EXPERIMENTAL STUDY OF TURBULENT FLOW IN A ROTATING CHANNEL

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Results are shown of measurements pertaining to the turbulence of flow in a short channel rotating about its axis.

Recent studies of the hydrodynamics and the heat transfer in rotating channels [1] have shown that, when a channel rotates about its geometrical axis, the hydraulic drag and the heat transfer rate within the turbulent flow region both decrease. The usual explanation for this is that the axially symmetrical centrifugal force field generated during rotation suppresses the turbulent velocity fluctuations. A weakening of the turbulence in rotating channels has also been confirmed by visual observations [2].

No data could be found by these authors pertaining to turbulence parameters of a discharge flow in a rotating channel. Only the turbulence structure of a purely circular stream, without axial flow, in an annular channel between two rotating coaxial cylinders has been measured so far [3, 4]. Here, when the outer cylinder rotates, a stabilizing effect of the centrifugal force field is also seen to suppress the turbulent fluctuations. However, the transverse profile of turbulence parameters is apparently different here than in a rotating short channel with discharge flow. Indeed, the centrifugal force field generated by the rotation of a cylinder becomes also a flow source and, in this way, such a rotation simultaneously generates and suppresses turbulence. The net effect of such a rotation on the distribution of turbulence parameters will depend on various factors: the cylinder speed, the distance from the cylinder surface, etc.

In this article we will report on a study of turbulent discharge flow in a short channel rotating about its axis.

The experiment was performed in an apparatus (Fig. 1) which includes, as the active component, a rotating short channel (l/D = 32) of circular cross section (D = 52 mm) and with smooth walls. The channel was mounted on two bearing supports and rotated by an electric dc motor through a V-belt drive. The bearings and the transmission had been designed for smooth and stable rotation of the channel up to 2000 rpm.

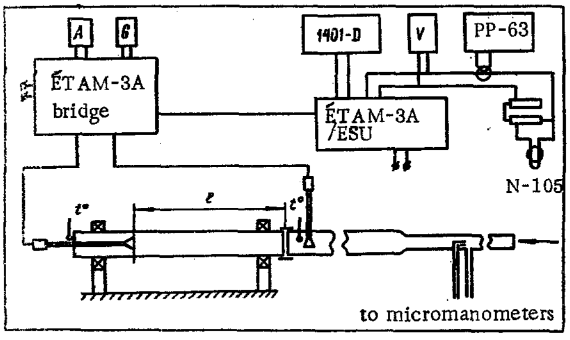

Fig. 1. Schematic diagram of the test apparatus.

The flow rate of air coming from a central system was measured with a pneumometer at the test segment of reduced diameter preceding the stabilization zone ahead of the rotating channel. The air temperature at the channel inlet and outlet was measured with a thermometer. The Reynolds number ranged from 4000 to 10,000.

The instruments for measuring the turbulence parameters included a model ÉTAM-3A electrothermoanemometer, a model ÉSU-2 amplifier, a model N-105 oscillograph, and a model 1401-D frequency spectrum analyzer. The thermoanemometer cups contained tungsten wires 20 μ in diameter and 4.0-4.5 mm long. A

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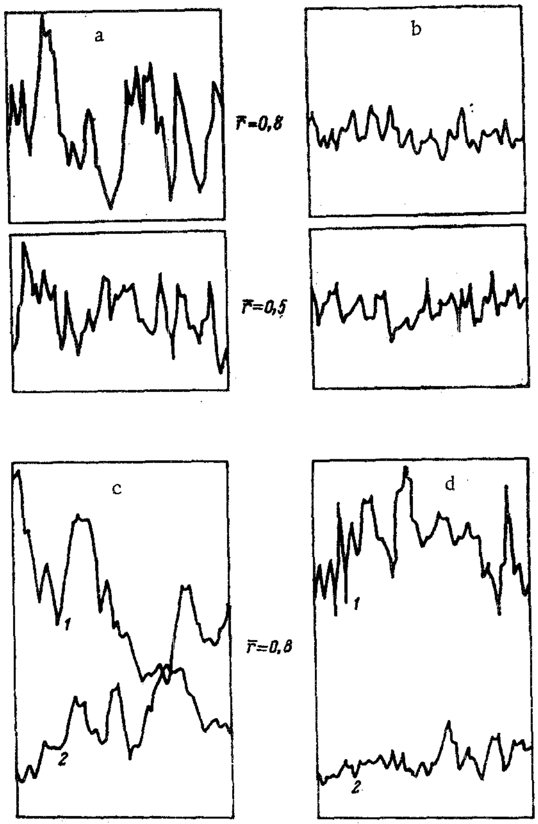

