DECAY OF TURBULENCE IN THE INLET REGION OF CIRCULAR AND PLANE CHANNELS

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The distribution of the velocity and turbulence level and the decay of turbulence in the inlet regions of channels are investigated experimentally. A relation is obtained, generalizing the experimental data on decay of turbulence.

The flow structure and, primarily, such a characteristic as the turbulence level of the flow core exert a significant influence on the boundary-layer regime in the initial section of a channel, as well as on the lengths of the laminar, transition, and turbulent segments; to a great extent they also determine the heat-transfer intensity. Consequently, the study of the turbulence level at the inlet to channels and the decay of artificially generated turbulence is a necessary prerequisite to the analysis of local heat transfer and the interpretation of experimental data on heat transfer in the inlet regions of channels.

We have previously published experimental data [1, 2] and generalized them for the computation of the turbulence level at the inlet to plane and circular channels with the placement of definite types of turbulence promoters at certain distances from the inlet.

We now present the results of an experimental study of the decay of artificially generated turbulence in circular pipes with diameters of 72 and 35 mm and in a plane channel with a cross section of 37.5 × 212.5 mm. The turbulence level was estimated according to the rms value of the longitudinal component of the velocity fluctuations. The measurements were conducted with an ÉTA-9 constant-temperature hot-wire anemometer.

The experimental arrangement, the structure of the test sections, and the experimental and data-processing procedures are described in [1-3].

Air was injected into the plane channel through a nozzle with a Vitoshinskii profile. Turbulence promoters were set up at various distances in front of the nozzle. In the case of the circular test sections, a nozzle was not used at the inlet and the turbulence promoters were set up directly in the entrant cross section. The structure of the turbulence promoters used for the plane test section is described in [1], the same turbulence promoters as in [2] were used for the circular section with a diameter of 72 mm, and devices similar in geometry to those described in [2] were used for the 35-mm circular section.

The velocity and turbulence level were measured in the following cross sections:

a) for the plane channel, $x/H = 0$, 1.95, 3.55, 5.15, 6.75, 9.95, 13.1, 17.9, 22.7;

b) for the 72-mm circular channel, $x/d = 2.38$, 2.86, 3.50, 4.49, 6.80;

c) for the 35-mm circular channel, $x/d = 3.83$, 6.69, 10.8, 14.74.

The first cross section for the circular pipes was chosen at the distance from the inlet where the profiles of the average velocity and longitudinal velocity fluctuations in the flow core were practically uniform. The variation of the average velocity and longitudinal-velocity-fluctuation profiles along the experimental sections is given in Fig. 1. The data of Comte-Bellot [4] for a plane channel yield a somewhat less rounded profile. This discrepancy between the results can be explained by the fact that our measurements were carried out at higher turbulence levels in the flow core. The velocity profiles for the circular channels also turn out to be more rounded in comparison with stabilized turbulent flow data [5], not only because of the higher core fluctuation level ε, but also because for $x/d < 15$ the velocity profile is still far from the stabilized state.

The data in Fig. 1c on the measured longitudinal component of the velocity fluctuation in a plane channel indicate that the turbulence decays downstream, most rapidly in the central part of the channel. The intensity

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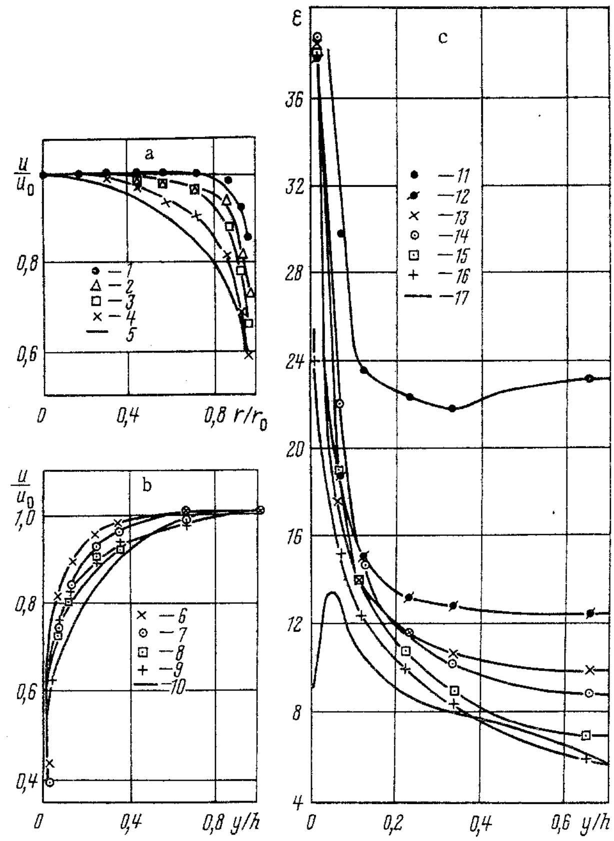

