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Magnetohydrodynamic Behaviour of Warm Dense Plasmas Created by Underwater Wire Explosion

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Abstract

A time-dependent one-dimensional magnetohydrodynamic (MHD) simulation is carried out for metal plasmas and shocked water produced by electrical wire explosion in water bath. A practical Saha-type equation-of-state (EOS) model for warm dense plasmas is utilized and, in case of electrical conductivity calculation, the strong Coulomb interactions between ions and electrons are taken into account. The initial plasma condition can be presumed from the shock propagation hydrodynamics in the underwater electrical wire explosion experiments that have been performed with aluminium or copper wire. Hydrodynamic behaviours in microsecond time scale have been observed by a fast framing camera, and from the photograph we obtain the evolution of the cylindrical plasma surface and the shock front trajectory in water. Current and voltage profiles of the plasmas have been also measured. Plasma temperatures are determined indirectly from the plasma EOS model used in MHD calculations. The measured electrical conductivities of the aluminium or copper plasma have been compared with the numerical simulation results.

I. INTRODUCTION

Plasmas in warm and dense conditions are of special interest in concern with their nonideal physical properties such as the high degree of ionization induced by pressure. In recent years, electrical discharge of thin metal wires in water bath made it practically possible to produce stable warm dense plasmas and further to measure the electrical conductivity in the regime of insulator-metal transition [1]. However, due to difficulties of diagnostics in those dense plasma experiments, magnetohydrodynamic (MHD) simulation is necessarily carried out at the same time for better understanding of the exploding wire behaviours [2].

The MHD simulation requires proper equation of state (EOS) models for both the wire material and water to describe the exploding plasma and the water shock propagation simultaneously. In this work, we use a semi-empirical EOS model for water given around the room temperature [3] and a Saha equilibrium EOS for wire metals in combination with the electrical conductivity model of nonideal plasma [4].

The calculated MHD behaviours of exploding metal plasma and water shock are compared with the measured experimental data obtained with a high-speed frame camera. We also check the validity of the nonideal plasma conductivity model employed in this simulation by evaluating the electrical conductivities of plasma column from the measured resistance.

II. SIMULATION MODEL

Figure 1 schematically illustrates the wire explosion and the water shock propagation (a) before and (b) after discharging. We assume that, shortly after the current is applied to the electrodes, the metal wire is instantly turned into uniform plasma of a certain temperature higher than the vaporization temperature and the current flows through the plasma column only. The initial temperatures of plasmas are presumed to be 6 000 K for aluminium of 76.2 μm radius and 7 000 K for copper of 63.5 μm radius.

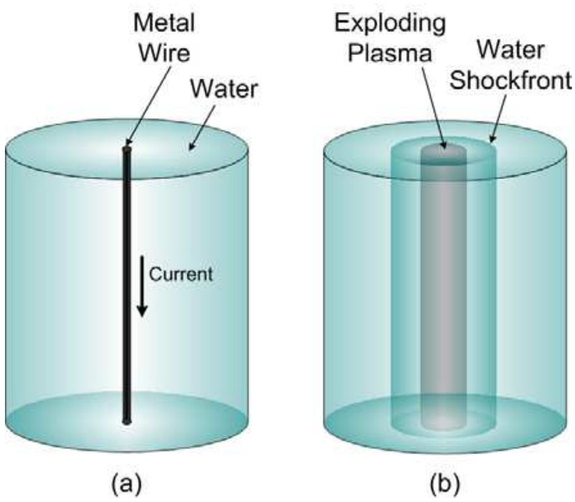

FIG. 1. Schematic diagram of metal wire explosion in water (a) before and (b) after discharging.

In this one-dimensional numerical model, the thermodynamic and magnetohydrodynamic behaviours of plasma and water are described by a set of governing equations consisting of the equations of motion, momentum conservation, energy conservation, magnetic field, current density, and the equation of state as follows:

(1) Equation of motion $$\frac{dr}{dt} = u,$$

(2) Momentum conservation $$\rho \frac{du}{dt} = -\frac{\partial p}{\partial r} - \frac{B}{\mu_0}\frac{1}{r}\frac{\partial}{\partial r}(rB),$$

(3) Energy conservation $$\frac{d\varepsilon}{dt} + p\frac{d}{dt}\left(\frac{1}{\rho}\right) = \frac{1}{\rho}\left[\frac{j^2}{\sigma} + \frac{1}{r}\frac{\partial}{\partial r}\left(r\kappa\frac{\partial T}{\partial r}\right)\right],$$

