INVESTIGATION OF THE FRINGE CURRENTS ASSOCIATED WITH THE MOTION OF A PLASMA ALONG THE CHANNEL OF A DISCHARGE TUBE THROUGH A NONUNIFORM MAGNETIC FIELD

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In [1] the deceleration of a plasma flow in a nonuniform magnetic field was experimentally detected and it was shown that when a plasma flows in a linear rectangular channel through a nonuniform magnetic field the plasma flow is decelerated ahead of the center of the magnet in the zone of increasing magnetic field intensity and beyond the center of the magnet in the zone of decreasing magnetic field intensity. In the presence of an external transverse magnetic field of intensity $B \sim 1$ Wb/m^2 in the center of the magnet a plasma flow with conductivity $\sigma \approx 100$ mho/cm was decelerated from $2.8 \cdot 10^6$ cm/sec at the entrance to the magnetic field to $1 \cdot 10^6$ cm/sec beyond the center of the magnet. On leaving the magnetic field the plasma underwent a sharp unexplained acceleration.

Flow deceleration in a magnetic field has been reported by a number of authors. For example, in [2] it was shown that the flux was decelerated in the exit zone of the magnetic field and the experimental value of the emp proved to be 17% lower than the calculated value, while in [3] the difference in emf reached 50% This difference is attributed to deceleration of the plasma flow in the zone of increasing magnetic field intensity as a result of fringe currents.

An investigation of plasma flow deceleration in a magnetic field is described in [4], where it is shown that at a plasma conductivity $\sigma \approx 70$ mho/cm the flow may be sharply decelerated in a magnetic field $B \approx 0.6$ Wb/m^2. The corresponding current density in the magnetic field zone was $j = 3200$ A/cm^2. Our object was to investigate the fringe currents and the induced magnetic field.

1. In order to determine the magnitude of the fringe currents in the zone of increasing and decreasing external magnetic field intensity we used a small Rogowski loop with an integrating network. The loop took the form of a toroidal coil consisting of 125 turns of 0.1-cm copper wire with a turn diameter of 0.5 cm. It was mounted in the 3×4 cm^2 rectangular channel so that the plane of the coil was perpendicular to the channel axis and parallel to the magnetic lines of force of the external field.

The loop enclosed the upper or lower half of the channel cross section, i.e., completely encompassed the fringe current of one of the current loops in some section of the channel relative to the center of the magnet. A large part of the torus of the Rogowski loop was located outside the channel cross section and only one quarter of it was located in the flow at the center of the channel cross section.

The integrating Rogowski loop was calibrated by means of a low-inductance shunt at a capacitor discharge current of 3000-7000 A. The Rogowski-loop calibration oscillogram is shown in Fig. 1a.

By means of the Rogowski loop we determined the boundaries of the fringe current loops. On investigating the current loop beyond the center of the magnet we found that the leading edge of the loop was located 3 cm downstream from the center of the magnet as the applied magnetic field varied from 0.16 to 0.96 Wb/m^2, while the trailing edge was located 13 cm from the center of the magnet. Thus, the length of the fringe current loop along the channel axis was approximately 10 cm.

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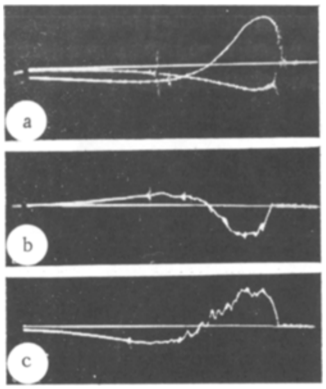

Fig. 1. Current oscillograms: a) shunt calibration of Rogowski loop (oscillogram with shunt underneath); b) for trailing fringe current loop, x = 3 cm; c) for leading fringe current loop, x = 8 cm.

At the same value of the external magnetic field the same signals are obtained from the Rogowski loop at distances of more than 5 cm but not more than 10 cm from the center of the magnet. At distances less than 3 cm and greater than 13 cm there are no signals from the Rogowski loop. Thus, the Rogowski loop completely encloses the fringe current at $10 \geq x \geq 5$ cm, where x is the distance from the center of the magnet. The location of the fringe current loops in the channel relative to the center of the magnetic field is shown in Fig. 2. The trailing loop extends almost 3 cm beyond the magnetic field.

A study of the traces on the lateral transparent walls of the channel after the experiment revealed that the edges of the fringe current loops are located about0.5 cm from the upper and lower channel walls. According to photographs obtained with a high-speed photorecorder the width of the current channel corresponds to the width of the gasdynamic channel.

