SOME RESULTS OF AN EXPERIMENTAL INVESTIGATION OF THE STRUCTURE OF A TURBULENT STREAM OF CONDUCTING LIQUID

B. A. Kolovandin

Inzhenerno-Fizicheskii Zhurnal, Vol. 10, No. 5, pp. 567–572, 1966

UDC 532.517.4

Results are presented of an investigation, made with the aid of an induction anemometer, of some characteristics of a turbulent stream of electrically conducting liquid in an open channel. External magnetic and electric fields are applied to the flow. It has been observed that the flow structure is appreciably affected by the Lorentz force normal to the channel floor. The characteristics obtained are compared with experimental results for an ordinary liquid.

1. The experimental problem. The object of this research was to investigate certain features of the turbulent motion of an electrically conducting liquid in an open channel (trough) with a magnetic field applied to the flow and with current supplied by conduction to the liquid from an external source. The investigation of the structure of this type of flow stemmed, on the one hand, from the need to solve a number of technical problems [1] and, on the other hand, from the possibility of broadening certain ideas about magnetohydrodynamic turbulence in general.

We have compared the results obtained with previous experimental turbulence characteristics [2] for ordinary channel flows with the object of making an experimental check on the effect of magnetic and electric fields on flow structure. An additional aim of the experiment was to investigate the distortion of mean velocity profile under the influence of the Lorentz force directed transverse to the flow.

A final aim was to verify the usefulness of the induction anemometer [3] in investigating the structure of magnetohydrodynamic turbulent flows.

2. Experimental setup. The subject of investigation was a turbulent stream of electrically conducting liquid in a rectangular channel, the working section being located in a comparatively strong magnetic field. In some of the tests the flow was subjected, in addition to a magnetic field, to the influence of an electric field, supplied by conduction from an external source.

A plane view of the setup is shown schematically in Fig. 1. The basic part is a closed liquid circuit, the working section of which was a rectangular channel with mirror-smooth walls. This was connected via a convergent inlet channel to a supply reservoir, located at 2.5 m from the beginning of the working section. After passing through the working section, the liquid was returned to the supply reservoir by means of a pump.

It was assumed that the comparatively long length of channel between the convergent section and the working section was sufficient for the flow to be considered fully developed at the entrance to the magnetic field.

The working liquid used was one of the strongest electrolytes—30% aqueous solution of sulfuric acid, with conductivity $\sigma \simeq 70\ (\text{ohm}\cdot\text{m})^{-1}$. In conducting the tests, special attention was given to maintaining the purity of the electrolyte; with this in mind, the whole of the liquid system was made of plastic and ceramic.

The working section of the channel was located in the magnetic field generated by a dc U-type electromagnet.

The movable poles of the magnet allowed control of the gap in the range 5–20 cm. The magnet had pole tips of cross section 90 × 10 cm, permitting a magnetic field to be generated over 70 cm of the working section in the flow direction, with field nonuniformity not exceeding 2.5%. The excitation windings of the magnet were supplied from dc generators of total power 120 kW, the alternating current component in

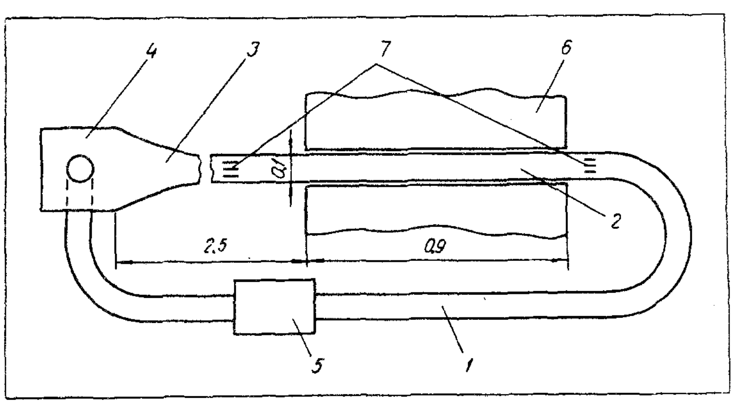

Fig. 1. Experimental setup: 1) general circuit; 2) working section; 3) convergent entrance section; 4) supply reservoir; 5) pump; 6) electromagnet; 7) electrodes.

the windings being removed by parallel capacitors of about 1000 μF. The magnetic induction B_0 in the 10 cm gap could be varied in the range 0–1.3 Wb/m^2.

