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Simulation of Electromagnetic Implosion of Metal Shells to Obtain Supercritical Fluids

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Abstract: This study analyzes the conditions for creating the energy density necessary to obtain supercritical fluids of substances with parameters (temperature T > 1 eV, density N > 1022 cm^{-3}, specific energy density ε > 100 kJ/g). The calculations are carried out on the basis of the one-dimensional (1D) two-temperature (2T) magneto hydrodynamic radiation model, which takes into account the physical processes occurring in the energy storage, switching system and the pulsed plasma load-a cylindrical compressible conductive shell. Developing a mathematical model, we assumed that physical processes were self-consistent. The simulation results were presented as time dependences of the main process parameters. Calculations showed that it becomes possible to sharpen the radiation pulse and pressure in the shock wave. As a result, we formulated the requirements for a laboratory energy source to establish the characteristics of a current pulse flowing through a conductive cylindrical shell and its dimensions (radius and thickness) necessary to achieve the goal.

Keywords: supercritical fluids; magneto hydrodynamic radiation model; shock wave

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1. Introduction

This work is a part of fundamental research aimed at obtaining materials with programmable features, which can be used for various purposes, including medical ones. In this article, we consider a numerical analysis of the conditions for creating supercritical fluids by the pulse method [1–3]. In this case, the compression and heating of substances to temperatures and densities exceeding their critical values occurs by a thin-walled metal shell in the process of its electromagnetic implosion. The study conducts full-scale experiments and mathematical modeling of the under-study processes. At present, there has been no single theory provided for the accurate assessment of the matter's thermodynamic properties in a sufficiently wide region of the phase space. The properties of matter in most mathematical models are described by the equations of state and formulas for transport coefficients. The correct choice of equations, therefore, is an important condition for the correct simulation of the conductor's electrical explosion.

There has been considerable interest from researchers on the state of the supercritical fluid of substances with high critical point parameters. This is due to the substance's unique properties in the field of supercritical parameters: phase transitions, compressibility, transfer coefficients, etc. [4–24]. A large group of related physical phenomena are determined by the fact that the possibility of these states means abrupt decay appears. As a result, an aerosol can form with a characteristic particle size of the order of 10–100 nm. To obtain supercritical fluids, it is necessary to create a high energy density in the substance, which is achievable using the methods of pulsed energy injection into a substance with a maximum peak power.

There are several possibilities for obtaining supercritical fluid. The simulation of electrical breakdown in a liquid is given in our previous works [25–27].

One of the methods for creating the required energy density in metals is an electric explosion capable of providing a high current density of 108 A/cm^2 and a high specific power of Joule heating of a substance. However, in this case, the requirements for the power system electrical circuit are extremely high. Requirements may be reduced by using mechanisms of spatial power concentration in the substance. In particular, this can be the magnetic implosion of cylindrical metal shells or multi-wire assemblies on the axis of the considered configuration.

2. Materials and Methods

The electromagnetic implosion of plasma shells makes it possible to obtain large magnetic field pressures with a short-rise front (~10 ns), which can be effectively converted into thermal plasma energy. Moreover, the conversion of magnetic pressure pulses into thermal pressure pulses can be carried out in the exacerbation mode [7].

In this research, we analyze the characteristics of a high-current Z-discharge through the plasma shell (liner), which allows powerful pressure pulses with amplitudes exceeding the critical pressure of many substances to be obtained. Figure 1 shows the configuration of the high-current Z-discharge considered in this work and its power supply system:

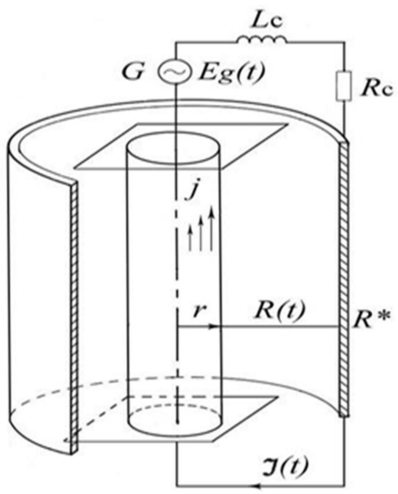

Figure 1. The electrical circuit of the discharge.

