EXPERIMENTAL INVESTIGATION OF THE REFLECTION OF A SHOCK WAVE FROM A CURRENT-CARRYING GRID

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The paper examines some results of an experimental investigation of the reflection of a strong shock wave, produced in a shock tube with a coaxial spark gap, from the magnetic field of a current-carrying grid. The velocities of the refracted and reflected shock waves are given as a function of the magnitude of the initial magnetic field and the distortion of the grid's magnetic field by a conducting gas. It is shown that if the magnetic field is sufficiently strong, a shock wave will pass through the grid at a velocity one third that of the incident wave.

The idea of a current-carrying grid is as follows: across the path of the conducting gas (the ionizing shock wave), several equally spaced metallic wires or bands are fastened between the channel walls, and an electric current is made to flow through them. The current in the grid and its magnetic field are normal to the channel axis and to the velocity vector of the gas. If the spacing δ between the bands is such that the magnetic Reynolds number determined from this spacing and the maximum parameters of the gas is $\mathrm{Rm}(\delta) < 1$, then the conducting gas cannot penetrate the field during its passage between the bands, and is forced everywhere to move perpendicularly to the field's line of force. The conductivity of copper bands exceeds by several orders of magnitude that of the gas (at $T \leq 5 \times 10^4$ °K), so that in terms of the magnetic field, the grid can be treated as an ideally conducting wall. At the same time the grid may take up only a small portion (≤ 0.1) of the channel's cross sectional area and may be "transparent" for an electrically nonconducting gas.

In the following we shall agree on the following dimensions: time t in μ/sec, linear dimensions in cm, pressure p in mm Hg, magnetic field intensity H in oersteds, velocity in km/sec.

In the experimental equipment, a strong shock wave was created by means of a coaxial source through which a bank of four IM-5-150 capacitors was discharged. The obtained cluster of electrically conducting gas moved toward the grid in a Plexiglas channel of square cross section (5×5 cm^2).

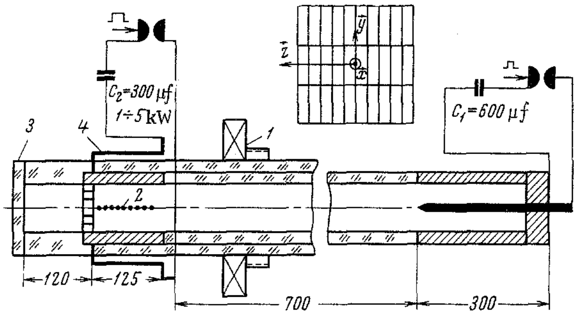

Fig. 1

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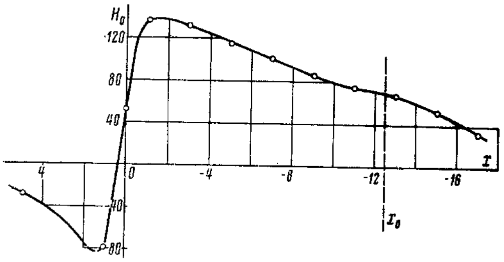

Fig. 2

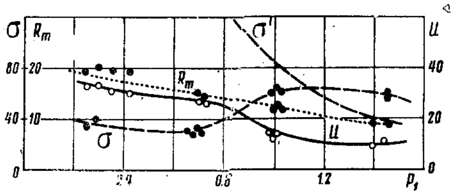

Fig. 3

A schematic diagram of the equipment is shown in Fig. 1. Here, 1) is an electrical-conductivity meter, 2) are magnetic probes, 3) is the end face of the channel, and 4) is a half-winding that generates the initial magnetic field.

The equipment was filled with atmospheric air at pressures ranging from 0.2 to 1.5 mm Hg. Preliminary tests proved that in order to obtain satisfactory reproducibility of the experiment, the entire volume of the equipment had to be blown with compressed air during several minutes after each discharge.

