METAL SHELL COLLAPSED IN A MAGNETIC FIELD

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ABSTRACT: This paper presents the results of experiments on metal shells (liners) collapsed in the magnetic field of a single-turn solenoid. Energies of the collapsing shells of the order of 100 kJ are obtained, i.e., ≈25% of the initial energy of the capacitor bank. The motion of the liner is calculated theoretically with certain simplifications. The experimental data are compared with the theoretical results.

One method of concentrating a large amount of energy in a small space is to use the kinetic energy of a collapsing shell. This shell may conveniently take the form of a thin-walled metal cylinder (liner).

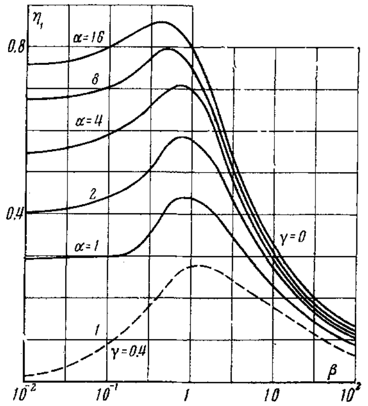

Fig. 1

To accelerate the liner it is customary to employ explosives [1, 2]. However, in laboratory experiments it is undoubtedly more convenient to use magnetic pressure [3]. In this case the energy transfer scheme is as follows: energy of capacitor bank—magnetic field of solenoid—kinetic energy of liner. In order to carry out such an experiment two conditions must be satisfied: the time of compression t_* must be less than the time required for the field to penetrate into the shell, i.e., $t_* < bd/D$ (b is the shell thickness, d the diameter of the shell, and D the coefficient of diffusion of the magnetic field); the pressure of the magnetic field must considerably exceed the ultimate strength of the shell material.

If the second requirement is satisfied, the shell may be regarded as a fluid, and its motion under the action of the magnetic pressure will be described within the framework of magnetohydrodynamics; a theoretical analysis of this motion (in a longitudinal magnetic field) shows that it is stable [4]. This paper presents the results of experiments on the collapsing of metal shells in a magnetic field (metallic theta pinch), which are compared with the data of a theoretical calculation of the motion of the shell. The magnetic field is created with a single-turn solenoid, inside which the shell is placed. Together with the low-inductance leads and power source—capacitor bank—the solenoid forms an RLC circuit. The total capacitance of the capacitors $C_0 = 5 \cdot 10^{-2}$ F, the initial voltage $U_0 = 4$ kV. Typical parameters of the aluminum (grade AD-1M) liners are: outside diameter d = 80 mm, wall thickness B = 2.5 mm, length l = 150 mm, mass M = 250 g; the corresponding parameters for copper (M1 copper) liners are: d = 80 mm, b = 1 mm, l = 150 mm, M = 350 g. In carrying out the experiments we measured the current in the circuit and the voltage on the capacitor bank. The position of the liner was fixed from the end face in transmitted light from a flashlamp (IFK-200) by means of a high-speed photorecorder working in the continuous-recording and time-magnifier regimes.

1. We shall consider the collapse of a conducting metal liner in a longitudinal magnetic field. The problem reduces to the joint solution of the equations of motion of the liner under the influence of the magnetic pressure and the equations describing the electrical processes in the circuit. In the solution the following factors are disregarded: the finite thickness of the liner, the energy lost in deformation, the penetration of the field into the liner, and the variation of the resistance of the circuit with time. With these simplifications the system of equations may be written in the following form (in Gaussian units):

$$M\frac{d^2\delta}{dt^2} = -\frac{I^2}{2c^2}\frac{\partial L}{\partial \delta}, \qquad \delta(t) = r_0 - r(t)$$
$$I = -C_0\frac{dU}{dt}, \qquad U = \frac{1}{c^2}\frac{d}{dt}(LI) + RI. \quad (1.1)$$

Here M is the mass of the liner, r_0 the radius of the solenoid, r the radius of the cylindrical shell, I(t), U(t) the capacitor current and voltage, R, C_0, L(t) the resistance, capacitance and inductance of the circuit, respectively, and c the speed of light. This system of equations was solved with the initial conditions

$$I(0) = \delta(0) = \frac{d\delta}{dt}\Big|_{t=0} = 0, \qquad U(0) = U_0. \quad (1.2)$$

The inductance of the circuit (without allowance for the ends of the solenoid) is easily expressed in terms of $\delta(t)$:

$$L(t) = L_0 + L_1(t) = L_0 + \frac{4\pi^2N^2\delta(t)\,[2r_0 - \delta(t)]}{l}. \quad (1.3)$$

Here L_1 is the inductance of the solenoid liner, L_0 the initial inductance of the circuit, and N, l the number of turns and the length of the solenoid, respectively.

System (1.1) may conveniently be reduced to a system of equations for the dimensionless quantities

$$y = \frac{\delta}{r_0}, \qquad z = \frac{U}{U_0}, \qquad \tau = \frac{ct}{\sqrt{L_0C_0}}.$$

After substitution of the second of Eqs. (1.1) in the third, and with account for (1.3), this system takes the form

$$\frac{d^2y}{d\tau^2} = \beta(1-y)\left(\frac{dz}{d\tau}\right)^2,$$
$$[1 + \alpha y(2-y)]\frac{d^2z}{d\tau^2} + \left[2\alpha(1-y)\frac{dy}{d\tau} + \gamma\right]\frac{dz}{d\tau} + z = 0,$$
$$\alpha = \frac{4\pi^2N^2r_0^2}{L_0 l}, \qquad \beta = \frac{4\pi^2N^2C_0^2U_0^2}{Mc^2 l}, \qquad \gamma = \frac{cR}{\sqrt{L_0/C_0}}. \quad (1.4)$$

The initial conditions (1.2) are changed correspondingly.