Fig. 1. Variation of the average-velocity profile along a circular channel of diameter d = 35 mm (a) and a plane channel (b), and of the velocity-fluctuation profile ε, %, along a plane channel (c). 1) x/d = 3.83; 2) 6.69; 3) 10.81; 4) 14.74; 5) data of [5]; 6) x/H = 3.55; 7) 6.75; 8) 9.95; 9) 22.7; 10) data of [4]; 11) 0; 12) 1.95; 13) 3.55; 14) 6.75; 15) 9.95; 16) 22.7; 17) data of [5]. 1-4) $\mathrm{Re} = 8 \cdot 10^3$; 6-9, 11-16) $\mathrm{Re_H} = 28.7 \cdot 10^3$.

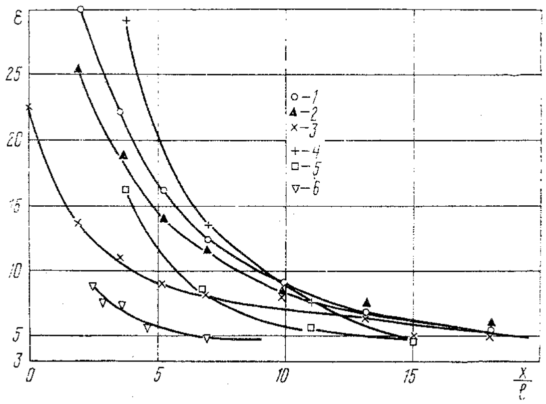

Fig. 2. Variation of the turbulence level in the flow core in the inlet regions of plane and circular channels. 1) $\mathrm{Re_H} = 12.4 \cdot 10^3$; 2) $35.9 \cdot 10^3$; 3) $28.7 \cdot 10^3$; 4) $\mathrm{Re} = 8 \cdot 10^3$; 5) $6 \cdot 10^4$; 6) 10^5. 1, 2) Identical turbulence-generating system (promoter No. 2), x = 0 [1]; 1-3) plane channel; 4, 5) circular channel, d = 35 mm; 6) the same, d = 72 mm.

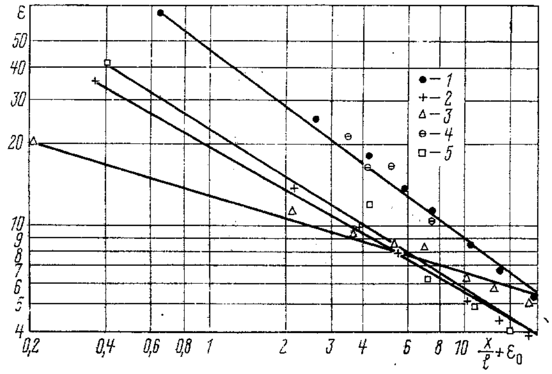

Fig. 3. Decay of turbulence along the channels. 1) $Re_H = 35.9 \cdot 10^3$; 2) $28.7 \cdot 10^3$; 3) $36.2 \cdot 10^3$; 4) $Re = 10^4$; 5) 10^5. 1-3) plane channel; 4) circular channel, d = 72 mm; 5) the same, d = 35 mm.

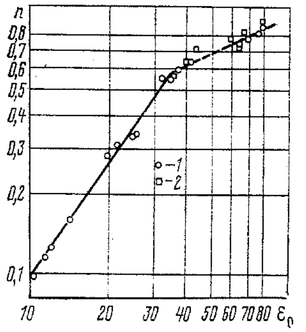

Fig. 4. Influence of initial turbulence level on the power exponent in relation (1). 1) Plane channel; 2) circular channels.

of the wall velocity fluctuations also diminishes in this case. Consequently, the degree of turbulence in the core characterizes, to a certain extent, the intensity of momentum transfer (and, hence, heat transfer) at the wall.

