EXPERIMENTAL STUDY OF PLASMA FLOW IN A DISK MHD CHANNEL UNDER CONDITIONS OF SPONTANEOUS FORMATION OF A CURRENT LAYER

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The results of an experimental study of the plasma flow in a disk channel under conditions of strong hydromagnetic interaction are presented. It is shown that if the condition $\mathrm{Re}_m H_0^2/8\pi \geq 0.2$ is satisfied for the magnetic Reynolds number at some point of the stream, then a current layer develops at that point characterized by a high electric-current density and high conductivity and temperature. The formation of the current layer leads to strong local retardation of the stream, the appearance of a shock wave, and a number of other nonlinear hydromagnetic phenomena. The experimental results are in agreement with theoretical studies conducted earlier.

1. The macroscopic stability of flows in MHD channels is of interest not only from the point of view of the conditions providing for a given flow structure. As shown in [1, 2], in a number of cases the reorganization of the flow occurring as a result of its instability can lead to positive consequences, in particular, to an increase in the efficiency of the hydromagnetic interaction. In this case the question concerns the superheating of the instability [3] which under certain conditions leads to the formation of a new self-sustaining macrostructure, called the current layer in [1].

The essence of this effect can be illustrated on the example of the flow of a dense plasma ($T_e = T_i = T_a$, $\omega_e \tau_e \ll 1$) in a disk channel. In an established mode of flow the temperature of each element of the plasma depends on the degree of its expansion, on the amount of Joule heat liberated in it, and on the heat emission. If the conductivity of the plasma is sufficiently high ($\mathrm{Re}_m \approx 1$), thenthe relationship between these three factors is determined at a given pressure by the magnitude of the applied magnetic field. If the magnetic pressure is less than the gas pressure everywhere in the channel, then the mode of flow is determined predominantly by the gasdynamical factors (pressure drop, channel profile, etc.). With an increase in the magnetic field strength the ponderomotive force, which increases in proportion to the square of the field strength, can at some point of the stream become comparable to the pressure gradient. As a result the stream velocity begins to decrease at this point, or at least ceases to grow, which simultaneously will mean a decrease in the rate of expansion and a corresponding decrease in the temperature of the element under consideration. Here the relative role of Joule dissipation increases in the given element, the density of which, as it is easy to confirm, is comparable with the specific internal energy of the plasma under these conditions ($\mathrm{Re}_m \approx 1$, $H_0^2/8\pi P \approx 1$).

In this situation the temperature will now be determined not by the degree of expansion of the gas, but by the liberation of Joule heat. Because of the nonlinear nature of the dependence between the temperature, electrical conductivity, the electric current density, the density of Joule dissipation, and the magnitude of the ponderomotive force the process which has begun leads to the localization of the electric current, strong local heating, and intensive retardation of the plasma. The effect of heat emission can be ignored in the initial stage of the process because of its relatively brief duration, although with an increase in temperature the role of heat emission grows, and in the final analysis the temperature in the current layer is determined by the ratio between the Joule dissipation and the heat emission. The conditions for the formation of a cur-

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rent layer were obtained in [2] in more precise form and in a more general form as well on the basis of a numerical solution of the problem of plasma flow in a disk channel. In the framework of single-fluid magnetohydrodynamics this condition is formulated in the form of the following inequality: $\mathrm{Re}_m H_0^2/8\pi P \geq$ const, where the value of the constant is determined by the shape of the channel.

The results of an experimental study of the process described are presented in the present report. The current layer effect observed in the experiment contains all the main aspects predicted in [1]: localization of the electric current, an increase in the temperature and electrical conductivity in this zone, strengthening of the hydromagnetic interaction, and, finally, the existence of a critical value of the magnetic field for each mode of flow such that if the actual field strength is less than critical the effect does not appear.

