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Simulation for double shell pinch*

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Basic shock phenomena are presented in a composite pinch, a hybrid of the Z-pinch. The successive transfer of current within the plasma structure is demonstrated by our calculations. Properties of the shock wave are described. The current distribution between the two shells after the outer shell hitting the inner shell is also discussed.

Keywords: Z-pinch, magnetohydrodynamics, shock wave, double shell
PACC: 5255E, 4660H

1. Introduction

High density Z-pinches, which are produced by discharging a high power through a liner or wire array liner, have played a great role in recent researches on high-energy density physics. 2D computer simulations[1] and experimental[2,3] results all show that when the liner is accelerated the Rayleigh–Taylor instability occurs unavoidably. To reduce the effect of this instability the use of a double shell liner[4,5] load or nested wire array system[6] has been suggested. In this system the outer shell is accelerated by a current while the inner shell remains still before being hit. When the outer shell hits the inner one and they are combined together, a shock wave is formed in the inner shell. In this paper this kind of phenomenon is discussed according to our one-dimensional Lagrangian radiation magnetohydrodynamics code.

2. Basic equations

The basic equations of one-dimensional magnetohydrodynamics[7] comprise the laws of conversation of mass, momentum, and energy. The three equations in a cylindrically symmetric system are given by

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} + \frac{\rho}{r}\frac{\partial}{\partial r}(ru) = 0,$$

$$\rho\frac{\mathrm{d}u}{\mathrm{d}t} + \frac{\partial}{\partial r}(p+q) + \frac{1}{r^2}\frac{\partial}{\partial r}\left(\frac{C_\theta^2}{2\mu_0}\right) = 0, \quad C_\theta = rB_\theta,$$

$$e_\mathrm{T}\frac{\mathrm{d}T}{\mathrm{d}t}(q + TP_\mathrm{T})\frac{\mathrm{d}v}{\mathrm{d}t} + \frac{1}{\rho r}\frac{\partial}{\partial r}(rF) - \dot{e}_\mathrm{D} = 0,$$

$$P_\mathrm{T} = \left(\frac{\partial P}{\partial T}\right)_\mathrm{V},$$

$$F = -K\frac{\partial T}{\partial r} - \frac{ac\lambda_\mathrm{R}}{3}\frac{\partial T^4}{\partial r},$$

where ρ and u are, respectively, the density and velocity of plasma resulting from a liner, t is the time, r is the liner radial position, p is the scalar gas pressure, q is the artificial viscosity pressure introduced to facilitate the numerical treatment of shock fronts, B_θ is the magnetic field in an azimuthal (θ) direction, which is produced by the current flowing axially in the liner, v is the specific volume ($v = 1/\rho$), $\dot{e}_\mathrm{D}$ is the ohmic heating rate of the plasma, F is the energy flux vector, μ_0 is the vacuum permeability and λ_R is the Rosseland mean free path.

Maxwell equations in this system can be correspondingly expressed as follows:

$$r\rho\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{C_\theta}{r^2\rho}\right) = \frac{1}{\mu_0}\frac{\partial}{\partial r}\left(\frac{\eta}{r}\frac{\partial C_\theta}{\partial r}\right),$$

where η is the resistivity.

In order to avoid time step limitation resulting from the Courant conditions, the coupling among the highly nonlinear equations is reduced by splitting the equations in our one-dimensional MHD code.

3. Computational results

Computational modelling of the experiment in which energy from a capacitor bank couples directly to an implosion load is discussed as follows. Figure 1(a) shows the discharge circuit containing an implosion load. The characteristic parameters of the circuit are capacitance of the capacitor bank, C=216μF,

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resistance R=0.3mΩ and inductance L=36nH. The load dimensions are described in Fig.1(b). Namely the outer shell has a radius R=5cm and thickness $\delta_1 = 0.2885 \times 10^{-8}$cm, and the inner shell has a radius r=2.5cm and thickness δ_2=0.577 $\times 10^{-8}$cm. The two shells have the same mass, 4.9mg.

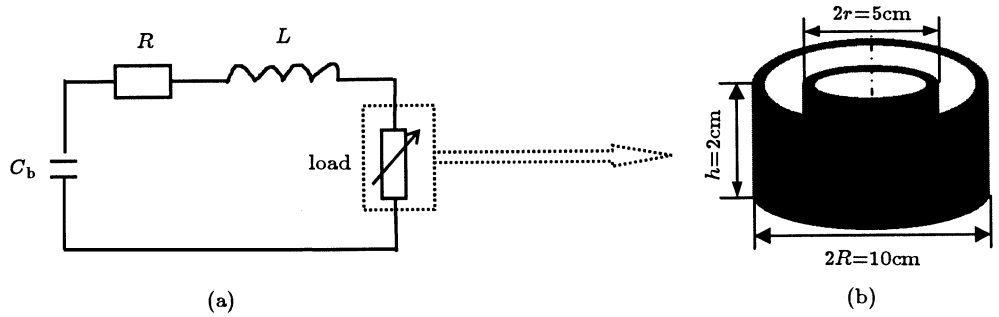


Fig.1. Schematic illustration of (a) an equivalent discharge circuit with a load and (b) aluminium foil load with thickness $\delta_1 = 0.2885 \times 10^{-8}$cm for the outer shell and $\delta_2 = 0.577 \times 10^{-8}$cm for the inner one. The two shells are both 2cm high.