Fig. 2. Oscillograms of fluctuations: at the section $l/D = 27$ of the channel (a) at $n = 0$ rpm; (b) rotating at $n = 1500$ rpm (Re = 400 in both cases); (c) at $n = 0$; (d) at $n = 2000$ rpm in the stationary supply tube (1) and in the channel (2) (Re = 5000 in both cases).

thermoanemometer cup was inserted into the rotating channel from the open end with the aid of a pentograph.

Conventional methods of measurement with single-wire cups situated in various section planes are hardly adequate for separating the components of the velocity vector fluctuations in a rotating channel. For this reason, we did not separate the fluctuation components during the first stage of testing, but only studied the effect of rotation on the flow fluctuations by means of a tapered cup with wire lying on the φz-surface for picking up simultaneously the axial and the radial velocity fluctuations W'_z, W'_r. We note that studying the effect of a centrifugal force field on the turbulence parameters must, in principle, be conducted under conditions of relative motion and that this requires rotating the thermoanemometer cup. On account of the technical difficulties involved in such an arrangement, however, all measurements during the first of testing were made with a stationary cup.

In Fig. 2a, b are shown typical oscillograms of velocity fluctuations recorded on the model N-105 oscillograph in the test channel at $n = 0$ and $n = 2000$ rpm. During a rotation of the channel, evidently, the turbulent fluctuations decrease and especially so near the channel wall.

For measuring the fluctuation intensity, a model TVB-5 thermo-vacuum converter had been connected to the output of the ÉSU-2 thermoanemometer amplifier. The fluctuation intensity was estimated from the thermal emf of the converter, since that emf was proportional to the rms value of the fluctuations picked up by the thermoanemometer wire. Qualitative data pertaining to the effect of rotation on the fluctuation intensity are shown in Fig. 3, indicating both the radial and the axial profile of the relative fluctuation intensity in the stream (the relative fluctuation intensity is defined here as the ratio of the fluctuation intensities at a given point in the stream with the latter rotating or not rotating).

It can be seen here that the relative fluctuation intensity in a rotating stream decreases along the channel radius and decreases more at sections farther away from the channel entrance.

The stronger attenuation of turbulence along the channel could also be tracked by measuring the coefficient of correlation between fluctuations picked up by the thermoanemometer cups both in the rotating channel and in the preceding it stationary tube. The coefficients of spatial correlation between fluctuations at the entrance and those at farther sections of the rotating channel at distances $l/D = 22$, 24, and 27 were 0.75, 0.67, and 0.26, respectively, at a channel speed of $n = 1000$ rpm and with a Reynolds number Re = 5000 (the cups were located at the radius $\bar{r} = 0.8$).

In order to check the extent of "upstream" laminarization, we simultaneously recorded the fluctuation oscillograms at two cup locations: one inside the rotating channel and one in the preceding it stationary stabilization segment. An analysis of the oscillograms (Fig. 2c, d) has shown that within the stationary segment the turbulence remained independent of both the channel rpm and the extent of laminarization in it. Thus, turbulent fluctuations are suppressed only within the range of the centrifugal force field and not farther upstream.

The frequency spectrum of turbulent velocity fluctuations was measured with a model 1401-D analyzer at the output of the thermoanemometer amplifier. In Fig. 4 is shown the frequency spectrum of turbulent flow fluctuations in the channel at $n = 0$ and $n = 2000$ rpm. According to the graph, during rotation there occurs a shift of the maximum amplitude toward higher frequencies. This indicates that rotation suppresses mostly the low-frequency large-scale fluctuations.