To permit recording of shock waves which had passed through the grid, a 12-cm length of the channel behind the grid was closed off by a plane end piece. This made it possible to study the characteristics of a wave behind the grid also from its reflection at the end piece.

The configuration and dimensions of the grid are given in Figure 1. The grid was put together from 11 copper strips, 0.5 mm thick and 10 mm wide. Adequate grid rigidity was achieved by adding to the 11 strips two perpendicular ones. The grid was soldered to the electrodes, in the form of 10-mm-thick copper plates, which were mounted flush with the inner channel surface along two parallel walls, over a length of 125 mm, facing the gas flow. When a shock wave arrives in the electrode area, the electromotive force induced in the gas behind the shock wave is shorted through the electrodes onto the grid. In this way, a closed current loop is formed which is compressed by the electrically conducting gas that moves along the electrodes.

The initial magnetic field was created by discharging another capacitor bank through the grid. To improve the uniformity of the field inside the channel in the area of the electrodes, the leads connecting the grid to the capacitor bank were made to run along the outer channel walls over a length equal to that of the electrodes. The first current half-period of this discharge circuit had a duration of 50 μ-sec at a peak current of 60 ka.

The discharges of both capacitor banks were synchronized in such a manner that the front of the incident shock wave reached the interaction zone at the moment of a maximum initial field. Along the electrodes, at the channel axis, the intensity H_0 of the circuit's magnetic field varied in the manner shown in Figure 2 (the line $x=x_0$ denotes the beginning of the electrodes; the current through the grid is 1 ka.) Inasmuch as H_0 is a function of time t and the coordinate x, the numerical values of H_0 indicated below are referred to the values $x=-1$ cm and $t=t_1$ (t_1 is the moment of arrival of the incident wave front at the ends of the grid electrodes). The nonuniformity of the field $H_{0z}=H_0$ (if the grid currents are directed along the axis y and the shock wave moves along x) along the coordinates y and z in the electrode gap does not exceed 20%, while the field components H_{0x} and H_{0y} are 50 to 100 times smaller than H_{0z}. The electric eddy field E_{0y} produced by the nonstationary magnetic field H_0 does not exceed 0.2% of the field $c^{-1}uH_0$ by the conducting gas flow.

The passage of a cluster of electrically conducting gas through the magnetic field of the grid was studied from photorecordings obtained with a high-speed streak camera. The disturbances of the z component of the magnetic field were controlled by magnetic probes placed in the channel wall at a depth of 2 mm from the inner surface of the channel. The grid current from a capacitor bank was measured by an integrating Rogovskii coil.

The maximum electrical conductivity of the plasmoid was measured by the method of forcing out a steady magnetic field by a gas flow [1, 2]. The σ measuring system was calibrated with a copper bar