Similar measurements were also made at $x < 0$. The leading edge of the current loop was located at $x = -11$ cm, and the trailing edge at $x = -1$ cm, i.e., the length of the leading loop along the channel axis, like that of the trailing loop, was about 10 cm. The same signals were received from the Rogowski loop at $-4 > x > -9$ cm. The signals from the Rogowski loop in the leading current loop differed in both sign and, in most cases, magnitude from the signal in the trailing loop. The different polarity of the signals indicates a different in the direction of the fringe current density vectors.

It is clear from Fig. 2 that the current loops are located asymmetrically in the channel relative to the center of the magnet, which may be attributable merely to "deformation" of the magnetic lines of force, since the magnetic Reynolds number in the flow reaches 10. The part of the channel free of fringe currents occupies the region $-1 < x < 3$ cm. When the dimensions of the loops were being studied, the Rogowski loop occupied the lower half of the channel cross section; check measurements for the upper half of the channel cross section gave similar results.

The dependence of the fringe currents on the external applied magnetic field was studied with the Rogowski loop at only two points 8 cm on either side of the center of the field ($x = \pm 8$ cm) i.e., approxiately at the center of the leading and trailing current loops. The external field was varied from 0.24 to 0.96 $\mathrm{Wb/cm^2}$. The dependence of the fringe current in both loops on the external magnetic field is shown in Fig. 3. The leading current loop is characterized by a certain increase in the electric current with increase in the magnetic field. As the magnetic field increases by a factor of 4, the fringe current increases from 1900 to 2900 A, i.e., by approximately 50%.

The trailing current loop is characterized by a current maximum of 2500 A at $B \approx 0.48\ \mathrm{Wb/m^2}$; as the magnetic field increases beyond 0.48 $\mathrm{Wb/m^2}$ the fringe current decreases, which is attributable to the sharp deceleration of the flow in the leading current loop.

2. In order to investigate the fringe current magnetic fields a magnetic probe in the form of a single-layer coil 0.5 cm in diameter consisting of 50 turns of 0.01-cm conductor was introduced into the region of the fringe current loops. The signal from the coil was integrated by means of a RC circuit and fed to the input of a OK-17M oscillograph.

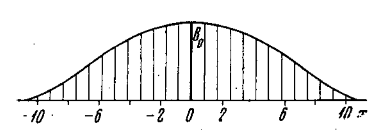

Fig. 2. Distribution of fringe current loops along channel axis relative to the center of the transverse magnetic field B_0.

Owing to the strong electric fields in the plasma the coil was placed in a grounded electric shield in the form of a slotted cylinder of nonmagnetic steel 0.01 cm thick.

As the plasmoid passes through the magnetic field, the coil registers the fringe current magnetic field in the form of a change in the shape of the oscillogram in the region of the maximum of the external magnetic field. The oscillogram of the induced magnetic field, whose sign depends on the position of the coil relative to the center of the magnet, is superposed

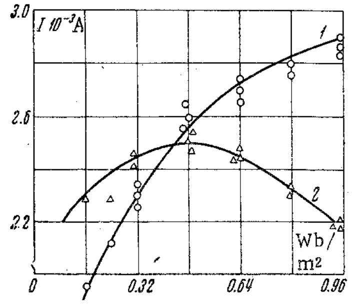

Fig. 3. Fringe currents as a function of the transverse magnetic field: 1) leading fringe current loop; 2) trailing fringe current loop.

on the oscillogram of the external magnetic field. For the trailing current loop the signs of the oscillograms coincide, for the leading loop the oscillograms have opposite signs.

In order to investigate the distribution of the induced magnetic field B_1 along the channel axis, the magnetic probe was displaced through distances of 10 cm on either side of the center of the magnet. The distributions of the field B_1 and the magnetic field in the plasma B_2 is shown in Fig. 4 for external fields of 0.24 and 0.96 Wb/m^2. The field of the leading current loop extends approximately 2 cm beyond the center of the magnet.

In most cases, at the same value of the external field B_0, the field B_1 in the leading current loop is greater than in the trailing loop. The leading loop is characterized by growth of the field B_1 with increase in the field B_0. As B_0 increases from 0.24 to 0.96 Wb/m^2, B_1 varies from 0.07 to 0.104 Wb/m^2, i.e., by not more than 50%, which corresponds to the experimentally determined increase in the fringe current.

The trailing current loop is characterized by a maximum of B_1 at $B_0 = 0.48$ Wb/m^2, the maximum being equal to 0.08 Wb/m^2. At $B_0 = 0.24$ and 0.96 Wb/m^2 the magnetic fields B_1 for the trailing current loop have values of 0.055 Wb/m^2. The distribution of the induced magnetic fields along the channel axis is similar to the fringe current distribution in the channel.