The system of nonlinear equations (1.4) has been solved for different parameters α, β, γ on an M-20 electronic computer.

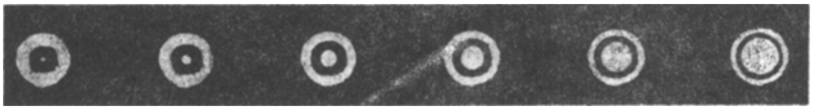

Fig. 2

Figure 1 graphically represents the dependence of the efficiency of the device η on α and β ($\gamma = 0$). The left parts of the curves correspond to slow compression, when the compression time is much greater than the period of the circuit. In this case the adiabatic relation

$$W / f = \text{const} \qquad (1.5)$$

holds true. Here W and f are the power and frequency of the circuit. From (1.5) we obtain

$$\eta = 1 - \frac{1}{\sqrt{1+\alpha}} \qquad (\beta \ll 1).$$

This law is approximately obeyed by the dependence of η and α (at small fixed β) obtained by calculation. The right sides of the curves correspond to the case of rapid compression, when the shell collapses in a time much shorter than the capacitor bank discharge time. In this case the efficiency is low:

$$\eta \approx \alpha / \sqrt{\beta} \ll 1 \qquad (\alpha \ll \beta).$$

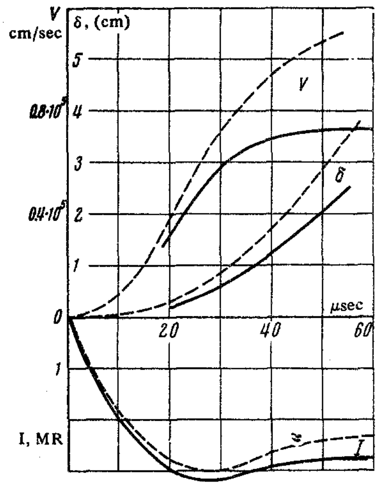

Fig. 3

As might be expected, the optimal value of the parameter $\beta \approx 1$ approximately corresponds to equality of the collapse time and the half-period of the circuit oscillations. In the same figure one of the curves (broken line) corresponds to the case $\gamma \neq 0$. As may be seen from the graph, taking γ into account considerably reduces the efficiency.

2. Figure 2 shows the phases of collapse of an aluminum shell as registered by the photorecorder in the time-magnifier regime. The interval between frames is 8 μsec. In accordance with theory [4], an external longitudinal magnetic field does not create magnetohydrodynamic instabilities. Within the limits of the measuring errors, the cross-sectional area of the ring visible in the photograms remains constant during compression of the shell. This indicates that up to the very moment of collapse the liner retains its original cylindrical shape.

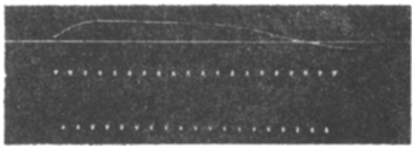

Fig. 4

Figure 3 shows the experimental (continuous curve) and theoretical (broken curve) dependences of the position of the liner δ, its velocity V, and the current in the circuit I on time; from this figure it is clear that the principal acceleration of the liner corresponds to the first half of the path. In the final stage of collapse the retarding forces due to the viscosity of the material and the resistance of the compressed air begin to exert an effect. The kinetic energy accumulated by the liner is converted into the explosive energy that completes the collapse process. The expansion of the conducting cloud formed by the explosion is accompanied by a reduction in circuit inductance. This explains the continuation of the plateau on the circuit current oscillogram after the moment of collapse of the shell (see Fig. 4, where the maximum value of the current is $2.8 \cdot 10^6$ MA and the frequency of the calibration signal 125 kHz). The copper liner is similarly compressed.

By means of frame photography it is possible to obtain a general picture of the motion and stability of the liner. In order to determine the position and velocity of the shell at any moment of time, we recorded the process in the continuous regime. The width of the photorecorder slit was so chosen that the parts of the liner that it cut out could be assumed to be virtually plane at all times during collapse of the shell. Figure 5 shows one of the photographs obtained under these conditions for an aluminum liner, while Fig. 3 presents the curves for δ(t) and V(t) = dδ/dt (continuous lines) obtained after analysis of these photographs. The same figure gives the experimental curve for the current. These curves are contrasted with the calculated curves (broken lines) at corresponding values of the parameters α, β, γ, which were determined from the experimental conditions. A certain deviation from theory may be attributable to inaccuracy in the determination of the parameters α, β, γ, and failure to allow for the hardness (in the initial period of motion) and viscosity (in the final stage of collapse) of the metal.

The kinetic energy of the liner acquired during acceleration $E_* = MV_*^2/2$ (M is the mass, V_* the maximum velocity of the shell in the final stage of compression) reached a value of 100 kJ (efficiency about 25%). This exceeds the previously obtained results of [5]. A metal shell collapsing with an energy of 100 or more kilojoules is undoubtedly of practical interest and could be used for heating plasma, obtaining high magnetic fields, etc.

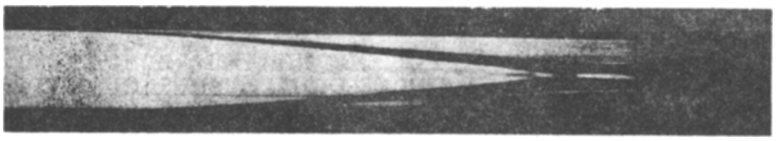

Fig. 5

In conclusion, the authors thank V. A. Polyakov and V. G. Belan for assistance in carrying out the experiments.

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