The main element of the plasma load is a cylindrical plasma shell consisting of heavy, highly-emitting ions. The plasma envelope is covered by a massive cylindrical shell coaxial, which acts as a "reverse conductor". In the center, along the axis of the plasma shell, a cylindrical plasma bunch with an initial diameter approximately ten times less than the inner initial diameter of the shell can be located. In such a "liner" system, the kinetic energy of the shell when it reaches the axis turns into the energy of a converging cylindrical shock wave. Moreover, before the onset of the shock wave, the plasma of the shell becomes denser; as a result of the compression of the shell, the possibility of sharpening the radiation pulses and pressure in the shock wave appears.

We consider a discharge power supply system based on lines with distributed parameters, which is more promising for use in comparison with systems with lumped parameters. The generator voltage is considered to be a given function of time. The wave impedance of the forming lines is also set as a parameter of the problem (Figure 1).

To describe the dynamics of the plasma shell, we use the approximation of single-fluid two-temperature radiation magnetic hydrodynamics (RMHD). We assume that electrons and plasma ions move as a single medium with one hydrodynamic velocity u and that the electrostatic field is small. In this case, each component has its own temperature T_i and T_e of ions and electrons, respectively. The system of equations was solved in the axisymmetric region, considering the azimuthal and longitudinal components of the electromagnetic field. Ions are heavy particles, considered as one subsystem with internal energy per unit mass E_i and pressure P_i. Electrons, light particles, are another subsystem of the medium with internal energy per unit mass E_e and pressure P_e, respectively. Both subsystems have the same hydrodynamic velocity.

To calculate the plasma composition, we used a simplified version of the impact-radiation model, which takes into account electron impact ionization, dielectronic recombination, triple collision recombination, and photo recombination The main processes that determine the ionization composition of plasma are ionization by electron impact, photo recombination at low density (in the "corona"), and recombination in triple collisions, which plays a role at a sufficiently high density. At a high density of heavy particles, the multiplicity of ionization can be determined using the Saha formulas [8].

The kinetics of ionization can be taken into account using the average ion model, in which the ionization state of the plasma is calculated from the average ion Z [14]. The change in Z in time is described by the equation:

$$\frac{dZ}{dt} = Z \cdot (v_i - v_r - v_\omega), \tag{1}$$

in which the rates of ionization by electron impact v_i, photo recombination v_r, and triple recombination v_ω are taken in the interpolation form.

$$v_i = 10^{-7} \cdot N_i \left(\frac{I_H}{I_Z}\right)^{3/2} \exp\left(-\frac{I_Z}{T_e}\right) \frac{(I_Z/Te)^{1/2}}{1 + (I_Z/T_e)},$$

$$v_r = 3.310^{-31} Z \cdot N_i^2 \left(\frac{I_H}{I_Z}\right)^{3/2} \left(\frac{I_H}{T_e}\right)^{3/2} \frac{(I_Z/T_e)^{1/2}}{1 + (I_Z/T_e)},$$

$$v_\omega = 6 \cdot 10^{-14} \cdot \lambda \cdot N_i \left(\frac{I_Z}{I_H}\right)^{1/2} \left(\frac{I_Z}{T_e}\right)^{3/2} \frac{1}{1 + (I_Z/Te)}$$

At high density, in the equilibrium case $dZ/dt = 0$, we have the system of Saha equations, and in the case of low density and high temperature, the coronal approximation. In this case, the ionization processes are not in equilibrium with increasing temperature.

From a comparison of the reaction rate constants, it follows that photo recombination plays a predominant role under the condition:

$$N_e = ZN_i << 10^{17} \left(\frac{T_e}{I_H}\right)$$

Otherwise, photo processes can be ignored. Then, in the case of equilibrium, we arrive at the Saha model in the Raiser approximation.

$$Z = 3.1610^2 m_i \rho^{-1} T_e{}^{3/2} e^{-\frac{I(Z)}{T}}$$

To simulate plasma dynamics using the RMHD method, we use Lagrangian variables. The system of equations describing the main features of the process under consideration has the following form:

$$\frac{du}{dt} = -r\frac{\partial P}{\partial m} + F;\ \frac{dr}{dt} = u;\ P = P_i + P_e + P_\omega;$$

$$P_\omega = -\rho(\nu + \nu_a)\frac{\partial u}{\partial m} + \mu_a \rho \left(\frac{\partial u}{\partial m}\right)^2; F = -\frac{\rho}{\mu_0 r}\frac{\partial}{\partial m}(rB)^2;$$