2. The experiments were conducted on an instrument for which a detailed description is contained in [4]. A coaxial discharger, on which a battery of IM-5-150 capacitors with a total capacitance of 600 μF and a voltage of 5 kV is discharged, serves as the plasma source. A round tube 350 mm long and 55 mm in diameter, which is an extension of the discharger, ends in a disk channel, the walls of which are perpendicular to the axis of the tube. The diameter of the disk channel is 250 mm and the width averaged over the radius is 20 mm (the width is somewhat greater in the axial region than at the circumference). The channel walls are made of transparent plastic. The channel is placed in the inner cavity of a solenoidal direct-current electromagnet in such a way that the direction of the magnetic field lines within the channel coincides with the direction of the axis of symmetry of the instrument. The magnetic field strength at the axis can be varied in the range of 0-4000 Oe. Because of the short length of the electromagnet coil in the direction of the axis of symmetry the magnetic field strength is minimal at the axis and maximal at the circumference of the channel. The distribution of the field over the radius in the absence of a plasma is shown in Fig. 1 (curve 1).

The plasma obtained in the electric discharge moves along the tube with a velocity of ~20 km/sec. After striking the end wall of the disk channel it spreads out in the radial direction with an average velocity (without a magnetic field) of ~10 km/sec. In the presence of the magnetic field because of the orthogonality of the vectors v and H_0 the induced emf is directed along the circumference so that the current j induced in the plasma is closed on itself along a circle, while the ponderomotive force $j \times H$ acts along the radius in the direction opposite to the stream velocity.

In the experiment measurements were made of the distribution over the channel radius of the gas pressure, the electric current density, the amount of deformation of the magnetic field, and the strength of the vortical electric field ($c^{-1}\partial B/\partial t$), and the process of expansion of the plasma in the channel was photographed with an SFR-1M camera operating as a photorecorder and with framewise photography.

The pressure measurement was conducted using pressure piezopickups distributed at radii of 40-110 mm every 10 mm. A TsTS-19 piezoceramic was used as the sensing element. The pickups were located on the front and back walls of the disk channel in such a way that the sensing element of a pickup was flush with the wall of the channel. The signals from nine pickups were recorded simultaneously.

The deformation of the magnetic field in the channel was measured with magnetic probes of the induction type. A probe consisted of six small coils placed in a glass tube 4.5 mm in diameter. The tube was inserted into the channel. It was preliminarily established that the insertion of the probe into the plasma stream makes almost no change in the general flow pattern in the disk channel and, in addition, the visual pattern of flow over the probe made it possible to obtain additional information concerning the nature of the flow. This probe construction permitted the simultaneous recording of the deformation of the field at six points over the width of the channel. Probes recording the radial and transverse components of the magnetic field were used in the experiments. The circular component of the field (H_φ) is equal to zero in the present case. The space–time distribution of the magnetic field strength in the channel measured in this way made it possible to find with acceptable accuracy (~20%) the distribution of current density j(r, z, t) on the basis of the equation $j = (c/4\pi)\mathrm{rot}\, H$.

Direct measurement of the electric current density was also conducted. For this purpose a specially developed insert, consisting of a system of shunts insulated from one another through which the currents in the plasma were closed, was inserted into the channel. A shunt consisted of two copper plates 5 mm wide between which a graphite resistor was sealed. The potential difference developing on the shunt during the flow of a current was fed through a decoupling pulse transformer to an OK-17M oscillograph. Eleven such shunts, assembled in the form of a single plate 4 mm thick, which reduced the disturbances produced by it

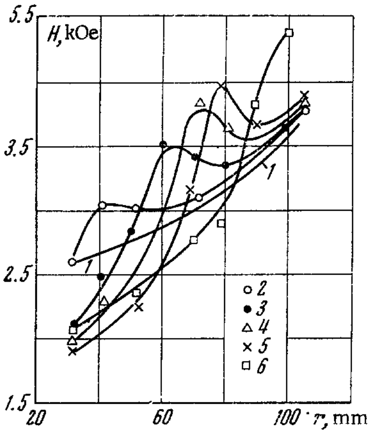

Fig. 1

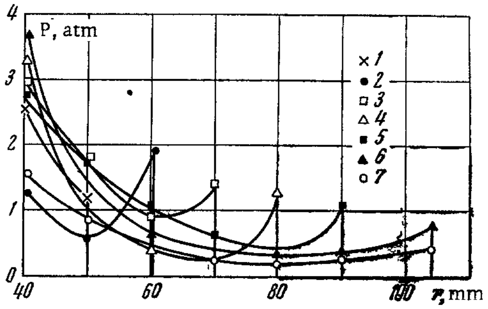

Fig. 2

to a minimum, were distributed along the stream in the channel. However, distortion of the flow pattern in the electrode zone, which was clearly recorded on the photographs, occurred because of the strong effect of electrode phenomena. For this reason the current-density distribution measured in this way did not always correspond to the distribution in the undisturbed zone (this is indicated particularly by the photographs, in which it is seen how the rather narrow luminous current ring spreads out in the electrode zone to almost the entire length of the measuring insert). Nevertheless, this method enables one to obtain rather abundant information concerning the dynamics of the current and its distribution, and in conjunction with the magnetic probes it gives very reliable information about the process.

