MOTION OF A LIQUID-METAL PISTON IN A MAGNETIC FIELD

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We consider the motion of a liquid-metal piston in a channel formed by two electrodes and walls made of insulating material in a transverse magnetic field. We show that under certain conditions the main mass of the piston remains in one piece, and the theory based on the hypothesis that a piston exists agrees satisfactorily with the experimental results. We also show oscillograms and motion picture frames which illustrate the process.

In accordance with the setup of the process (Fig. 1) we derive an equation in which the liquid-metal piston is regarded as a progressively moving body of constant shape and mass. Neglecting friction, we can write

$$\rho bhl dv/dt = bh\,[P_1(x) - P_2] - jHbhl/c. \qquad (1)$$

Ohm's law is

$$vHh/c = jblR^\circ. \qquad (2)$$

We use a quasi-unidimensional approximation.

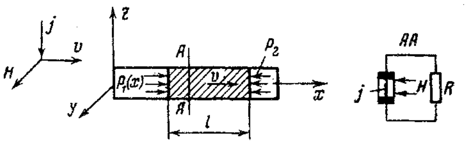

Fig. 1

The magnetic field induced by the current flowing in the electrodes and liquid metal is ignored, since we are dealing with processes occurring at low R_m.

After simple transformations and normalization Eqs. (1) and (2) take the form

$$v_* v_*' = D\,[P_{1*}(x_*) - P_{2*}] - 2S_0 v_*$$

$$v_* = \frac{v}{v_0}, \quad x_* = \frac{x}{l}, \quad (\;)' = \frac{d}{dx_*}(\;);$$

$$P_{1*}(x_*) = \frac{P_1(x_*)}{P_0}, \quad P_{2*} = \frac{P_2}{P_0}$$

$$\sigma^\circ = \frac{h}{blR^\circ}, \quad R^\circ = R + r, \quad D = \frac{P_0}{\rho v_0^2},$$

$$S_0 = R_{m0}\frac{H^2/8\pi}{\rho v_0^2}, \quad R_{m0} = \frac{4\pi\sigma^\circ v_0 l}{c^2}. \qquad (3)$$

Here D is a dynamic parameter; S_0 is the magnetic interaction parameter; R_m is the magnetic Reynolds number; H is the magnetic field strength, which is constant along the channel; R is the resistance of the electric circuit connected to the electrodes; r is the resistance of the liquid metal, the contact with the electrodes, and the electrodes; v_0 is the velocity of the piston in the initial cross section; $P_1(x)$ is the gas pressure in front of the piston and varies in accordance with a prescribed law—for instance, in the form of an adiabat Ax^{-k}; P_2 is the pressure behind the piston and is assumed to be constant.

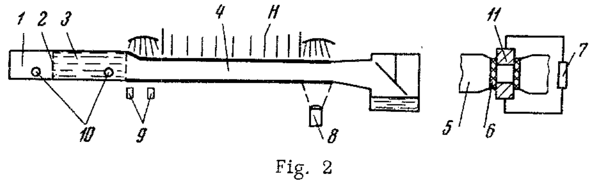

Fig. 2

We can show that for some decreasing function P(x) there is always a solution of (3) which satisfies the boundary conditions

$$x_* = 0, \quad v_* = 1; \qquad x_* = L_*, \quad v_* = 1,$$

where L_* is a completely defined value satisfying the condition

$$\int_0^{L_*} \{D\,[P_{1*}(x_*) - P_{2*}] - 2S_0 v_*\}\,dx_* = 0, \qquad (4)$$

which means that the work of expansion of the gas is spent on overcoming the electromagnetic body forces and, hence, is equal to the

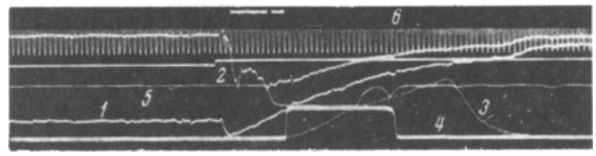

Fig. 3

Joule heat released in all the elements of the closed circuit. This energy, referred to the volume of the channel bhL, is given by the formula

$$e = 2R_m\frac{H^2}{8\pi}$$

$$(R_m = R_{m_0}\langle v_*\rangle)$$

$$\langle v_*\rangle = \frac{1}{L_*}\int_0^{L_*} v_*\,dx_*.$$

If these equations are to be used for calculations, the stability of the liquid-metal piston and, hence, the applicability of the "piston" theory must be verified experimentally. Some support is also provided by the following facts. We have Dering and Cole's experimental data [1] which indicate that the boundary between the gas and water in the expansion of a gas bubble after an explosion remains undisturbed for a fairly long time and there is hardly any mixing of the gas and water. This effect is presumably due to the absence of significant tangential components of the gas velocity at the boundary.

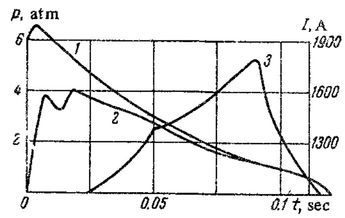

Fig. 4

Such components, as we know from [2], are the reason for the occurrence of unstable capillary waves on the surface of a liquid. We assumed that a suitable choice of the geometry of the gas-admission region and a sufficiently rapid rise of the gas pressure would ensure a "piston-type" flow of the metal.

