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EXPERIMENTAL INVESTIGATION OF A FREE SHEAR FLOW WITH TWO-DIMENSIONAL TURBULENCE STRUCTURE IN A TRANSVERSE MAGNETIC FIELD

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Averaged and fluctuating characteristics of a plane jet flow without any longitudinal pressure gradient in a strong magnetic field were investigated. It was shown that the originated turbulence is two-dimensional and of great strength. The intensity and direction of the momentum and energy transfer processes in the flow cross-section were analyzed using the data on the distributions of the longitudinal and transverse velocity fluctuation strengths, of the Reynolds shear stresses, of the turbulence energy generation, and of the asymmetry coefficient of the turbulent perturbations.

Introduction. Based on the method of their formation, the free turbulent MHD shear flows in a transverse magnetic field provisionally can be separated into two classes. The first of these encompasses the plane-parallel and rotating flows which are producible by means of the interaction between a nonuniformly distributed electric current transversely passing through the fluid and an external magnetic field [1-3]. The second class is made up of flows, which are produced by the nonuniform conductivity of the walls which are perpendicular to the field [4-6]. Both classes combine a generality of mechanisms of forming the shear flow structure, since in the first case the nonuniform distribution of the current flowing through the fluid, and in the second case, the nonuniform distribution of the induced currents in the zones where the wall conductivity is changing, give rise to vorticity along the magnetic field. At large Hartmann numbers, the generated vorticity forms two-dimensional nonuniform flows in a plane that is perpendicular to the field whose thickness is proportional to $Ha^{-1/2}$. Such flows are very unstable [1, 3] and at large Reynolds numbers generate large-scale two-dimensional turbulence in a plane perpendicular to the field [2, 4-6].

The instability of a plane-parallel jet-type flow, which has an initial perturbation development segment, as a function of the magnetic field has been investigated in [1]. The investigators showed that in a strong field such flow is characterized by the Kelvin—Helmholtz two-dimensional instability with a high intensity level of the two-dimensional perturbations.

In the present report we present the data from experimental flow investigations [1] at large Reynolds numbers in a strong magnetic field. We investigated the structures of the averaged and the fluctuating flows, the third-order moments for the longitudinal and transverse velocity fluctuations, the distributions of the shear stresses, and the production of the turbulent energy.

1. The Experimental Facility and the Measurement Methodology. The experiments were performed in an open, insulated channel whose length and width were 500 and 40 mm, respectively (Fig. 1). Two rectilinear copper electrodes (with a b_0 = 10 mm distance between them) having length l = 530 mm and 1 mm width were installed at the bottom of the central channel portion. These electrodes were used to pass a constant electric current I $\leq$ 50 A across the fluid in the transverse direction. Two wide, open by-pass channels, which provided for an influx of the fluid having passed through the test section of the channel into its entry, were symmetrically arranged on both sides of the channel. The entire facility was filled with an InGaSn eutectic melt to a height h = 50 mm and was placed in a DC electromagnet producing an induction B $\leq$ 1.45 T with a 150-mm gap. The physical characteristics of the eutectic melt at T = 20°C were: density ρ = 6,400 kg/m^3, kinematic viscosity $\nu = 34\cdot 10^{-7}$ m^2/s, and electrical conductivity $\sigma = 3.46\cdot 10^6\ \Omega^{-1}\cdot\mathrm{m}^{-1}$.

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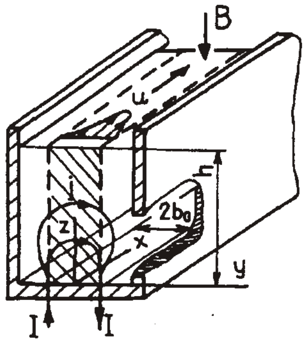

Fig. 1. Schematic of the experiment.

As in [1], the flow was induced by the interaction of the electric current flowing through the fluid with the external magnetic field (Fig. 1). Since the supplied electric current is uniformly distributed along the length of the electrodes, the electromagnetic force producing the flow does not vary along the duct. As a result, a jet-like flow is developed without any longitudinal pressure gradient. In a strong magnetic field, the motion-produced EMF in the flow core almost completely offsets the applied electric field. Because of that, the supplied current is displaced into the Hartmann boundary layer on the wall which is perpendicular to the field and the lateral free shear layers parallel to the field. The small currents flowing within the flow beyond the mentioned layers produce forces which offset the frictional forces in its core.