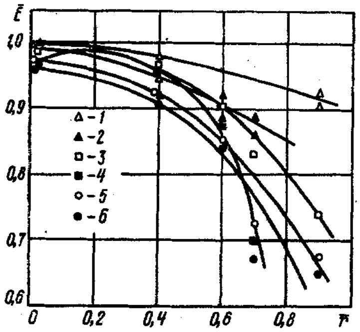

Fig. 3

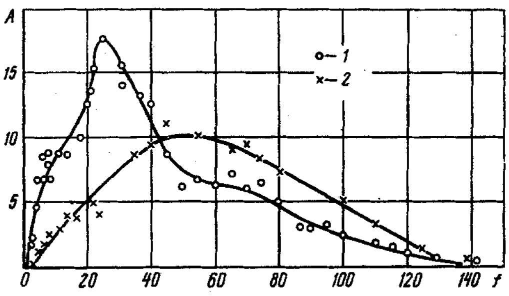

Fig. 4

Fig. 3. Radial and axial profiles of the relative fluctuation intensity $\bar{E}$ in the channel (Re = 4500). At l = 22D and 1) n = 1500 rpm, 2) n = 2000 rpm; at l = 24D and 3) n = 1500 rpm, 4) n = 2000 rpm; at l - 27D and 5) n = 1500 rpm, 6) n = 2000 rpm.

Fig. 4. Frequency spectrum of turbulent fluctuations (Re = 4000, l/D = 27, $\bar{r}$ = 0.8), at 1) n = 0; 2) n = 2000 rpm; amplitude A (%), frequency f (Hz).

The last finding is very important. It suggests a hypothesis that the nonuniformity of the body force field [1] plays the predominant role in determining the effect of rotation on the turbulence structure. When large-scale fluctuations are suppressed foremost by rotation, then the centrifugal forces become more nonuniform (this nonuniformity is measured in terms of the difference between the centrifugal forces at two points in the stream separated by a distance equal to the characteristic dimension corresponding to the fluctuation scale).

Taking into account the predominant role played by the nonuniformity of the body force field with regard to its effect on the turbulence structure, one may conclude that the way the suppression of turbulent fluctuations is distributed in a rotating channel depends on the initial distribution of the turbulence scale and on the centrifugal field intensity. In long channels with a taper formed according to the rigid body mode, the profile of centrifugal field intensity is linear and the profile of turbulence suppression across a channel section depends solely on the turbulence scale and, therefore, the central region with the largest eddies should become laminarized first [5]. In short channels, where the liquid has not yet formed a taper, the intensity of the centrifugal force field is not linear: the forces increase along the radius, but only slightly in the mainstream and very rapidly near the wall (up to a magnitude $\rho\omega^2 R$, with R denoting the channel radius). The profiles of fluctuation intensity, which have been obtained in our tests and are shown in Fig. 3, indicate that the intensity profile of the centrifugal force field plays the decisive role in short channels. The volume of liquid develops a taper in long channels and, therefore, the effect of rotation on the turbulence becomes stronger here.

We note that, since the scale of turbulent fluctuations decreases as the Reynolds number becomes higher, the suppression of turbulent fluctuations by centrifugal forces will be most effective at low values of the Reynolds number.

It has been possible in our tests to obtain qualitative data concerning the effect of rotation on the turbulence characteristics of discharge flow. Further studies, including separate measurements of the fluctuation components, should make it possible to establish a quantitative relation and to more thoroughly analyze the structure of a turbulent stream in rotating channels.

NOTATION

ω	is the angular velocity of channel rotation;
$\vec{r}$	is the radius-vector;
λ	is the friction coefficient;
$Re = WD/\nu$	is the Reynolds number;
W'_r and W'_z	are the radial and the axial components of velocity fluctuations;
r	is the local radius;
φ and z	are the angular and the axial coordinates;
ρ	is the density of a liquid;
R	is the channel radius;

$\bar{r} = r/R$ is the relative radius;
L and D are the channel length and diameter;
n is the channel rpm;
l is the distance from channel entrance to place of measurement;
$\bar{E}$ is the relative fluctuation intensity;
A and f are the fluctuation amplitude and frequency.

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