As was to be expected, as a result of the existence of the induced fringe current fields the maximum of the magnetic field in the plasma B_2 is shifted to the right relative to the maximum of the applied magnetic field B_0 by approximately 2 cm. Whereas in the section $x = \pm 10$ cm the external magnetic field is equal to zero, the magnetic field in the plasma $B_2 < 0$ in the section $x = -10$ cm and $B_2 > 0$ in the section $x = 10$ cm.

Thus, the above-mentioned asymmetry of the fringe currents relative to the center of the field B_0 is associated with a downstream displacement of the transverse magnetic field in the plasma B_2. The fringe currents are symmetrical about the center of the magnetic field in the plasma.

The fringe current fields were calculated for an isotropic plasma moving in a channel with nonconducting walls in the presence of a stepped external field. It was found that for a magnetic Reynolds number $R_m \simeq 10$ the induced magnetic field amounts to 50% of the external applied field. It was found experimentally that the field B_1 reaches 30% of the applied field B_0 at $B_0 = 0.24$ Wb/m^2. At $B_0 = 0.96$ Wb/m^2 $B_1 = 0.11$ B_0, i.e., as the applied field increases the percentage increases in the induced magnetic field decreases. It should be kept in mind that in reality the magnetic field does not have a step shape and the plasma is anisotropic; moreover, the external field has the indicated values only at the center of the magnet.

3. In [1] it was noted that beyond the center of the magnet at $x > 4$ cm the leading front of the plasmoid begins to accelerate. This acceleration exceeded the deceleration of the plasmoid in the same trailing current loop, although the acceleration took place at lower values of the external magnetic field, since the corresponding zone was further from the center of the nonuniform field.

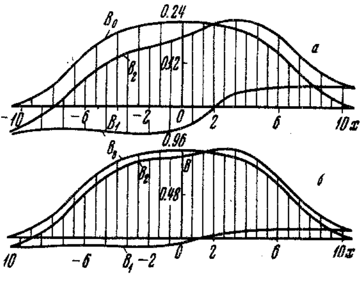

Fig. 4. Distribution of transverse magnetic field along the channel axis: a) $B_0 = 0.24$ Wb/m^2; b) $B_0 = 0.96$ Wb/m^2.

In [1] it was suggested that not all the plasmoid is accelerated to the same degree, most of the acceleration taking place in a small region near the leading edge.

An examination of the motion of the leading edge at $x > 0$ shows that when the leading edge of the plasmoid enters the zone of a decreasing external field, a trailing fringe current loop is formed, and a certain part of the plasmoid near the leading edge is then able to enter the acceleration zone without undergoing deceleration, while the bulk of the flow is retarded by the resulting current loop, i.e, by the interaction of the leading half of the fringe current loop and the external magnetic field, and only then enters the acceleration zone beyond the center of

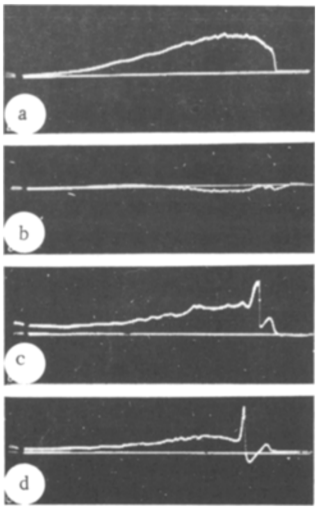

Fig. 5. Oscillogram of the emf between electrodes at $h = 2$ cm, $B_0 = 0.96$ Wb/m^2 at various distances of the electrodes (x) from the center of the magnet: a) $5 > x > -8$ cm, b) $x = -10$ cm, c) $x = 8$ cm, d) $x = 10$ cm.

the trailing loop. The unretarded part of the plasmoid near the leading edge then becomes separated.

It is not possible to determine the plasma velocity within the plasmoid by means of probes, since they respond only to the plasma conductivity front. Accordingly, we investigated the emf with cylindrical electrodes mounted 2 cm apart in various sections of the channel relative to the center of the magnet. The electrodes were introduced successively at 2 cm intervals between the sections $x = -10$ cm and $x = -10$ cm.

The oscillogram in Fig. 5a represents the emf at $4 \geq x > -8$ cm. At $x > 4$ cm the form of the oscillogram changes (Fig. 5c), and we obtain a forward emf peak that depends almost linearly on the magnetic field and corresponds on the time scale to 2-4 μsec, i.e., the length of the leading plasmoid is 5-10 cm depending on the magnetic field and the distance from the center of the magnet.

The emf oscillograms at $x > 4$ cm confirmed the assumption of acceleration of part of the plasmoid in the region of the leading edge beyond the center of the magnet. The flow velocity calculated from the peak values of the emf (Fig. 5c) coincides quite closely with the value obtained by the probe method at $x > 4$ cm, i.e., the probes in fact register only the velocity of the leading edge of the plasmoid, which does not always coincide with the velocity of the main flow.