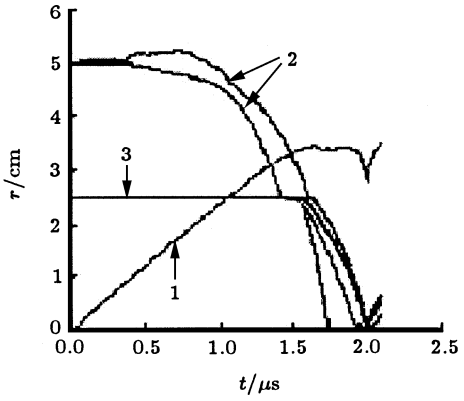


Fig.2. Liner radius vs time. (1) Current in circuit; (2) outer liner; (3) inner liner.

Experiments show that at the initial stage the current concentrates in the outer shell.[8] So in our simulation there is no current flowing through the inner shell before it is hit by the outer shell. Figure 2 displays the position versus time for the two shells. The outer shell is accelerated by the current and pinched towards the axis. About 1.5μs later it hits the inner shell. Then the two shells move together towards the axis and finally reach the axis at 1.7–2.0μs. The outer shell gains a great speed (about 80km/s) before hitting the inner one. While its hitting takes place, shock wave is produced in the inner shell. As shown in Fig.3, the hitting exerts little influence upon the outer shell while great shock takes place in the inner one. This phenomenon was caused by the difference in their states, specifically by the great difference in density between the two shells during the outer shell hitting the inner one. While the inner shell keeps solid, the outer one is heated up and finally vaporized. According to shock wave theory this difference may produce great difference in pressure on the two shells after the shock wave passes by.

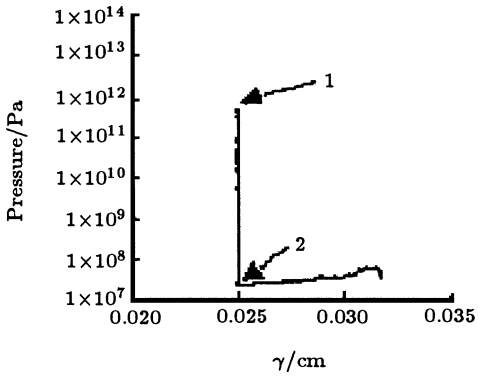


Fig.3. Material pressure at the moment after collision. (1) inner liner; (2) outer liner.

Shock wave thus propagates in the inner shell towards the axis. Figures 4 (a), (b), (c), (d) display the pressure at different times in the process of wave propagation. The propagation of the wave crest from the outside to inside in the inner shell can be seen from the figures. And the wave amplitude decreases. The speed of wave propagation reaches up to 14750m/s from our calculation. This speed agrees quite well with the estimated by shock wave theory. It is found that no shock phenomenon appears in the outer shell. This may be because of the low density of the outer shell due to its heat expansion.