The averaged velocities and the strength of the velocity fluctuation components were measured by the conductive anemometer method with a four-electrode sensor. The sensor electrodes were made from a 0.25-mm diameter insulated copper wire. The electrode ends were in electrical contact with the liquid metal. Two electrodes which measured the longitudinal velocity component were placed across the flow, while two others, measuring the transverse velocity component, were arranged along the flow. The distance between the electrodes in both cases was 1.8 mm. In the averaged velocity measurements, the signal from the sensor was fed into a DC amplifier having a $3 \cdot 10^{-6}$-1 V measurement range. In the velocity fluctuation intensity measurements two amplifiers were used with a $3.3 \cdot 10^5$ amplification coefficient and a 0.07-μV noise level. A special positioning device allowed one to move the sensor both transversely and along the flow.

The following dimensionless parameters were used in the processing of the measurement results: the Reynolds number $Re = Vb_0/\nu$, where $V = 1/2L(\sigma\mu)^{1/2}$, and L is the electrode length, the Hartmann number $Ha = Bb_0(\sigma/\mu)^{1/2}$, and the MHD interaction parameter $N = Ha^2/Re$.

The results presented below were obtained in a B = 1.45 T magnetic field, which corresponds to Ha = 412.

2. Results of the Investigations. The considered flow is a flow without any longitudinal pressure gradient; therefore, the velocity distributions at various cross-sections along the flow, with the exclusion of $x/b_0 = 4$, practically coincide. Here the nondimensionalizing of the local velocities was made with respect to the value of the maximum velocity $U_m = 22.6$ cm/s which for $x/b_0 \geq 2$ remained constant along the entire flow length. In the $x/b_0 = 1$ cross-section, U_m was 21.12 cm/s. From the shape of the averaged velocity profile it can be concluded that the development of the averaged flow structure is completed at the cross section $x/b_0 = 8$. As in the annular analog [2], in the present flow the distribution of the velocities in the magnetic field direction differs from a uniform one approximately by 10% (Fig. 2b). Thus, in the given magnetic field, a submerged two-dimensional jet-type flow with free shear layers, which are elongated along the field, is formed in the channel. It is known that such flows (similar to a flow in the wake behind a cylinder with the axis parallel to the field [7]) are highly unstable and at large Re generate two-dimensional perturbations of considerable strength. It is precisely the presence of the inflection points in the velocity profiles that creates the condition for producing such turbulent perturbations along the flow length.

It is evident from Fig. 3 that as the Reynolds number is increased, the fluctuation intensities of the perturbed flow, referred to the corresponding U_m values in the developed flow segment, increase threefold. The marked rise in the perturbed flow strength is related to the two-dimensional structure of the produced perturbations, since the two-dimensional perturbations, unlike the three-dimensional, are not subject to a strong Joule dissipation. At the various Re numbers the intensities of the longitudinal velocity fluctuations have a pronounced minimum on the flow axis and maxima on the averaged velocity gradients in the inflection point regions (Fig. 3a and 2a), i.e., in the regions, where, as will be shown below, the Reynolds stresses reach the maximum value. This agrees with the point of view which assumes that in flows with velocity shear the energy from the mean flow is transferred to the fluctuating motion through the longitudinal fluctuation velocity component. Thereafter this energy is redistributed between the other components and in the present case, between the longitudinal and the transverse