A comparison of our data in Fig. 1c with those published in [5] for stabilized flow leads to the conclusion that the velocity-fluctuation intensity is greater in the inlet region than where the flow is stabilized. This conclusion is further supported by the results of Barbin and Jones [6]. The lengthwise variation of the profile has quite a different character in the case of circular channels.

The variation of the turbulence level along plane and circular channels is shown in Fig. 2, from which we draw the following conclusions. The decay of artificially generated turbulence is rapid and becomes more so the higher the value of ε at the inlet. For $\frac{x}{H}\left(\frac{x}{d}\right) \approx 15$, ε attains roughly the same value regardless of the level of the initial disturbances. The geometric parameters of the turbulence promoters are not found to have any appreciable effect on the nature of the decay of ε.

In order to derive generalizing relations for the decay of ε we use the characteristic form of the graphs $\varepsilon = f(x/H)$ and $\varepsilon = f(x/d)$, which evinces a power-law behavior. We therefore represent the measurement results by the expression

$$\varepsilon = f\left(\frac{x}{l} + \varepsilon_0\right),$$

in which $l \equiv H$ for a plane channel, $l \equiv d$ for circular channels, and ε_0 is the turbulence level in the flow core at the channel inlet.

The results of processing of the data from several series of tests are given in Fig. 3. It is evident in the figure that all the experimental data can be approximated by power-law relations, for which the deviation of the majority of the experimental data is not greater than ± 15%. It is important to mention the fact that ε_0 was determined from direct measurements for the plane channel. The value of ε_0 for the circular channels with turbulence promoters situated directly in the entrant cross section was interpreted as the value that would occur at the pipe inlet if it were assumed that the power-law dependence $\varepsilon = f(x/d)$ does not change as the entrant cross section is approached. Judging from the data obtained for the plane channel, this assumption is entirely justified.

An inspection of Fig. 3 reveals that the power exponent for $\varepsilon = f\left(\frac{x}{l} + \varepsilon_0\right)$ is a single-valued function of the turbulence level at the channel inlet, as is postulated in the generalization of the results. The fundamental analytical relation has the form

$$\varepsilon = \varepsilon_0 \left(\frac{\frac{x}{l} + \varepsilon_0}{\varepsilon_0} \right)^{-n}. \quad (1)$$

To determine the exponent n for plane channels it is necessary to use the dependence $n = f(\varepsilon_0)$ given in Fig. 4. The accuracy of approximation can be increased by generalizing the experimental data in intervals

$$n = 3.71 \cdot 10^{-3} (\varepsilon_0)^{1.41}, \quad 5\% \leqslant \varepsilon_0 \leqslant 35\%, \quad (2)$$

$$n = 0.113 (\varepsilon_0)^{0.45}, \quad \varepsilon_0 > 35\%. \quad (3)$$

In the interval $\varepsilon_0 > 35\%$ the computation of the turbulence decay according to expressions (1) and (3) in plane and circular channels must be regarded as approximate only. The trouble is that, for large flow-velocity fluctuations, automatic compensation of the time constant and compensation of the disturbance associated with the nonlinearity of the wire calibration curve in hot-wire anemometers with a constant wire temperature is unreliable [7]. The values of ε_0 at the inlet can be calculated, for example, according to [1, 2] or other data.

Relation (1) involves only the value of the turbulence level ε_0 at the channel axis in the entrant cross section. Consequently, this relation can be used for computations in every case where the value of ε_0 exists independently of the turbulence-generating configuration for the investigated turbulence promoters.

NOTATION

u, u', average and fluctuation values of longitudinal velocity component; $\varepsilon = \sqrt{u'^2}/u$, relative rms value of longitudinal component of velocity fluctuation; u_0, velocity at channel axis; r, variable radius; r_0, radius of pipe; y, coordinate normal to channel wall; H, height of channel; h = H/2; x, longitudinal coordinate; $Re = ud/\nu$, $Re_H = uH/\nu$, Reynolds numbers for circular pipes and plane channel.

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