Within the limits of error of the measurements the velocity calculated from the emf at $x < 4$ cm coincides with the velocity measured by the probes. The oscillogram emf was measured approximately 10 μsec after the appearance of a signal, i.e., at 20-30 cm from the leading edge. It should be noted that the plasmoid flow time depends on the magnetic field and, for example, at $B_0 \approx 1$ Wb/m^2 is about 70 μsec, whereas in the absence of a magnetic field it is 150 μsec. Measurements of the velocity based on the emf at different moments of time showed that almost half the plasmoid has a constant velocity equal to the velocity of the leading edge.

In order to determine the flow velocity at $x > 4$ cm we measured the emf from the oscillograms behind the emf peak 10 μsec after the appearance of a signal, as for $x < 4$ cm. Calculations for different magnetic fields and distances from the center of the magnet showed that at $x > 4$ cm the flow is accelerated by approximately 20% in the section $x = 10$ cm, which is much less than the acceleration of the part of the plasmoid near the leading edge, the minimum velocity of the main plasma flow being at $x = 6$ cm, and not $x = 4$ cm as for the leading edge.

4. In order to study the plasma flow picture in a nonuniform magnetic field we photographed the flow in the channel with a high-speed photorecorder. The best picture is obtained by photographing through the upper transparent wall of the channel, i.e., through the gap between the magnet coils. For this purpose part of the upper channel wall 20 cm long was replaced by a transparent sheet 0.1 cm thick. The process was photographed at various magnetic fields.

In the photographs it is possible to distinguish two dark zones, i.e., regions where flow deceleration is taking place, one in front of the center of the magnet about 5 cm long, which falls about 2 cm short of the center of the magnet, and a second region beginning exactly at the center of the magnet and extending for 4-5 cm. The width of the dark zones is equal to the width of the channel.

There are no traces of shock waves and the supersonic flow is probably decelerated gradually without shock formation. The first dark zone is located between the center and the end of the leading fringe current loop, while the second zone begins before the trailing loop.

It is clear from a comparison of the deceleration zones with the velocity dependence of the leading edge [1], that the leading dark zone coincides with the flow deceleration zone ($-3 > x > -8$ cm), while the second zone coincides with the deceleration zone ($5 > x > 0$). The marks on the lateral walls of the channel ($-8 \leq x \leq 5$ cm) coincide exactly with the boundaries of the dark zones.

5. An investigation of the interaction of a plasmoid and a nonuniform magnetic field at $R_m > 1$ for an anisotropic plasma in a rectangular insulated channel showed that for a high-velocity flow of completely ionized plasma in the zones of nonuniformity of the magnetic field, owing to charge leakage, two fringe current loops are formed, the current in these loops depending on the velocity and electrical conductivity of the flow and the applied magnetic field.

The conduction anisotropy affects the electrical conductivity of the plasma, sharply suppressing the growth of the fringe current with increase in the external magnetic field.

The magnetic fields induced by the fringe currents are so directed that in the zone of increasing external magnetic field they reduce the transverse magnetic field in the plasma, i.e., the induced magnetic field is opposite in sign to the external field, while in the zone of decreasing external field B_0 they increase the magnetic field in the plasma, i.e., the induced field has the same sign as the external field. We observe a downstream displacement of the center of the magnetic field in the plasma characteristic of $R_m > 1$.

The effect of the induced magnetic field is especially noticeable at small external fields, when $B_1 = 0.3\ B_0$, since as the applied field increases the induced fields vary only slightly as a result of the conduction anisotropy of the plasma.

The interaction of the fringe currents with the transverse magnetic field in the plasma creates a ponderomotive force $F = c^{-1} j \times B$, which decelerates the flow in front of the center of the magnet and in the leading half of the loop beyond the center of the magnet, and accelerates the flow in the other half of the trailing current loop. The supersonic flow is decelerated smoothly without the formation of shock waves.

In the zone of decreasing magnetic field the flow separates with the formation of a precursor plasmoid, whose length does not exceed 5% of the length of the plasmoid as a whole. The fringe current loops are asymmetrical relative to the center of the external field, but symmetrical relative to the center of the magnetic field in the plasma.

The experimental values of the fringe current and the induced fields are closer to the calculated values at small applied fields, but at $B_0 \geq 0.1\ \text{Wb/m}^2$ the Hall effect must be taken into account.

High-speed photography and probe measurements revealed the existence of two flow deceleration zones. Consequently, in calculating the emf it is necessary to know the flow velocity in the region of the electrodes with allowance for flow deceleration in the zone of increasing magnetic field, the magnetic field in the plasma with allowance for the induced fields, and the velocity profile with allowance for the boundary layer.

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