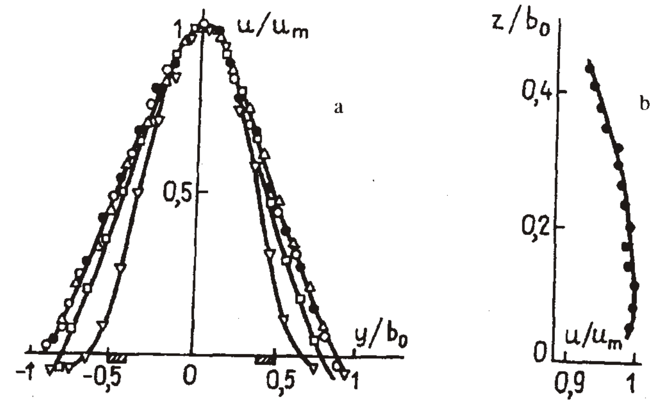

Fig. 2. Profiles (along the y-axis) of the averaged longitudinal relative velocity u/u_m at x/b_0 = 4 (▿), 8 (□), 18 (▵), 38 (•) and 47 (o) (a); (b) — the same, along the magnetic field direction at x/b_0 = 38; Re = 7,680.

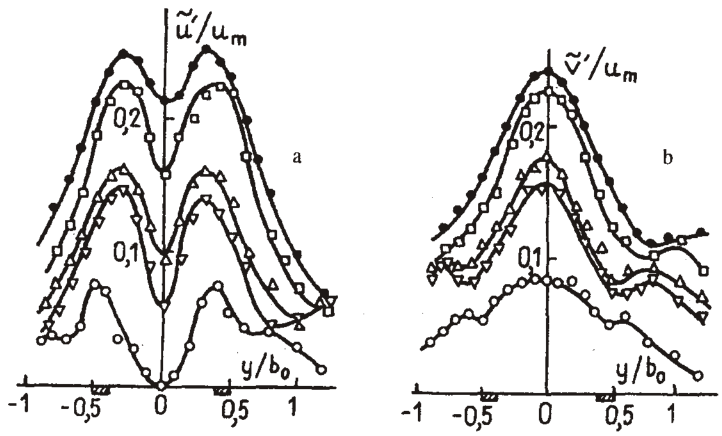

Fig. 3. Profiles of the longitudinal (a) and the transverse (b) velocity fluctuation intensities at x/b_0 = 38 and at the following u_m (cm/s) and Re: 2.26 and 768 (o), 4.54 and 1,536 (▿), 6.78 and 2,304 (▵), 13.56 and 4,610 (□), and 22.6 and 7,680 (•).

fluctuations. A comparison of the intensity distributions of the longitudinal (Fig. 3a) and the transverse (Fig. 3b) velocity fluctuations for all the presented Re numbers also indicates a generation of large-scale perturbations with a transverse scale that is comparable to the flow width and which are elongated along the magnetic field.

This is confirmed by the measurement of the double-point correlation coefficient in the magnetic field direction which was made with the aid of two sensors and by the visualization of the free fluid surface. For a correlation distance $\Delta z/b_0 = 4$, the correlation coefficients values were R_{uu}, R_{vv} = 0.9 while large vortical structures were observed on the free surface. For an MHD interaction parameter N > 1, in the two-dimensional turbulence the relation between the ratio of the scales of perturbations along the field to the transverse scale and N is expressed as $l_{\parallel}/l_{\perp} = k\sqrt{N}$. In the present case, N = 22.1 and $k \approx 1.06$.

The characteristics of the turbulence development in the flow direction for a fixed Reynolds number are explained by the data presented in Fig. 4. In the cross section x/b_0 = 1, the strength of the longitudinal and transverse fluctuations does not exceed 0.5% of the U_m = 21.12 cm/s value in that cross-section (Fig. 4a), i.e., a practically unperturbed flow of fluid enters the channel. In the cross section x/b_0 = 4, where the flow still goes through the formation stage, in spite of the large velocity gradients (see Fig. 2a), the production of perturbations is insignificant, and the fluctuation strength amounts only to 4%. Further downstream, the fluctuation strength rises and at $x/b_0 \geq 6$ the strength distributions of both fluctuation components reach 25% of the maximum flow velocity (see also Fig. 3, curves 5). The nature of the perturbation development along the flow is explainable by the oscillograms (see Fig. 4b). Indeed, in the cross section x/b_0 = 1 there are practically no velocity