$$\frac{d\varepsilon_i}{dt} = -P_i \frac{d}{dt}\left(\frac{1}{\rho}\right) - Q_{ei} - P_\omega \frac{d}{dt}\left(\frac{1}{\rho}\right); \tag{2}$$

$$W_e = -\chi_e \rho^2 \frac{\partial T_e}{\partial m};\ Q_j = \frac{1}{\mu_0 \sigma} E_z \frac{\partial}{\partial m}(rB_\varphi);$$

$$\frac{d}{dt}\left(\frac{B_\varphi}{r\rho}\right) = -\frac{\partial E_z}{\partial m};\ E_z = \frac{\rho}{\mu_0\sigma}\frac{\partial}{\partial m}(rB_\varphi).$$

Here:

ε_i, ε_g—specific internal energy of the ionic and electronic components;
Q_{ei}—rate of energy transfer from ions to electrons;
W_e—heat flow in the electronic component;
Q_j—power of joule heat;
χ_e¯coefficient of electronic thermal conductivity;,
σ—plasma electrical conductivity;
E_z—longitudinal component of the electrical field;
B_ϕ—azimuthal ccomponent of the magnetic field
S—radiation energy flux.

The contribution of radiation to the energy equation for the electronic component is determined by the expression:

$$\frac{\partial S}{\partial m} = \int_0^\infty k_\nu \cdot (U_{\nu p} - U_\nu) \cdot d\nu, U_\nu = 2\int_{-1}^{1} d\gamma \int_{-1}^{1} \frac{I_\nu}{\sqrt{1-\mu^2}} d\mu. \tag{3}$$

In the numerical solution, the frequency integral is replaced by the sum over the spectral intervals, in which the absorption coefficient is assumed to be independent of the frequency:

$$\frac{\partial S}{\partial m} = \sum_{i=1}^{k} k_i(U_{ip} - U_i). \tag{4}$$

The magnetic field at the shell boundary is determined by the current flowing through the shell, which depends on the characteristics of the electrical circuit. For the stationary case, the equation is written as:

$$Ug(t) - R_\rho I - L_C\frac{dI}{dt} - \frac{d}{dt}(L_\Delta I) = 0. \tag{5}$$

Here, L_C is the inductance of the electrical circuit; L_Δ is the gap inductance "reverse" conductor, the outer surface of the plasma envelope.

As equations of the state of the shell plasma and the plasma bunch, we applied the generalized equations of state of the "average ion" type [10], in which we used the results of calculating the ionization according to the simplified impact-radiation model described above. The calculation of plasma transfer coefficients is based on a wide-range semi-empirical model described in [13,14].

The equations of plasma dynamics, together with the equations of the electric circuit, radiation transfer, and the ionic composition of plasma, are solved by a completely conservative implicit difference scheme implemented by the combined sweep method.

3. Results

We considered the process of the electromagnetic implosion of a cylindrical plasma shell with an outer radius of 0.02 m and an inner radius of 0.01 cm, obtained as a result of an electric explosion of a cylindrical aluminum shell. The simulation results are shown in Figures 2–5. The initial values of the plasma temperature and density are T_0 = 0.7 eV and ρ_0 = 0.05 g/cm^3, respectively. The characteristics of the initial state of the plasma are chosen so that the initial temperature of the plasma is approximately equal to the critical temperature of the metal, and the density is less than the density of the metal at the critical point by more than an order of magnitude. The values of the critical parameters for aluminum and copper are presented in Table 1.