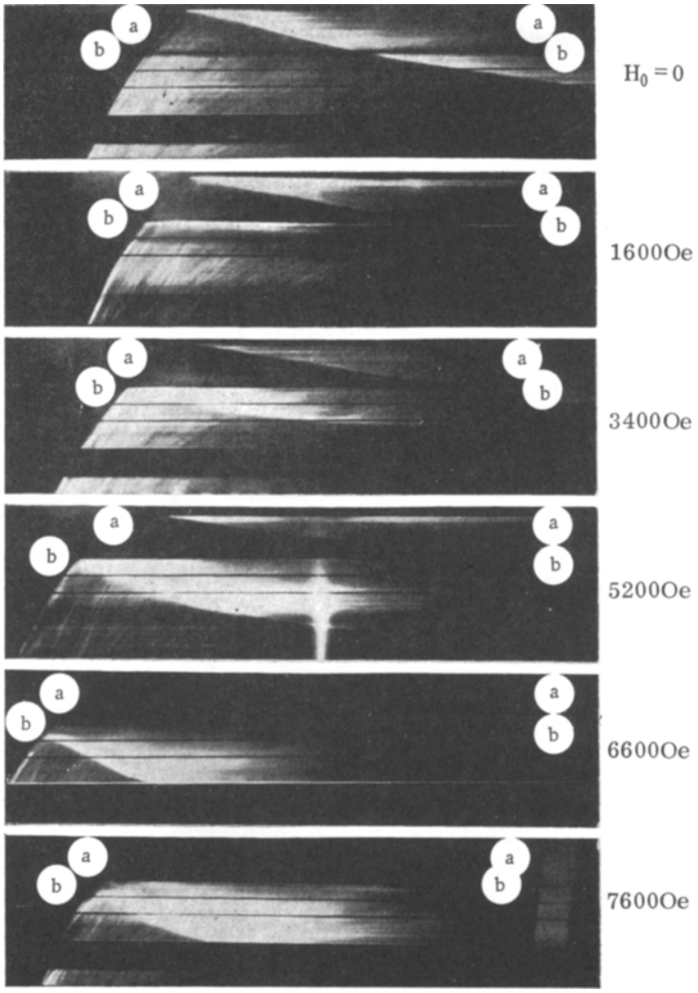

Fig. 4

5×5 cm^2 in cross section. Time synchronization of the signals was achieved by recording the synchronizing pulse and the spark created by it on the oscillograms and streak camera photographs.

It has been repeatedly shown (see, for example [3, 4]) that in electrical discharge sources, the shock-heated gas may mix with the ionized gas from the discharge. Specifically, as a result of this, the parameters of the developing cluster of conducting gas will differ from their computed values behind the shock front.

The basic experiments were performed for initial air pressures greater than 0.7 mm Hg. As shown in [4], under these conditions, there exists behind the shock front a plugged region of shock-heated gas followed by the ionized gas from the discharge. Measurements showed that the gas has its maximum electrical conductivity near the luminous front. From there on, the conductivity decreases slowly along the cluster, until it drops abruptly to half the maximum value over a length of roughly 10 cm. The pronounced changes in the conducting-gas parameters may be observed also from an acceleration of the wave reflected from the end face of the channel, after colliding with the end portion of the incident cluster.

The velocity u (in km/sec) of the leading front of the cluster, its electrical conductivity σ (in ohm$^{-1}\cdot$cm^{-1}), and the magnetic Reynolds number R_m (for a characteristic dimension equal to an electrode length of 12.5 cm) were varied for various initial pressures p_1 in the manner shown in Figure 3 (the dashed curve σ^1 represents the computed equilibrium value of the electrical conductivity behind a plane shock wave which moves at the velocity of the cluster's luminous front). For $p_1 > 1$ mm Hg, a certain agreement

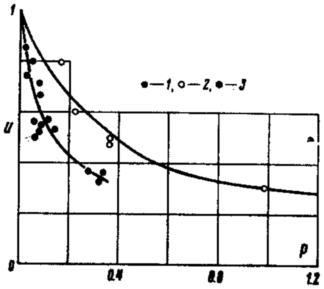

Fig. 5

may be already observed between the computed and experimentally obtained values of σ. By using an electrical discharge source, it proved possible to obtain a strong shock wave and a large magnetic Reynolds number (10 to 15) of the electrically conducting gas cluster.

The picture of the interaction between the shock wave and the magnetic field of the grid is shown by photorecordings in Figure 4 (the scale on the time axis is 1.5 mm/μ sec; the initial air pressure is 0.7 mm Hg; H in oersteds, the exposure times of the photographs vary; a-a is the end face and b-b the grid). With increasing initial magnetic field, the shock wave velocity and the velocity of the refracted shock wave behind the grid decrease. A luminous front reflected from the magnetic field of the grid is created, which moves toward the oncoming flow. In the following it will be called the reflected luminous shock front, although additional investigations are required to establish its structure.