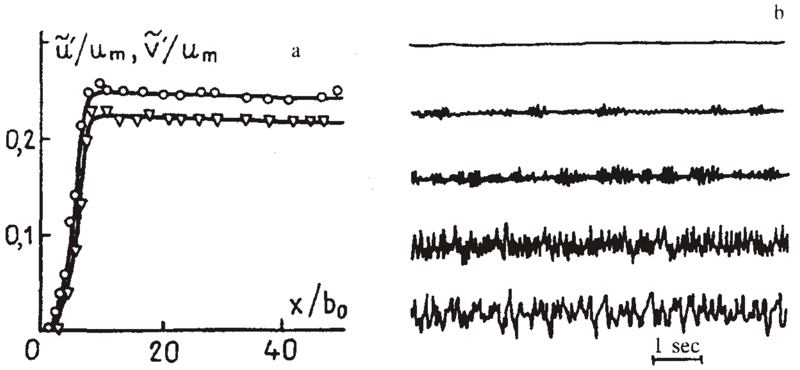

Fig. 4. Distributions of the longitudinal $\tilde{u}'/u_m$ (o) and transverse $\tilde{v}'/u_m$ (▿) velocity fluctuation strengths along the longitudinal channel axis (a) and the oscillograms of the transverse velocity fluctuations at $y/b_0 = 0$ at various channel cross-sections from top to bottom for $x/b_0 = 1, 2, 3, 6$, and 38, respectively (b).

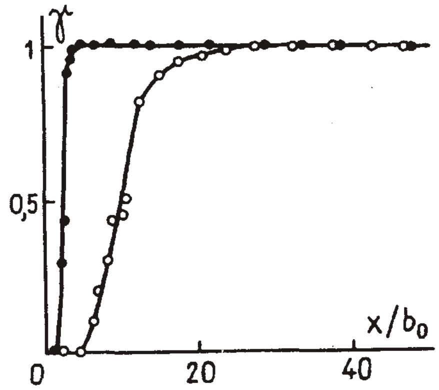

Fig. 5. Dependence of the intermittence coefficient on the longitudinal coordinate for Re = 768 (o) and 7680 (•).

perturbations. Starting at the cross section $x/b_0 = 2$, quasi-periodic fluctuations appear in the flow in the form of discrete wave packets. Within the segment $x/b_0 = 3$-6, the oscillograms indicate an interaction of these fluctuations. Their strength grows from 0.01 to 0.142 (Fig. 4a). In the cross section $x/b_0 = 6$ and further downstream, the fluctuations display a continuous random characteristic and have the above-mentioned constant maximum strength level. The shape of the oscillograms shown for $x/b_0 = 38$ correspond to these fluctuations.

The oscillograms, which were obtained at the various cross-sections along the flow, allowed one to determine the velocity fluctuation intermittence coefficient γ as a ratio of the fluctuation observation time and the total signal realization time. It follows from the distributions presented in Fig. 5 that in the turbulent regime (curve 1) the γ coefficient in the perturbation development segment $x/b_0 = 1$-6 changes from zero to one. It is noteworthy that when the degree of supercriticality is low, $Re/Re_{cr} = 1.2$ (curve 2) the perturbation development segment is markedly longer, with the coordinate at which the perturbations begin to rise being shifted downstream (see also [1]). If the Reynolds number is calculated using the longitudinal coordinate, as is done when investigating the transition to turbulence in a boundary layer on a plate with a sharp leading edge, then for both presented Re numbers the ratio of the lengths of the segments, where γ increases to one, is found to be ten. In other words, a tenfold velocity increase in the present experiment resulted in an initial segment reduction by the same ratio. Practically, this means that as the Re number is increased, the velocity perturbation propagates upstream and consequently, the point of the transition to turbulence is shifted toward the initial cross-section. Because of that, the initial perturbation growth segment is shortened.