The motion and stability of the liquid-metal piston were investigated on the experimental setup shown in Fig. 2. A mercury piston of length l = 175 mm, held in container 3, was admitted into the channel 4 (working volume 5 · 5 · 400 mm) in the field of a permanent magnet 5 by breakage of the diaphragm 2 under the pressure of the air contained in reservoir 1. R, a calibrated resistor 7 was connected to the electrodes. If the piston remained whole and in good contact with the electrodes 11 a current flowed in the circuit.

We measured the following quantities: the voltage drop on the load, the air pressure at two points by strain gauges 10, and the distribution of the magnetic field along the channel by an IMI-3 instrument. In addition, before the experiment we measured the electric resistance of the piston at rest by the voltmeter-ammeter method with class 0.5 instruments. The insulating walls 6 were of clear plastic. This enabled us to determine the times when the piston passed a particular point in the channel by means of photodiodes 9 and to photograph the situation before entry into the magnetic field and on emergence from it with a high-speed camera 8. The camera and the photodiodes were illuminated with transmitted light. The quantities which varied in time were recorded on an oscillograph. The time marks on the oscillograph films and on the camera were synchronized.

Fig. 5

Figure 3 shows a typical oscillogram of the process for H = 6000 Oe, $R = r = 1.5 \cdot 10^{-5}$ ohm; in this figure 1) is the pressure in reservoir 1; 2) is the pressure in container 3; 3) is the current; 4) and 5) are the marks of the photodiodes; 6) is the time marking (500 cps). Figure 4 shows the interpretation of the oscillogram.

A photograph of the process in the channel on emergence from the magnetic field and corresponding to the oscillogram is shown in Fig. 5, where 1) is the photographed portion of the channel, 2) is the moving mercury piston, and 3) is the time marking (1000 cps).

In several experiments we recorded the motion of the piston by means of contacts mounted in the electrodes and in the insulating walls. However, we did not succeed in obtaining satisfactory results by this method.

The experimentally measured variation of the current with time and the energy dissipated in the load agree with the calculations made from "piston" theory only if the liquid-metal piston remains in one piece throughout the process.

Any significant rupture of the piston in the actual process will lead to an increase in its electrical resistance, a change in its mass and velocity, in the induced electromotive force and, hence, in the current.

We compared the results of calculation based on the resistance measured at rest with the results of the experiment with the moving piston.

For the calculation we used the equations

$$\frac{l^2}{v_0^2}\frac{d^2x_*}{dt^2} = D\left[(\varepsilon_1+\varepsilon x_*)^{-k} - P_{2*}\right] - 2S_0\frac{l}{v_0}\frac{dx_*}{dt},$$

$$I = \frac{\sigma^\circ H b l^2}{c}\frac{dx_*}{dt}, \qquad E = \int_0^T RI^2\,dt,$$

$$\varepsilon_1 = \frac{V_1}{V_0}, \quad \varepsilon = \frac{V}{V_0}, \quad V = bhl, \quad k = \frac{C_p}{C_v},$$

$$v_0 = \left\{\frac{2P_0V_0}{\rho V(k-1)}\left[1-\left(\frac{V_0}{V_1}\right)^{(k-1)}\right]\right\}^{1/2}. \qquad (5)$$

Here V_1 is the volume of air at the moment when the piston is about to enter the magnetic field; V_0 is the volume of air before the start of the process; v_0 is the velocity of the piston before entry into the channel. For all the quantities we substituted the values used in the experiments. The value of E was determined also from the measured relationship I(t).

Figure 6 shows the calculated and measured values of the electrical energy E for different load resistances. The curve was plotted from the theoretical data and the points represent the experimental results. The agreement between calculation and experiment is quite satisfactory, which indicates that the "piston" theory is valid and also that the motion has no significant effect on the contact resistance between the liquid metal and the electrodes. These data were confirmed by the motion picture frames.

It is important to note that a stable piston is formed when the pressure increase is sufficiently rapid and there is a gradual constriction of the cross section of the metal flow on entry into the channel. It would probably be best to have a constriction with a Vitoshinskii profile, since this would give the most uniform cross-sectional velocity distribution.

In the experiments the cross section at the entry was reduced by half. If there is no constriction the liquid metal and the electrodes do not make electrical contact.

We can postulate that the stability of a liquid piston in the presence of electromagnetic body forces retarding and compressing the

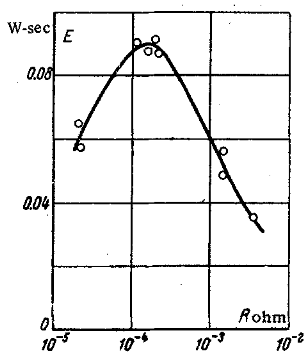

Fig. 6

liquid will be greater than in the case of motion in similar conditions without the transverse magnetic field.

REFERENCES

1. R. Cole, Underwater Explosions [Russian translation], Izd. inostr. lit., 1950.

2. J. B. Strutt (Rayleigh), Theory of Sound [Russian translation], Gostekhizdat, vol. 11, 1955.

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