The intensity of the vortical electric field was measured using single concentric so-called E-coils [4].

The velocity of plasma propagation in the tube and channel was measured from photoscans of the plasma motion. All the experiments were conducted on air with an initial pressure of 0.7 mm Hg.

3. Because of the great heterogeneity of the plasma formation obtained in the electric discharge preliminary studies were made of the nature of the flow in the disk channel without a magnetic field to determine the duration of the flow, the radial distribution of the parameters, etc. The pressure distribution and the propagation velocity of the leading front were measured directly, while the electrical conductivity and temperature were estimated by indirect means.

The following was established. The rate of movement of the leading front along the channel was ~14 km/sec at a radius of 40 mm, 10-11 km/sec at a radius of 50 mm, and the velocity then decreased slowly to 8.5-9 km/sec at the end of the channel.

The total pressure measured at the channel axis is 80-100 atm for 15 μsec and then decreases to 10-15 atm and stays at this level for 100-150 μsec. The static pressure in the stream at the entrance to the disk channel ($r \approx 40$-60 mm) is subject to the strong effect of the initial heterogeneity of the plasma and the establishment of a mode of flow hardly occurs in this region. However, at large radii the effect of these heterogeneities is smoothed out (although it does not disappear completely), and a quasistationary pressure distribution characteristic of supersonic flow is established along the channel in the range of 60-110 mm. The pressure falls from 4-5 atm at $r = 40$ to 0.5 atm at $r = 105$ mm. The formation of a pressure profile at the leading front also takes place practically at a radius of ~60 mm. This profile has a form characteristic for a cylindrical shock wave.

The space–time pattern of the pressure distribution for this case is presented in Fig. 2. The results of an analysis of the pressure oscillograms for $H_0 = 0$ are shown here. The numbers of the curves correspond in increasing order to the times $t = 1$, 2, 3.5, 5, 6.5, 9.5, and 15 μsec. Here and later the start of the time frame ($t = 0$) is taken as the moment the leading front of the plasma reaches a radius of 40 mm.

The synchronization in time of the signals from pressure pickups located on opposite walls of the channel at the same radius made it possible to establish that the pressure front at radii of < 60 mm is not perpendicular to the channel walls (the pickups located at the back wall of the disk channel record the shock wave front somewhat later than the pickups located at the front wall). With an increase in radius this slant of the pressure front becomes vanishingly small.