The shear flow turbulization essentially depends on the strength of the turbulent diffusion between the layers of the fluid which is accompanied by the ejections of turbulent fluid masses from the flow regions with smaller velocities into those

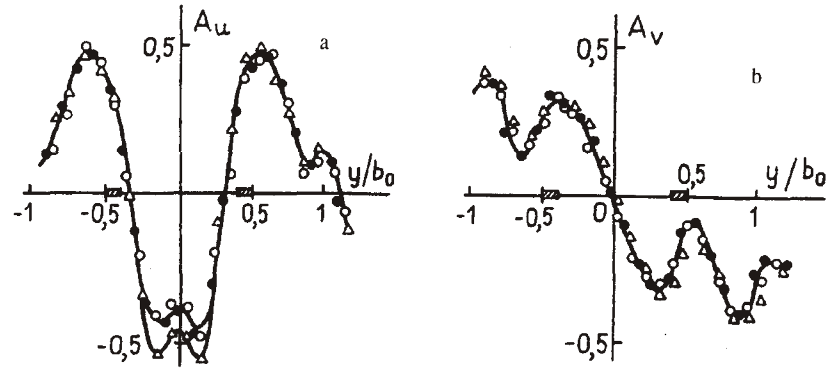

Fig. 6. Distributions (along the y-axis) of the asymmetry coefficients of the longitudinal A_u (a) and transverse A_v (b) velocity fluctuations in the cross-sections at $x/b_0 = 18$ (△), 38 (•), and 47 (○) at Re = 7,680.

with higher velocities, and conversely. Such transfer process for the present flow is governed by the asymmetry coefficients of the longitudinal and the transverse velocity fluctuations

$$A_u = \overline{u'^3}/(\overline{u'^2})^{3/2},\ A_v = \overline{v'^3}/(\overline{v'^2})^{3/2},$$

which may be either positive or negative quantities [8]. It is evident from the distributions shown in Fig. 6a that in the outer developed flow regions the A_u coefficient is positive, which points to an intrusion of accelerated fluid from the near-axis region into these regions. On the other hand, in the region close to the axis, the A_u coefficient becomes negative, i.e., this region receives incursions of decelerated fluid from the outer flow regions. In the zones where $A_u = 0$, the appearances of longitudinal velocity fluctuations with different signs are equally probable. The strength of the longitudinal velocity fluctuations produced by the flow in these zones must reach the maximum value. In fact, as follows from Fig. 3a, at the locations where $A_u = 0$, the strength of the velocity fluctuations is at its maximum.

The deviant characteristic of the transverse velocity fluctuations (Fig. 3b) determines different behavior of the A_v coefficient (Fig. 6b). On the flow axis, where the transverse fluctuations are the greatest, the coefficient $A_v = 0$, which corresponds to an equal likelihood of the appearance of transverse fluctuations with different signs in the flow plane of symmetry. It is typical that in the zones where $|A_v|$ has maximum values, $A_u = 0$ or is close to zero (Fig. 6a). Consequently, in the indicated zones the strongest energy exchange occurs between the longitudinal and the transverse velocity fluctuations, which, as noted above, the perturbations receive from the averaged flow through the longitudinal fluctuations. The symmetrical and antisymmetrical nature of the A_u and A_v distributions is caused by the coincidence and difference in the phase relations for the longitudinal and transverse velocity fluctuations, respectively, from the right-hand side and from the left of the flow symmetry plane. We also note that the symmetry coefficients measured in the various cross-sections along the developed flow are practically the same.

We next consider the third-order moments of the velocity fluctuations $\overline{u'^2v'}$ and $\overline{v'^2u'}$, related to the turbulent transfer processes. These correlations characterize the transfer of the energy of the longitudinal fluctuations $\overline{u'^2}$ in the transverse direction and of the transverse fluctuations $\overline{v'^2}$ in the longitudinal direction. The results from the measurements of these quantities are presented in Fig. 7 in dimensionless form:

$$K_u = \overline{u'^2v'}/(\overline{u'^2})^{3/2};\ K_v = \overline{v'^2u'}/(\overline{u'^2})^{3/2}.$$

It follows from the distribution of the K_u coefficient that the energy of the longitudinal velocity fluctuations is transported from the zone of their maximum strength, where $K_u = 0$ (see also Fig. 3a) in various directions toward the axis and to the flow periphery. This is indicated by the sign change of K_u in these zones to the right and left of the $y/b_0 = \pm 3.5$ coordinate. We note that the largest transfer of energy of the longitudinal velocity fluctuations is directed toward the periphery, where the generation of perturbations by the mean flow is insignificant. The distribution of the K_v coefficient indicates that the longitudinal transfer of the transverse velocity fluctuations is markedly greater on the flow periphery than in the near-axis region, which, in turn, can be explained by the incursion of accelerated fluid masses into the periphery.