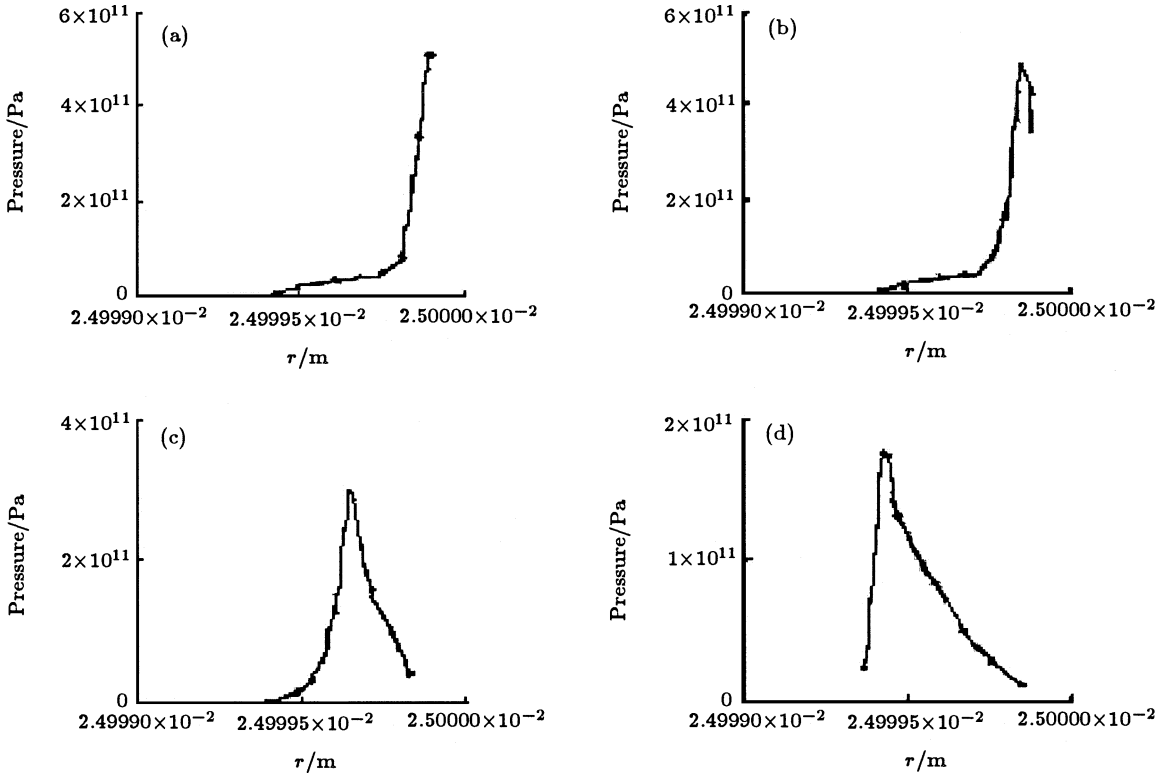


Fig.4. Propagation of shock wave in inner line. (a) t_a=1.799471600844569×10^{-12}, (b) t_a=6.298150602955991×10^{-12}, (c) t_a=1.889445180886797×10^{-11}, (d) t_a=3.329022461562449×10^{-11}, t_a is the pinching duration after collision.

As shown in Figs.5 and 6 the temperature and density of the inner shell increase rapidly after the shock wave.

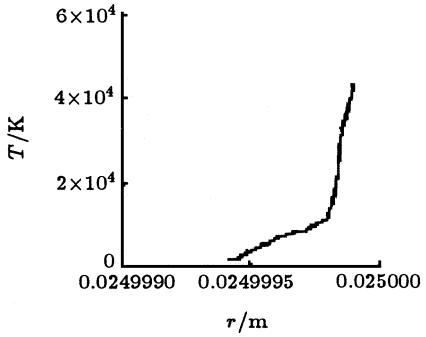


Fig.5. Liner temperature vs position of the inner liner.

After the outer shell hitting the inner one, magnetic field diffuses into the inner shell. The magnetic field diffusion equation is

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) + v_{\mathrm{m}} \nabla^2 \boldsymbol{B},$$

where the second term on the right-hand side is the magnetic diffusion and $v = \sqrt{v_{\mathrm{m}}} = \sqrt{\dfrac{c^2}{4\pi\sigma}}$ is the diffusion speed. It is indicated that the speed v is much larger than the propagation speed of the shock wave. Therefore before the shock wave arrives at the inside of the inner shell, the current and magnetic field have reached and come to accelerate the inside of the inner shell. Certainly, the speed of the inner shell will not be high compared with that of the shock wave because of the short duration of the magnetic force action before the shock arrives at the inside of the inner shell. But this phenomenon is quite different from those in the common collision events.

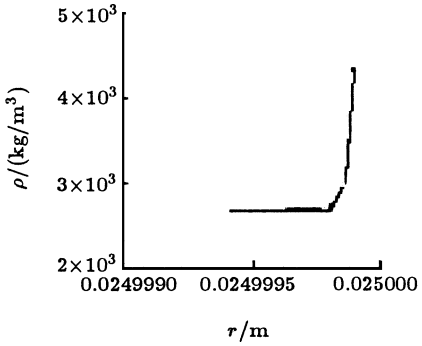


Fig.6. Liner density vs position of the inner liner.

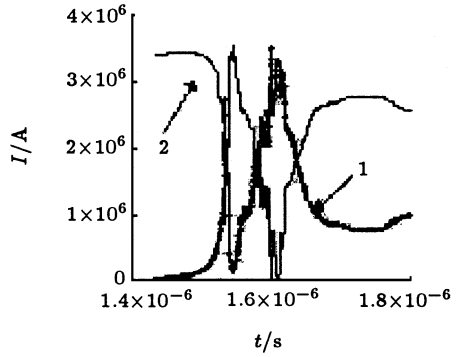


Fig.7. Current distribution between both liners. (1) Inner shell, (2) outer shell.

At the first stage before the outer shell hits the inner one the current concentrates in the outer shell with much lower resistance caused by the larger radius. During the outer shell hitting the inner one the outer shell is heated up to be vaporized, thus its resistance increases while the inner shell still keeps solid state with a relatively lower resistance. Consequently most of the current is shunted from the outer shell into the inner shell. Figure 7 shows the current distribution between the two shells after the outer shell hits the inner one. The value of $\mathrm{d}I/\mathrm{d}t$ can arrive as high as $30\mathrm{MA}/\mu\mathrm{s}$ in the inner shell.

4. Conclusions

We have developed a one-dimensional double region MHD code for Z-pinch simulation. One of our calculations has been discussed in the paper. We obtain a picture of propagation of shock wave in the inner shell, which includes the shock wave crest, wave speed, etc. The current distribution between the two shells after the outer shell hits the inner one has also been discussed. It is indicated that the value of $\mathrm{d}I/\mathrm{d}t$ can be high in the inner shell after it is hit by the outer shell.

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