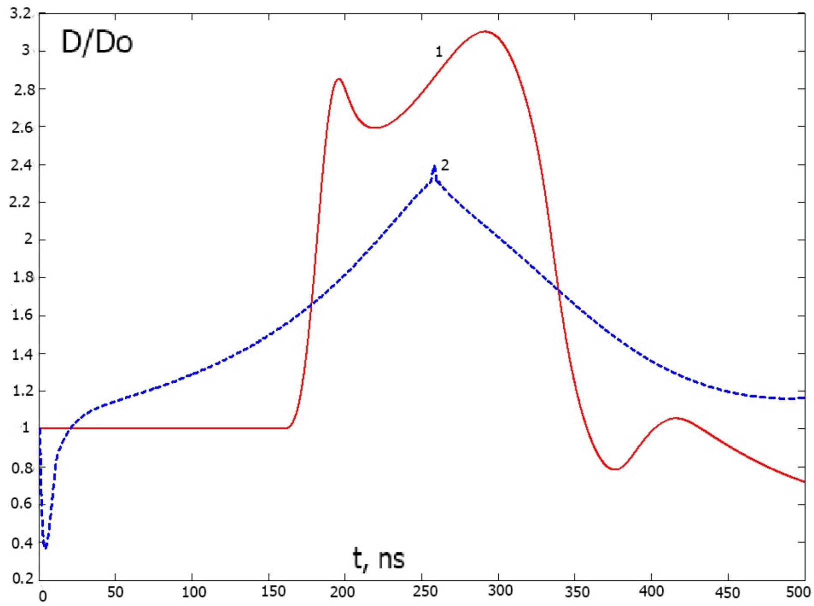

Figure 2. Change in density on the axis (1) and at the plasma boundary (2). The plasma density on the axis exceeds the critical value for 15 ns.

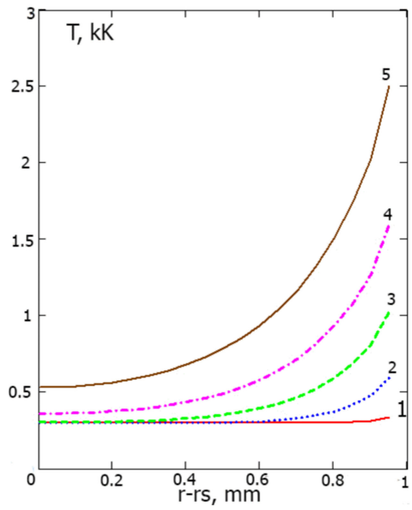

Figure 3. Radial temperature distributions in a copper cladding 1 mm thick at different times; *t*, ns: 1–5, 2–20, 3–50, 4–100, 5–200.

Table 1. Critical parameters of metals.

Temperature, K	Density, g/cm^3	Pressure, GPa
Aluminum, 8000	0.64	0.45
Cuprum, 8400	0.89	0.75

The temporary change in the discharge current is shown in Figure 2. The amplitude of the current pulse is ~90 kA; the front of the current rise is about 20 ns. The magnetic fields pressure of the magnetic field on the shell's surface PB = 6 GPa.

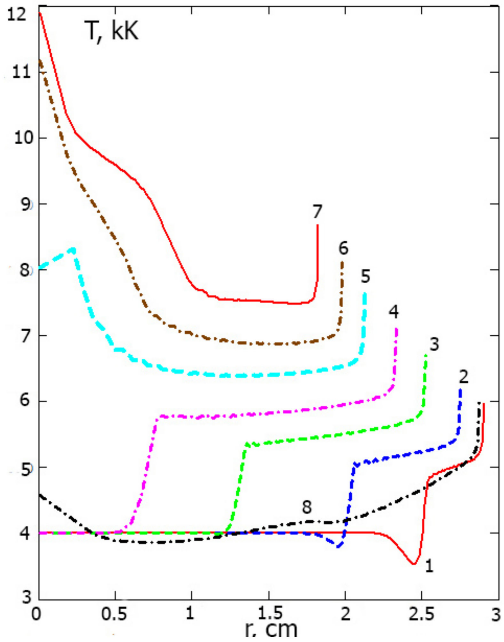

Figure 4. Temperature distributions of plasma compressed by a copper sheath; *t*, ns: 1–50, 2–80, 3–120, 4–150, 5–180, 6–200, 7–300, 8–360.

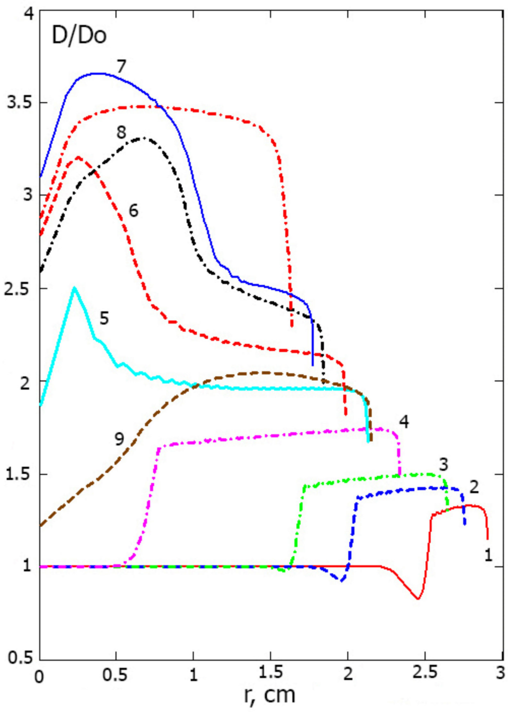

Figure 5. Density distributions of the plasma compressed by the shell at different times; *t*, ns: 1–50, 2–80, 3–100, 4–150, 5–180, 6–200, 7–220, 8–260, 9–290.