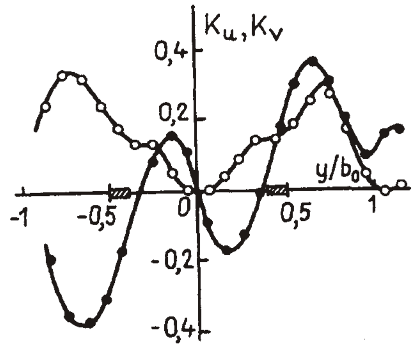

Fig. 7. Distributions (along the y-axis) of the coefficients of the energy exchange between the components of the velocity fluctuations K_u (•) and K_v (○) at $x/b_0 = 38$ and Re = 7,680.

Additional information on the turbulent shear flow properties is provided by the Reynolds stress $\rho\overline{u'v'}$ distributions and the production of the perturbed flow energy P across the flow cross-section. The relation between them in the two-dimensional case can be expressed in the form [9]:

$$P = -\rho\,(\overline{u'^2} - \overline{v'^2})\,\partial U/\partial x - \rho\,\overline{u'v'}\,(\partial U/\partial y + \partial V/\partial x).$$

Since in the present flow $\partial U/\partial x = 0$, the transverse velocity, as shown by the measurements, $V = 10^{-2}U$, i.e., is small due to the absence of a transverse fluid flow, and the quantities $\overline{u'^2}$ and $\overline{v'^2}$ are of the same order, this equation can be transformed into the form

$$P = -\rho\overline{u'v'}\,\partial U/\partial y,$$

where the right-hand side characterizes the energy exchange between the fluctuating and the averaged flows.

The distributions of the Reynolds shear stresses across the flow width are presented in Fig. 8a. Within the limits of the initial perturbation development segment at the $x/b_0 = 4$ coordinate, the shear stresses are small, being a factor between 6 and 7 smaller than in the developed perturbed flow region. For all presented cross-sections the maximum values of $|\,u'v'\,|$ are located at y/b_0 coordinates to the left and right of the flow symmetry plane where the mean velocity profiles have inflection points, and the strength of the longitudinal velocity fluctuations is maximum (Fig. 2 and 3a, curve 5). This fact also indicates that the averaged flow transfers its energy to the perturbations directly to the longitudinal velocity fluctuations through the Reynolds stresses.

Within this context it is possible to introduce another interpretation of the correlations K_u and K_v presented in Fig. 7, if their numerators are represented in the forms $\overline{(u'v')\,u'}$ and $\overline{(u'v')\,v'}$. Then K_u and K_v can be considered to be coefficients of turbulent momentum transfer in the longitudinal and transverse directions at the various flow cross-section points. The intrusion of turbulized fluid on the flow periphery increases the longitudinal momentum transfer in this region, and $|\,K_u\,|$ has a pronounced maximum here. The intrusion of decelerated fluid into the near-axis region diminishes such transfer; the maximum $|\,K_u\,|$ value in this region is one half of that on the periphery. For the same reason K_v on the flow periphery reaches the maximum values, and in the near-axis region has a tendency to increase only slightly. The antisymmetric nature of the K_u distribution with respect to the symmetry plane and the positive K_v values across the entire cross-section agree with the phase relations in the first case between u'v' and u', and in the second — between u'v' and v'.

It is evident from Fig. 2a and 8a that to the right of the symmetry plane $\partial U/\partial y > 0$, $\rho\overline{u'v'} < 0$, and to the right of it, $\partial U/\partial y > 0$ and $\rho\overline{u'v'} < 0$. Consequently, across the entire flow width P must have a positive sign.