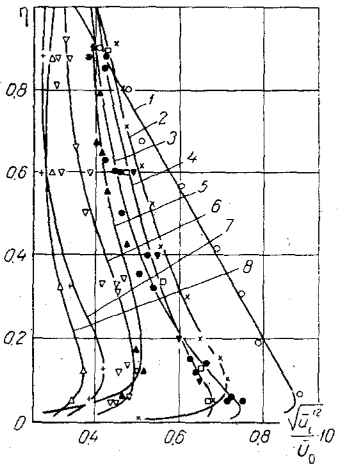

Fig. 2. Distribution across the stream of the rms longitudinal $\sqrt{\overline{u'^2}}$ and transverse $\sqrt{\overline{v'^2}}$ fluctuation velocities referred to the velocity at the free surface ($\sqrt{\overline{u_i'^2}}/U_0$ is the relative intensity of the i-th velocity fluctuation): 1) $\sqrt{\overline{u'^2}}$ for the tests of [2] for a channel with R = 20 · 10^3; 2) the same for a flat tube at R = 80–400 · · 10^3; 3) and 4) the same in our tests for a channel with $\gamma = 0.64 \cdot 10^{-2}$ and δ of 0 and 0.11, respectively; 5) $\sqrt{\overline{v'^2}}$ according to the tests of [2] for a channel with R = 20 · 10^3; 6), 7), and 8) the same according to our tests, with $\gamma = 0.64 \cdot 10^{-2}$, and δ of 0, 0.11, and 0.16, respectively.

The magnet, being rigidly connected to the main part of the liquid system, had a special rotary mount to permit it to be aligned at the requisite angle to the flow. In addition, there was provision for control of liquid level in the channel at an assigned value. In our tests the mean flowrate of the liquid was $4 \cdot 10^{-3}$ m^3/sec, at a mean liquid level of $\overline{H} = 5$ cm.

In a number of tests an electric current was supplied externally to the flow, in addition to the magnetic field. Supply of current by conduction was accomplished by means of electrodes connected to a storage battery. The current density J_0 of the external source was varied in the limits $0–1.5 \cdot 10^3$ A/m^2.

Thus, the flow tested had the following parameters: Reynolds number $R = \overline{U}_m \overline{H}/\nu = 40–50 \cdot 10^3$; Hartmann number $M = \sqrt{\sigma/\rho\nu}\, B_0 \overline{H} = 15–20$; Stewart number $\gamma = M^2/R = 5–8 \cdot 10^{-3}$; electromagnetohydrodynamic interaction parameter

$$\delta = J_0 B_0 \overline{H}/\rho U_m^2 = 0.02-0.28.$$

During the tests measurement was made of the mean longitudinal velocity, the root mean square values of the longitudinal and transverse components of fluctuation velocity, and of their one-point correlation. The measurements were made at a distance of 70 cm from the beginning of the magnetic field, in a plane symmetrically located with respect to the side walls of the channnel.

Measurement of the mean longitudinal velocity was performed using a glass Pitot-Prandtl tube of diameter 4 mm. Velocity measurements in a horizontal plane showed that the velocity in the central region was practically constant. This allowed us to consider that the influence of the side walls on the velocity distribution in the mean vertical plane was very slight.

The flow structure was investigated with the help of our own induction anemometer.*

3. Experimental results. The tests were carried out with a fixed direction of the magnetic field and with the external-source current oriented upstream or downstream. Then the Lorentz force was directed toward the floor or to the free surface.