4. Discussion

The study revealed the following features of the process.

In order for the plasma compression to be effective, it is necessary to form a magnetic piston that compresses the plasma towards the axis. Therefore, the current rise time t_0 must be less than the plasma compression time $t_{imp} \sim R_0/U_A$, where R_0 is the initial plasma radius and U_A is the Alfen velocity.

The relationship $D_s << R_0$ must also be satisfied; where D_s is the thickness of the skin layer. These conditions determine the requirements for matching the characteristics of the current pulse and the plasma load, as well as the initial states of the plasma (temperature and density).

The efficiency of gas (plasma) compression decreases if during the compression time the magnetic field of the current flowing through the shell penetrates into the shell. Therefore, the thickness Δr of the shell is chosen from the condition that, during the compression time, the magnetic field of the discharge current does not penetrate inside the shell, i.e., skin layer thickness $\delta S < \Delta r$. No less important is the condition that, during the compression, the shell substance remains in a condensed (solid or liquid) state, i.e., will not heat up above the temperature at which intensive vaporization begins. These conditions determine the shell thickness Δr. We find this quantity by considering the nonlinear diffusion of a pulsed magnetic field into a cylindrical heating shell.

Under the action of an increasing magnetic field, a shock wave propagates through the plasma of the liner. As a result, the ions are heated more strongly than electrons. Electrons continuously lose energy mainly through radiation. The ion-electron energy exchange due to elastic collisions is not effective due to the small value of the mass ratio of electrons and ions.

The magnetic field of the discharge current acting on the outer boundary of the plasma leads to the formation of a relatively narrow layer of dense high-temperature, highly-ionized plasma near the outer boundary of the shell. In the process of accelerating the shell to the axis, the plasma density in this layer increases to values greater than the initial plasma density in the shell by more than an order of magnitude. The temperature of electrons and the average charge of ions increase several times.

It should be noted that, at the stage of acceleration of the shell toward the axis, the inclusion of radiation does not have a strong effect on the plasma dynamics. When the radiation is taken into account, the maximum electron temperature and the thickness of the dense high-temperature layer turn out to be no more than 20% less than without taking it into account.

At the final stage, the plasma envelope accelerated to high speeds accumulates at the axis. As a result, the kinetic energy is converted into the thermal energy of the plasma, and a clot of dense high-temperature, highly ionized plasma is formed, in which a pulse pressure is formed that exceeds the maximum pressure of the magnetic field created by the discharge current. The pressure pulse duration is $\Delta\, t \;=\; \Delta\, r/U_r$. In this study, there is a maximum pressure that is several times greater than the pressure at the critical point.

A plasma bunch formed on the axis effectively emits in the short-wave spectral range. At this stage, radiation plays an essential role. Plasma parameters determined with and without radiation transfer can differ by more than two times. As the results of calculations of the photon path lengths show, averaged "over the bar" and "over the Rosseland" are many times larger than the characteristic size of the cross-section of the plasma bunch formed on the axis. Therefore, plasma can be considered transparent in the continuum.

5. Conclusions

An idealized version of the plasma shell electromagnetic implosion, which does not take into account important factors such as line radiation and the development of instabilities, was considered. According to preliminary estimates, these factors can reduce the plasma parameters, which are formed approximately 1.5–2 times in the process of shell accumulation at the axis. This limits, but does not exclude, the possibility of obtaining the considered method of supercritical states of substances using moderately high currents (I ~ 100 kA).

Thus, the calculations show the fundamental possibility of obtaining a supercritical fluid by the method of electromagnetic implosion.

It is possible to continue this research work in the following directions. Firstly, the current pulses considered in the calculations can be obtained, but technologically, this is not an easy task, due to the stringent requirements for the total inductance of the electro-physical system. Secondly, the paper considers rather high initial parameters of the plasma state.

In this regard, it is expedient to consider implosion at longer fronts of the current pulse and at lower initial plasma parameters.

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