At initial field intensities above 5000 Oe, in the electrode gap, behind the shock wave, a luminous gas layer starts to develop which moves at a velocity somewhat below that of the incident wave (Fig. 4). Since, in its further course, this layer is strongly decelerated, and does not reach the grid at strong fields, it may be safely assumed that the main current flowing through the gas is concentrated in this layer and that the latter possesses both maximum electrical conductivity and temperature. Since, in the given case, the magnetic field has no distinct boundary (Fig. 2), and the creation of this layer is not associated with the beginning of the electrodes, the formation of such a layer may be possibly regarded as a manifestation of the instability of the unsteady conducting-gas flow in a magnetic field, as described in [5], while the luminous gas is a T-layer. Pronounced deceleration of the T-layer leads to the generation of a strong reflected shock wave and to a deceleration of the refracted shock wave.

For magnetic fields below 5000 Oe, the T-layer is strongly decelerated only near the grid. This is why the reflected shock wave seems to branch out from the grid (Figure 4, H_0 =3400 Oe). A decrease in the velocity of the refracted wave and the formation of a strong reflected wave becomes apparent at magnetic fields as low as H_0 =1500 Oe.

At field values of $H_0 \approx 3400$ Oe, the velocity of the shock wave reflected from the field of the grid increases to that of a wave reflected from a solid wall. This will occur at small ratios of the magnetic pressure of the initial magnetic field to the dynamic head behind the incident shock wave

$$P = \frac{H_0^2}{8\pi\rho_1 u^2} \approx 0.1.$$

In this case, the refracted wave is still rather strong. For still higher values of the magnetic field, the stagnation point of the current sheet separates from the grid to a distance of 5 cm.

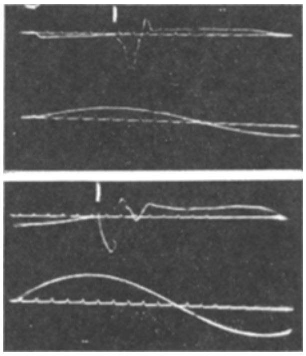

Fig. 6

The propagation of shock waves in a transverse magnetic field has been studied in a number of papers. In [6, 7], experiments were conducted in a radial (disk) channel with concentric short-circuited conductors, while in [8] an experiment was performed using an installation with current-collecting electrodes for low-resistance loads at $R_m < 1$. In [8], a slight change in the velocity of the refracted wave was observed, whereas the velocity of the wave reflected from the magnetic field reached (and did not exceed) the velocity of a wave reflected from a rigid wall in the absence of a magnetic field.

The authors wish to note that due to the cordiality of S. G. Zaitsev they were able to acquire knowledge on some results of a detailed investigation of the structure of a steady gas flow generated by a shock wave in a transverse field for $R_m < 1$, when the emf induced in the gas is shortened by a small external load.

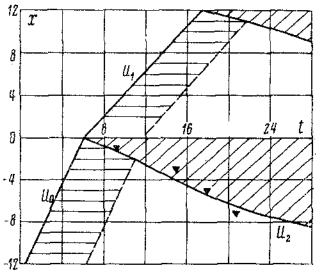

Fig. 7

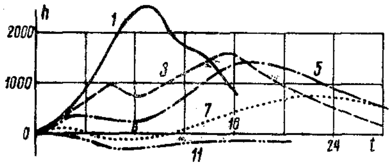

Fig. 8

The experiments described in the present paper were performed at $R_m > 1$. In order to eliminate a possible penetration of shock waves through the lines of force of the magnetic field [9], use was made of a current-carrying grid of such a characteristic dimension that magnetic Reynolds numbers calculated from it are less than unity.

Let u_0 be the shock wave velocity for $H_0 = 0$, and u_1 and u_2 the velocities of the refracted and reflected shock waves, respectively, in the presence of a magnetic field ($H_0 \neq 0$).

Figure 5 shows a plot of the relative velocity $u = u_1/u_0$ of the refracted wave vs. the interaction parameter P, for the above conditions. The experimental points correspond to the following parameter combinations: 1) ($R_m = 15$, $p_1 = 0.7$); 2) ($R_m = 12.5$, $p_1 = 1.0$); 3) ($R_m = 10$, $p_1 = 1.5$).