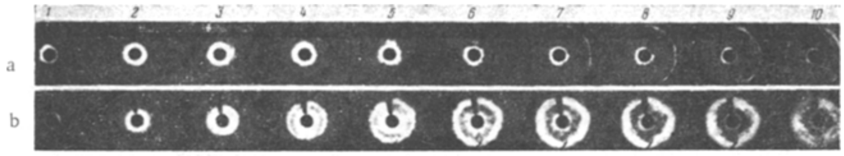

Fig. 3

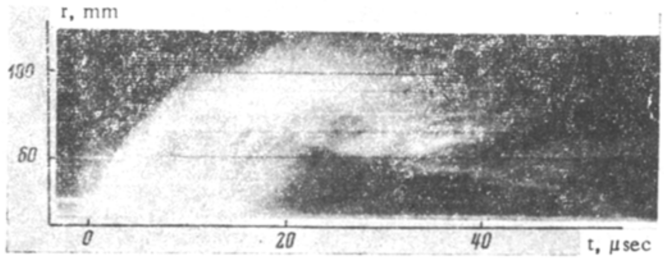

Fig. 4

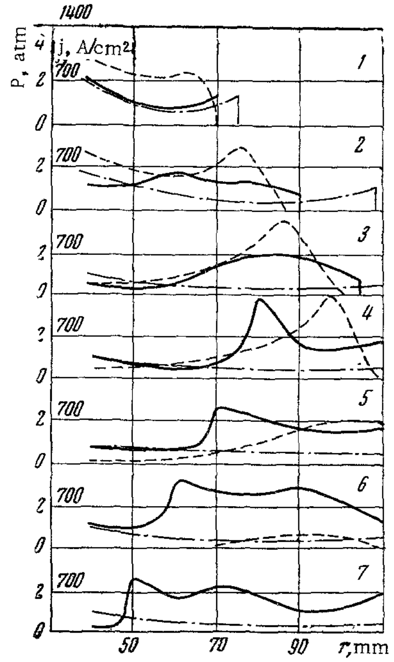

Fig. 5

The indirect estimate of the electrical conductivity and temperature of the plasma, made on the basis of measurements of the disturbance in a very weak magnetic field (≤100 Oe), gives values of 5-10 $\Omega^{-1}\cdot cm^{-1}$ and $(8\text{-}10)\cdot 10^{3}$°K, respectively, in the zone of established flow at r = 80 mm. These values are not in bad agreement with the calculated parameters of the air behind the shock wave.

Thus, it can be assumed with sufficient basis that quasistationary supersonic flow with a duration of ~15-20 μsec is established in the channel in the zone of r = 60-110 mm.

Photographs of the plasma expansion in the disk channel for the cases of $H_0 = 0$ and 3000 Oe are presented in Fig. 3a and b, respectively. Here the time between frames is 2.66 μsec and the dark disk at the center is an opaque screen.

The following properties of the process can be detected from a comparison of these photographs. In the central (axial) part of the channel (frames 1 and 2) the nature of the plasma luminosity is the same in the two cases: the luminosity is very great at small radii. Then it decreases so much that it is not always recorded on the film (a consequence of the strong expansion and cooling of the gas, as noted earlier). During the further motion of the plasma in the channel (frames 3-9) in the absence of a magnetic field the distribution of luminosity along the radius has a sharply decreasing nature. The brightly glowing ring visible in frames 6-9 is caused by a shock wave which arose as a result of the reflection of the plasma stream from structural elements located outside the channel.

The presence of a magnetic field such that the magnetic pressure $H_0^2/8\pi$ becomes comparable to the static pressure in the stream leads to a qualitative change in the flow pattern. A brightly luminescent ring, which moves with a velocity of ~8 km/sec up to r ≈ 85 mm and then is sharply retarded with its velocity decreasing to 2-3 km/sec, appears at some distance beyond the weakly glowing leading front (Fig. 3b, frame 3) ~5-6 μsec after the start of the expansion (by this time the leading front of the plasma reaches a channel radius r ≈ 70 mm). A shock wave travels from this brightly glowing zone in the direction toward the center of the channel. It is well seen both in the framewise photography of the process and in the photoscan of Fig. 4. The presence of this wave, as will be shown below, is also confirmed by the pressure measurements. At first this wave is carried by the oncoming gas stream toward larger radii and then it stops and begins to move toward the center of the channel with a velocity of ~2 km/sec.

The results of an analysis of the pressure oscillograms for $H_0 = 3000$ Oe, presented in Fig. 5, show that in the central part of the channel the radial pressure distribution is the same as in the absence of a magnetic field. Here the pressure distribution is shown by solid lines while the dashed lines show the distribution of current density. The pressure distribution for $H_0=0$ is shown by the dash-dot line. The numbers of the curves in increasing order correspond to the times t = 4.5, 8, 12, 15, 20, 27, and 37 μsec. At large radii, however, the pressure pickups record a marked difference in the course of the process. At the time t = 12 μsec (by this time the leading front of the plasma has already left the limits of the channel) in the zone of the brightly glowing ring ($r \approx 80$ mm) a characteristic pressure peak appears which is then formed into the shock wave moving off toward the center. The moment of formation of this wave and its position found from the results of the pressure measurement agree well with the photographs of the expansion process (Figs. 3 and 4) synchronized with it. The pressure in the front of the newly formed wave reaches 3-3.5 atm. In the region behind the front the pressure is ~2 atm and stays at that level for the entire time of existence of the brightly glowing ring.