The influence of the electromagnetic forces on the intensity of velocity fluctuations may be judged from the graphs of Fig. 2, where it may be seen that the data of our tests for $\sqrt{\overline{v'^2}}$ at $\delta = 0$ and of the tests of [2] near the floor ($\eta = y/\overline{H}$ small, y being the vertical coordinate) coincide, while near the free surface ($\eta \simeq 1$) our results are somewhat low. No results for different values of γ are shown in the graph in question, nor in subsequent graphs; this stems from the fact that the maximum value of Stewart number in our tests was $\gamma = 0.8 \cdot 10^{-2}$, and the test results with $0.6 \cdot 10^{-2} < \gamma < 0.8 \cdot 10^{-2}$ practically coincide. The curves for the cases $\delta = 0.11$ and $\delta = 0.16$ at $\gamma = 0.64 \cdot 10^{-2}$ indicate that the application of the Lorentz force to the flow from without, directed toward the floor of the channel, leads to damping of the velocity fluctuations.**

The same figure shows the distribution across the section of the intensity of longitudinal fluctuations for $\delta = 0$ and $\delta = 0.11$ with $\gamma = 0.64 \cdot 10^{-2}$. For comparison, Minskii's test results are shown for a flat tube and a rectangular channel. It may be seen that at $\delta = 0$ our results, as is also the case for the transverse fluctuations, are somewhat low in comparison. With $\delta = 0$ and the previous value of γ, an increase of longitudinal fluctuation intensity is observed over almost the entire flow. The data of the tests with $\delta = 0.16$ are not shown on the graph, since they practically coincide with the results for $\delta = 0.11$.

Thus, when a Lorentz force directed toward the floor of the channel acted on the turbulent stream, in the range of δ examined, we observed a decrease in the transverse, and an increase in the longitudinal, velocity fluctuations, the degree of reduction of the

*Matters pertaining to the flow structure characteristics investigation technique were examined in [3].

**We did not examine the influence of Lorentz forces in the opposite direction.

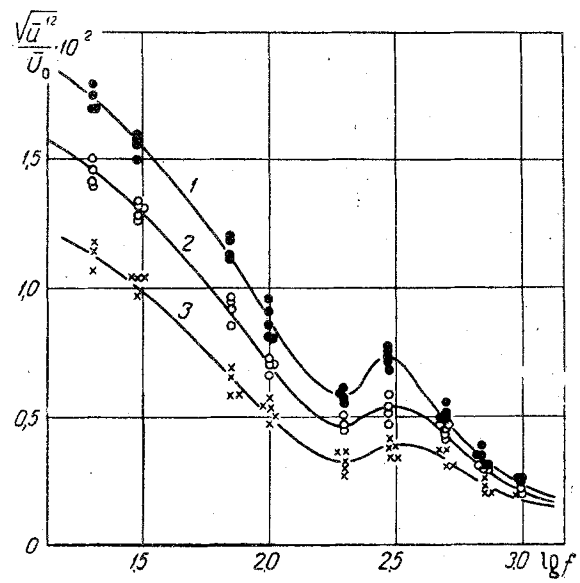

Fig. 3. Distribution of relative intensity of longitudinal velocity fluctuations with their frequency f (cps) for various points across the flow with $\delta = 0$, $\gamma = 0.64 \cdot 10^{-2}$ and the dimensionless coordinate $\eta = 0.06$ (1), 0.33 (2) and 0.88 (3).