In Fig. 8b we have presented the results which illustrate the variation of the energy generation across the flow width. It is found that along the stream, in the presented cross-sections $P > 0$ everywhere. In the initial segment, at $x/b_0 = 4$, in spite of the large velocity gradients at that cross-section, P are small, since the Reynolds numbers calculated using the longitudinal coordinate are small, and the perturbations still have an irregular characteristic (Fig. 4a and b). The difference by a factor of

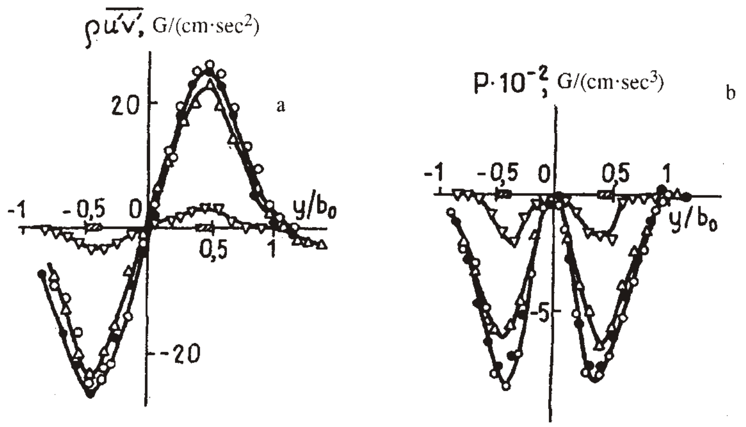

Fig. 8. Distributions (along the y-axis) of the turbulent friction (a) and of the perturbation energy generation intensity (b) at x/b_0 = 4 (▿), 18 (▵), 38 (•), and 47 (○); Re = 7,680.

1.3 in the P value at $x/b_0 \geq 18$ is explained by a transition to a steady energy redistribution between the velocity fluctuation components.

The positive value of the energy generation agrees with the concept according to which the averaged shear flow passes its energy into the turbulent fluctuations. However, in the shear flows having a two-dimensional turbulence structure, conditions can be created at which an inversion of the energy transfer can set in, such as an energy transfer from the perturbations to the averaged flow [10, 11}. In [10] it was experimentally shown in a plane jet-like turbulent flow in a magnetic field oriented along the long jet flow side that the large-scale two-dimensional turbulent perturbations, which were generated in the upstream cross-sections and which arrive at a given cross-section, surrender their energy to the averaged flow. In this case, the shear stresses change signs to the opposite ones, and the energy generation becomes negative over the entire cross-section (the "negative viscosity" phenomenon). The absence of this effect in the jet-like flow considered here which possesses a two-dimensional perturbation structure and does not change longitudinally is linked to the fact that in every cross-section a balance exists between the turbulent energy production and its dissipation in the perturbations on account of the Hartmann friction on the wall perpendicular to the field.

The presented data on the shear stresses and the turbulent energy generation allow one to estimate the vortical viscosity coefficient μ_T which, as is well known, in the general hydrodynamics of channel flows is two orders of magnitude greater than the molecular viscosity μ. The μ_T quantity can be calculated from the formula

$$\mu_T = -\frac{\rho\overline{u'v'}}{\partial U/\partial y}.$$

Calculations have shown that in the developed flow segment the ratio of the viscosity coefficients at the coordinates $y/b_0 = \pm 0.4$ is $\mu_T/\mu = 3.6\cdot10^4$, while on the flow periphery at the coordinates $y/b_0 = \pm 0.75$, where $U/U_m = 0.1$, $\mu_T/\mu = 3.3\cdot10^3$.

Conclusions. In plane shear flows without any longitudinal pressure gradient in a strong transverse magnetic field, turbulence is generated which has a two-dimensional perturbation structure. The strength of the fluctuations reaches 25% of the main flow velocity. The energy generated by the averaged flow enters the perturbations via the longitudinal velocity fluctuations; therefore, the perturbation structure has a markedly asymmetrical characteristic. The values of the Reynolds shear stresses and the turbulent energy generation vary greatly across the flow cross-section with the absolute maxima appearing in the regions of the inflection points on the averaged velocity profiles. The vortical viscosity coefficient is two orders of magnitude greater than in channel flows and is four orders higher than the molecular viscosity coefficient.

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