The results of the measurement of current density presented in Fig. 5 indicate that a maximum also appears in the current distribution (for weak fields of $H_0 \leq 1000$ Oe this distribution has a monotonic nature). The current density reaches ~1500 A/cm^2, and the total current flowing through the plasma in the zone of the maximum reaches ~10^4 A. A comparison of the distributions of pressure and current density shows that the developing zone of increased pressure initially corresponds to the maximum in the current density. However, the subsequent intense retardation in the magnetic field of the zone of maximum currents leads to the formation of a shock wave and to the clear spatial separation of the zones of maximum currents and pressures. This separation is not only retained, but even increases in the later stage of the process because of the movement of the shock wave toward the center. At the same time the spatial position of the zone of the intensely luminous ring is clearly connected with the maximum in the current density.

This is also confirmed by the pattern of deformation of the field in the channel presented in Fig. 1 (here the numbers of the curves correspond in increasing order to the times t = 3, 6, 8, 10, and 15 μsec). The width of the brightly glowing zone averages 2 cm, and the electrical conductivity in it, calculated from the measured current density, velocity, and magnetic and electric field strengths, reaches 80-100 $\Omega^{-1} \cdot cm^{-1}$. This value is ~10 times greater than the electrical conductivity at this point of the stream with subcritical magnetic fields and is evidence of a considerable increase in the plasma temperature in the zone of the brightly glowing ring. The only thing that can serve as the cause of the intense heating of the air is the high local density of Joule dissipation, reaching ~0.2 J/cm^3 in the initial stage of the process, which exceeds the value of the internal energy of the gas and therefore can provide for its rapid heating.

Under the conditions of the experiment the characteristic time of the process, i.e., the time it takes the leading front to traverse the entire channel, is 10 μsec. The time of development of the current layer from the moment of its inception to the attainment of the maximum current density is 3-5 μsec, as seen from Fig. 5. As mentioned above, the moment the leading front of the plasma reaches a radius of 40 mm is taken as the start of the time frame. The time of existence of the current layer is ~20 μsec, and as seen from the illustrations presented, its decay occurs predominantly as a consequence of the intense luminescence and the decrease in current density caused by the sharp drop in velocity owing to the retardation of the layer in the magnetic field. In a number of cases disturbances characteristic of a Rayleigh–Taylor instability, the size of which increased to 20-30% of the width of the layer, were observed at the time of maximum negative accelerations at the outer boundary of the current layer. However, not once was a case of the decay of the layer because of such an instability observed. On the contrary, these disturbances rapidly died out (in 2-5 μsec) and the form of the outer boundary was thereby restored. This fact is in agreement with the results of [3], where it is shown that the plasma–magnetic-field boundary is stable in the presence of an increasing magnetic field, which exactly corresponds to the conditions of the experiment.

LITERATURE CITED

1. A. N. Tikhonov, A. A. Samarskii, L. A. Zaklyaz'minskii, P. P. Volosevich, L. M. Degtyarev, S. P. Kurdyumov, Yu. P. Popov, V. S. Sokolov, and A. P. Favorskii, "Nonlinear effect of formation of a self-sustaining, high-temperature, electrically conducting gas layer in nonstationary processes of magnetohydrodynamics," Dokl. Akad. Nauk SSSR, 173, No. 4 (1967).
2. L. M. Degtyarev, L. A. Zaklyaz'minskii, S. P. Kurdyumov, A. A. Samarskii, V. S. Sokolov, and A. P. Favorskii, "Development of finite local disturbances in electrical conductivity in a stream of weakly conducting gas in the presence of a magnetic field," Teplofiz. Vys. Temp., 7, No. 3, (1969).
3. B. B. Kadomtsev, "Hydromagnetic stability of a plasma," in: Problems of Plasma Theory [in Russian], No. 2, Atomizdat, Moscow (1963).
4. V. A. Derevyanko, L. A. Zaklyaz'minskii, S. S. Katsnel'son, A. Yu. Kerkis, E. F. Lebedev, N. A. Trynkina, and V. P. Fomichev, "Study of nonstationary interaction of a cluster of conducting gas with a given electrical contour," Zh. Prikl. Mekhan. Tekh. Fiz., No. 2, (1968).