'^2 \rangle$ evolves in an oscillating boundary layer for $\partial\bar{p}/\partial x > 0$.

We will study an oscillating turbulent flow of air in a conical diffusor with harmonically varying flow rate. The experiments were performed in an open type aerodynamic device. Special attention was given to formation of flow conditions at the input of the experimental segment. Use of a Vitoshinskii nozzle and special forechamber allowed production of a practically uniform flow field behind the nozzle. Harmonic velocity oscillation was produced by a rotating flap installed ahead of the forechamber.

Preliminary development of the turbulent flow occurred in a cylinder with diameter D = 50 mm, length L = 325 mm, so that on entry to the diffusor the boundary layer had an average thickness of $2\delta/D \approx 0.2$. In the conical diffusor with $\tan\alpha = 0.05$ three control sections for performing measurements were available. To study the longitudinal velocity component a single wire type constant temperature thermoanemometer sensor was used, movable along the normal to the channel axis by a special positioner. In addition, another thermoanemometer sensor was used to measure the velocity at the output of the flow control nozzle. Selection and processing of thermoanemometer output signals was carried out by a measurement—calculation

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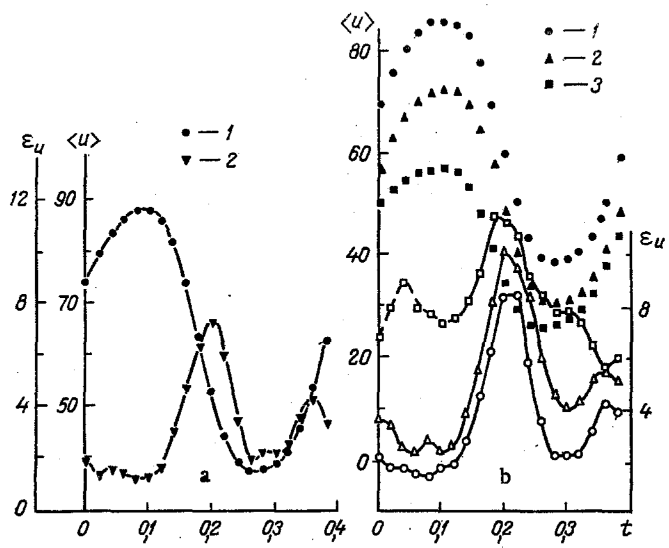

Fig. 1. Quantities <u> and ε_u vs time for r = 0: a) x = 0; 1) $\langle u_1 \rangle$; 2) ε_{u1}; b) dark points, <u>; light, ε_u; 1) x = 0.350; 2) 0.450; 3) 0.550; x, m; u, m/sec; ε_u, %; t, sec.

complex based on an "Élektronika DZ-28" microcomputer. Three type F-7077/1 analog—digital converters permitted parallel conversion of the analog signals from each channel into digital form in 8 μsec. Synchronization of the commencement of measurement of instantaneous anemometer signal values to the phase of the flow rate oscillation was accomplished by a special marker device, coupled to the rotation of the flap in the pulsator. Over a single oscillation period 20 values of the signals were recorded every 20 msec. Averaging of all these points was carried out over 100 periods. The instantaneous velocity value was represented in the form of a sum u = <u> + u'. Using the set of turbulent velocity fluctuations u' the second order moment $\langle u'^2 \rangle$ and the intensity of longitudinal turbulent pulsations

$$\varepsilon_u = \sqrt{\langle u'^2 \rangle} / \langle u \rangle 100\%$$

were calculated.

Figure 1 shows the time evolution of the mean velocity <u> and the turbulent pulsation intensity ε_u on the channel axis for various measurement sections. At the input to the cylinder the quantity $\langle u_1 \rangle$ can be described quite accurately by a sinusoid, but down the flow there is some disruption of the character of the <u> oscillations, especially noticeable for the third section in the diffusor. For x = 0 there are two peak values in the ε_u oscillations. For the first peak appears, as would be expected, in the phase of greatest flow braking: then ε_u decreases to practically prepeak values. It is more difficult to explain the appearance of the second peak which occurs during the flow acceleration phase (Fig. 1a). On the whole the character of the change in ε_u over the period is identical to the character of ε_u oscillations at x = 0, the only difference being that in the third section the second peak is shifted to the region of maximum flow acceleration. As in the case of steady-state flow there is an increase in the mean oscillation level ε_u over channel length.

To illustrate the time evolution of the quantities <u> and $\sqrt{\langle u'^2 \rangle}$ over diffusor radius the values were referenced to the mean values over time $\bar{u}$ and $\sqrt{\overline{u'^2}}$ for each point (Fig. 2). While $\langle u \rangle / \bar{u}$ oscillates about unity, $\sqrt{\langle u'^2 \rangle} / \sqrt{\overline{u'^2}}$ oscillates about a value less than unity; the quantity $\sqrt{\overline{u'^2}}$ can be obtained by averaging the signal u' over time, as obtained by subtraction of the signals: u' = u — <u>. It should be noted that both quantities oscillate in phase up to y = 8, indicating that ε_u changes insignificantly over the period. With further motion toward the channel axis the character of the $\sqrt{\langle u'^2 \rangle} / \sqrt{\overline{u'^2}}$ oscillation changes. In the evolution of this quantity there is a segment with a clearly expressed peak.