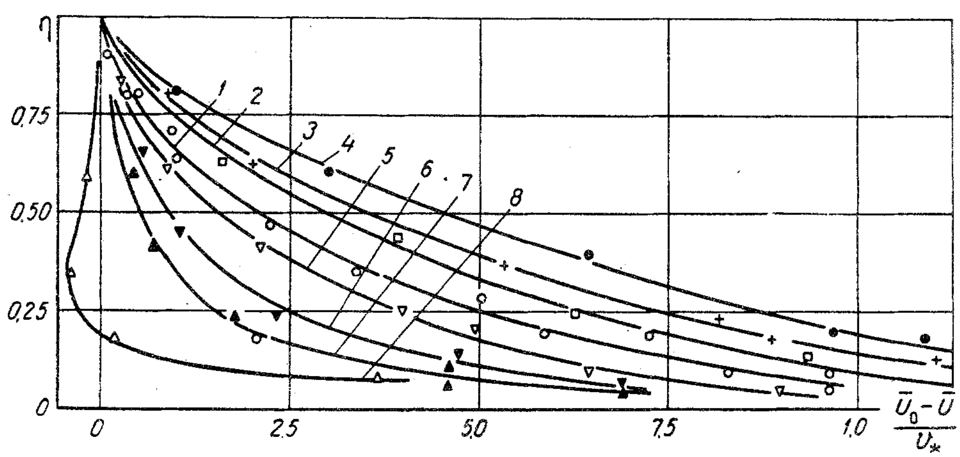

Fig. 4. Distribution of mean velocity in a vertical plane with $\gamma = 0.9 \cdot 10^{-2}$ and $\delta = 0$ (1), 0.12 (2), 0.175 (3), 0.28 (4), −0.08 (5), −0.12 (6), −0.175 (7) and −0.28 (8) ($(\overline{U}_0 - \overline{U})/v_*$ is the dimensionless velocity defect).

former predominating over the degree of growth of the latter.

It may easily be seen from Fig. 3 (the range of frequency from 20 cps to 1 kc was investigated) that the main contribution to the turbulence intensity is that of low-frequency fluctuations, the intensity of velocity fluctuations increasing in the direction from the free surface toward the floor, in the whole frequency range investigated. It is interesting that the decrease of energy of the fluctuations from the low frequencies to the higher does not proceed monotonically, the curves having an extremum at a frequency of approximately 200 cps.

In addition to the velocity fluctuation intensity, a distribution across the flow was obtained for the Reynolds friction stresses $\rho u'v'$. Graphical differentiation of the mean velocity profile and use of the results of measurement of the one-point correlation of longitudinal and transverse fluctuations enabled us to determine the distribution of friction stress. The values of friction stress on the floor for various values of parameter δ were found by using a graph of distribution of friction stress across the flow, by means of extrapolation of the appropriate results. In particlular, when $\gamma = 0.64 \cdot 10^{-2}$ and $\delta = 0$, we obtained $\tau_W/\rho = v_*^2 = 19.5 \cdot 10^{-4}$ m^2/sec^2. Analysis of Fig. 4 shows that when a vertically directed Lorentz force is applied to the stream, either the velocities across the channel become equal, or a less full (in comparison with the case $\delta = 0$) velocity profile ensues. In the first case the electromagnetic force is directed toward the free surface, and in the second—toward the floor.

The results presented show that the application to a stream of conducting liquid with a free surface of combined magnetic and electric fields may effect an appreciable change of flow structure features. A necessary condition in this situation is the presence of velocity fluctuations at the free surface.

NOTATION

$\overline{U}$—mean velocity, m/sec; $\overline{U}_0$—velocity at free surface; $v_* = \sqrt{\tau_W/\rho}$ —dynamic velocity, m/sec; τ_W—friction stress at wall, kg/m · sec^2; $\sqrt{\overline{u'^2}}$, $\sqrt{\overline{v'^2}}$ —RMS values of longitudinal and transverse velocity fluctuations, m/sec; $\overline{u'v'}$—one-point correlation of velocity fluctuations, m^2/sec^2; $\overline{U}_m$—flow velocity, m/sec; B—magnetic induction, Wb/m^2; J—external source current density, A/m^2; $\overline{H}$—ordinate of free surface, m; ρ—density, kg/m^3; ν—kinematic viscosity, m^2/sec; $\eta = y/\overline{H}$—dimensionless vertical coordinate; $\sqrt{\overline{u_i'^2}}/\overline{U}_0$ —relative intensity of i-th velocity fluctuation; lg f—natural logarithm of fluctuation frequency; f—frequency, cps.

REFERENCES

1. Technical Electromagnetic Hydrodynamics, Proc. of Conference on Application of Electromagnetic Hydrodynamics to Industry [in Russian], Izd. "Metallurgiya," Moscow, 1965.

2. E. M. Minskii, Tr. TsAGI, no. 625, 1947.

3. N. I. Bolonov, B. A. Kolovandin, I. L. Povkh, and E. F. Skrinnik, Izv. VUZ. Energetika, no. 1, 1966.

20 December 1965

Donetsk Institute of Ferrous Metallurgy