The deceleration $(u_0 - u_1)/u_0$ of the shock wave in the grid varied from 30 to 60% for the value of three for the parameter R_mP (which characterizes the ratio of the ponderomotive force, which decelerates the flow, to the gas pressure), whereas in [8], for the same values of R_mP, deceleration was not a sharply defined function of the magnetic field and did not exceed 10%. In the present tests, the maximum value of shock-wave deceleration $(u_0 - u_1)/u_0$ was up to 70%.

The moment of arrival of the shock wave at the electrodes was precisely recorded by the magnetic probes. At this moment, the electrically conducting gas behind the shock wave closes the electrode-grid circuit, and the electromotive force $c^{-1}uH_0d$ (where $d = 5$ cm is the width of the electrode gap), which causes a current (and field) jump in the circuit, is switched into the latter. Figure 6 gives oscillograms of the magnetic-probe signals $\partial H/\partial t$ for initial field values of 3400 Oe (upper photograph) and 7600 Oe (lower photograph). The lower traces on the oscillograms are recordings of the current which induces the initial magnetic field. The white line denotes the time t_1, i.e., the moment at which the incident cluster front reaches the electrodes (the time scale is 5 μ-sec). From the oscillograms in this figure, it can be seen that the current flowing in the circuit formed by the electrodes, the grid, and the ionized gas has very little effect on the current in the circuit formed by the capacitor bank and the grid.

It can be observed that together with the reflected wave which moves toward the flow, there moves a maximum h of the wave of the disturbed magnetic field, i.e., the field associated with the currents in the gas-electrode-grid circuit. The magnetic field at the front of the reflected wave varies smoothly during this process. This is illustrated by Figure 7 which shows the relation h(t, x=const) for an initial field $H_0 = 2600$ and $p = 0.7$, as well as by Fig. 8 which gives a plot of the motion u_0 of the incident shock, the motion u_1 of the refracted wave, the motion u_2 of the wave reflected from the grid, and the motion of the wave reflected from the end face of the tube (the numbers 1, 2, 3, 5, 7, 11 on the h(t) curves are the coordinate values of -1, -3, -5, -7, and -11 cm, respectively). The increase of the total field $H = H_0 + h$ becomes noticeable only in the region $x > -7$ cm, the first maximum h(t) occurring at the moment where the luminous front arrives at the point of observation. After this, the field in the region already occupied by the electrically conducting cluster decreases. The creation of a wave reflected from the grid, and its propagation toward the incident flow cause a new increase in the magnetic field. The second maximum which appears on the h(t) curve also corresponds to the passage of the luminous front of this wave (on the x vs t plot, the moments of time where h(t) has a maximum value are denoted by triangular points). Thus, the patterns of the magnetic field variation associated with the motion of an incident and a reflected shock wave along the electrodes are qualitatively alike.

The magnetic probe signals indicate that a field maximum ($h_{max} \approx H_0$) occurs in direct proximity of the grid ($x = -1$ cm). Further along the electrodes, the ratio h/H_0 decreases (for $x = -3$ cm, h_{max} does not exceed $0.35\ H_0$).

To conclude, we shall make some inferences. It has been shown that for $R_m \approx 10$ to 15 and $P \leq 1$, a strong interaction is to be observed between the electrically conducting gas behind a shock wave and the magnetic field of a current-carrying grid with attached electrodes. The refracted shock wave is decelerated to 6 km/sec at $H_0 = 8000$ Oe (the velocity of the incident wave is 25 km/sec), and becomes weakly ionized. At $H_0 \geq 1500$ Oe, from the grid, toward the oncoming flow, there begins to move a reflected wave whose luminous front displaces the peak of the disturbed magnetic field. The luminous gas layer which was observed behind the shock wave at $H_0 \geq 5000$, and which experienced strong deceleration during its further motion may be associated with a nonlinear effect observed in [5] for the nonstationary motion of a conducting gas in a magnetic field. The formation of such a T-layer may be one of the causes for the observed deceleration of the refracted wave and for the creation of a high-intensity reflected wave.

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