The quantity ε_u changes significantly over both velocity oscillation period and space (Fig. 3). While the character of the ε_u oscillations for section 1 (Fig. 3a) basically coincides with the evolution of ε_{u_1}, for control section 3 the character of the time change of ε_u differs (Fig. 3b). The quantity ε_u for the last measurement section changes only slightly over the velocity oscillation period and is higher in absolute value. Apparently simultaneous action of oscillations of the external flow and the positive pressure

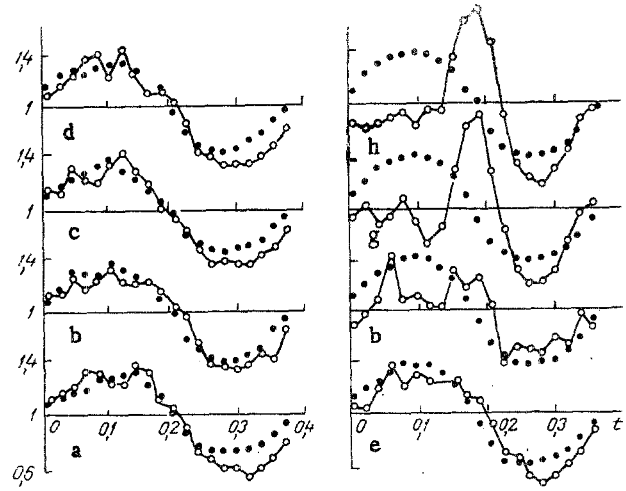

Fig. 2. Oscillation of $\langle u\rangle/\bar{u}$ (dark points) and $\sqrt{\langle u'^2\rangle}\,/\,\sqrt{\overline{u'^2}}$ (light points) over period: a) y = 0.20 mm; b) 1.0; c) 2.0; d) 4.5; e) 8.0; f) 15.0; g) 21.0; h) 27.5 mm.

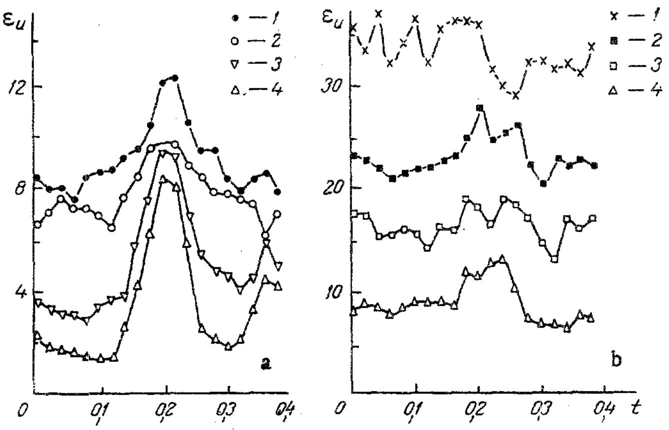

Fig. 3. Quantity ε_u vs time: a) x = 0.350; 1) y = 0.4 mm; 2) 2.0; 3) 6.0; 4) y = 19.0 mm; b) x = 0.550; 1) y = 2.0 mm; 2) 10.0; 3) y = 15.0; 4) y = 24.0 mm.

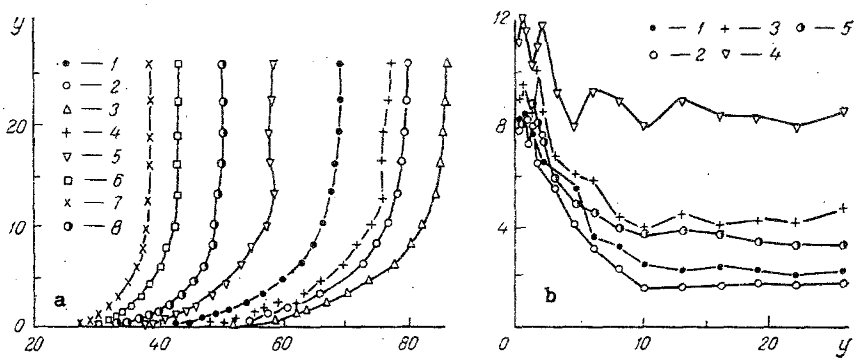

Fig. 4. Profiles of $\langle u\rangle$ and ε_u for various phases, x = 0.350: a) $\langle u\rangle$; 1) t = 0; 2) 0.04; 3) 0.10; 4) 0.16; 5) 0.20; 6) 0.24; 7) 0.28; 8) t = 0.36; b) ε_u; 1) t = 0; 2) 0.04; 3) 0.16; 4) 0.20; 5) 0.36; t, sec.

gradient causes development in the turbulent flow of coarse scale energy-containing vortices, which lead to the in-phase variation of the quantities $\langle u\rangle$ and $\langle u'^2\rangle$. A detailed answer can only be given by spectral analysis of the turbulent flow.

The opinion exists that external flow oscillations do not lead to marked deformations of $\bar{u}$ profiles, but that the <u> profiles do distort, but this can be applied only to reverse flows. For breakoff-free flows the form of the <u> profiles changes insignificantly (Fig. 4a) even when <u> changes severely over time. A similar pattern is shown by the turbulent pulsation intensity profiles ε_u (Fig. 4b). On the whole, the value ε_u for all phases increased with approach to the wall and equalizes in the external flow.

NOTATION

x, y, coordinates along and across channel; u, v, velocities in x and y directions, respectively; r, distance along channel radius from axis; t, time; D, cylinder diameter; δ, boundary layer thickness at input to diffusor; L, cylinder length; 2α, total diffusor aperture angle; ε_u, turbulent pulsation intensity. Subscripts: 1, at input to cylinder; u, with respect to velocity u; $(\ )'$, pulsation quantity; bar above quantity indicates time average; symbol < > indicates average over set of values.

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