(4) Magnetic field $$\frac{dB}{dt} = \frac{1}{\mu_0}\frac{\partial}{\partial r}\left[\frac{1}{\sigma r}\frac{\partial}{\partial r}(rB)\right] - B\frac{\partial u}{\partial r},$$

(5) Current density $$j = \frac{1}{\mu_0 r}\frac{\partial}{\partial r}(rB),$$

(6) Equation of state $$p = p(\rho, T), \quad \varepsilon = \varepsilon(\rho, T).$$

The external current applied to the wire is approximated to be a single short pulse with the peak value of 9 kA decreasing to zero in 0.4 μs and this current profile provides the time-dependent boundary condition for magnetic field on the plasma surface. The point of time when the wire material is believe to have completely turned into plasma state is guessed from the experimental observations of the wire radius expansion.

An ideal Saha equilibrium approximation is used to model the thermodynamic properties of exploding plasma while the electrical conductivity data is from ionization balance calculation with nonideal effects taken into account [4]. The water EOS is given by a semi-empirical formulation that is valid up to a few hundred kbar [3].

III. RESULTS AND CONCLUSTIONS

The MHD model equations presented above have been transformed into numerically viable finite difference forms and then the metal wires exploding in water are simulated for two wire materials: aluminium and copper. The initial diameters of aluminium and copper wires are 0.006 in (152.4 μm) and 0.005 in (127.0 μm) to match the experimental setup.

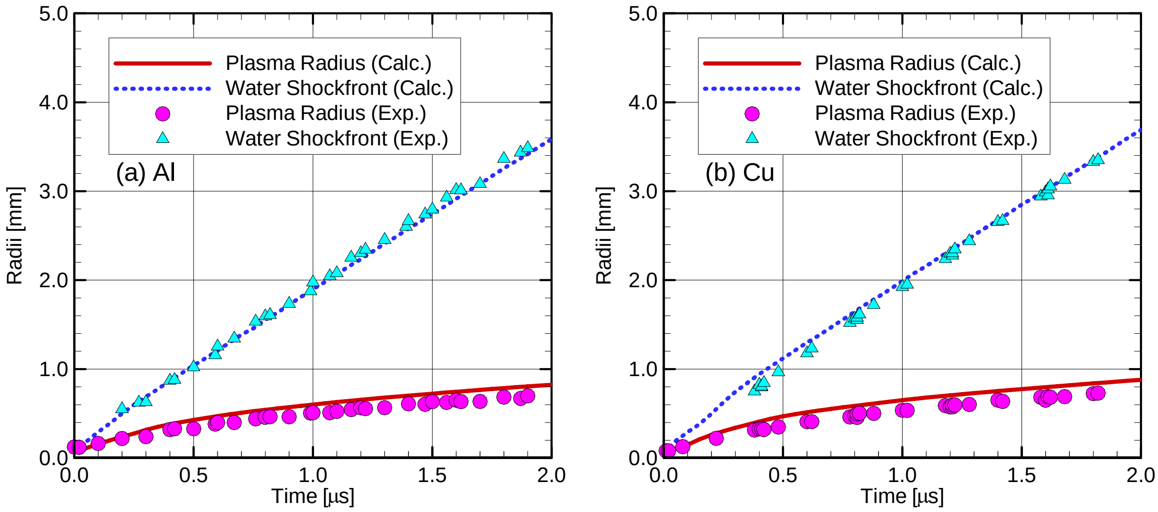

FIG. 2. Calculated trajectories of plasma column radii and water shockfronts of (a) aluminium and (b) copper wires.

Figure 2 shows the calculated trajectories of plasma column radii and water shockfronts of (a) aluminium and (b) copper wires in comparison with the experimental data from the photo shots taken by a frame camera. In this figure, the calculated speeds of plasma surface expansion are up to 20% higher than the measured values for both wire materials while the shock propagations in water agree well in two results. Nevertheless, the simulation, employing the Saha equilibrium EOS combined with a nonideal plasma conductivity model, seems reproducing the overall behaviours of exploding wires to a reasonably acceptable degree.

The calculated temporal profiles of electrical conductivities are plotted in Fig. 3 with the data obtained from experiments for (a) aluminium and (b) copper. The solid lines in this figure represent the values averaged over the plasma column. The calculated conductivities appear higher than those measured, in particular, after 0.2 μs. The overestimated conductivities in calculation are related to the temperature profiles sustained high to correspond the EOS models used in this simulation. However, since the total current vanishes and consequently there is no Joule heating in plasma after 0.4 μs, the effect of electrical conductivity on hydrodynamics can be practically ignorable.

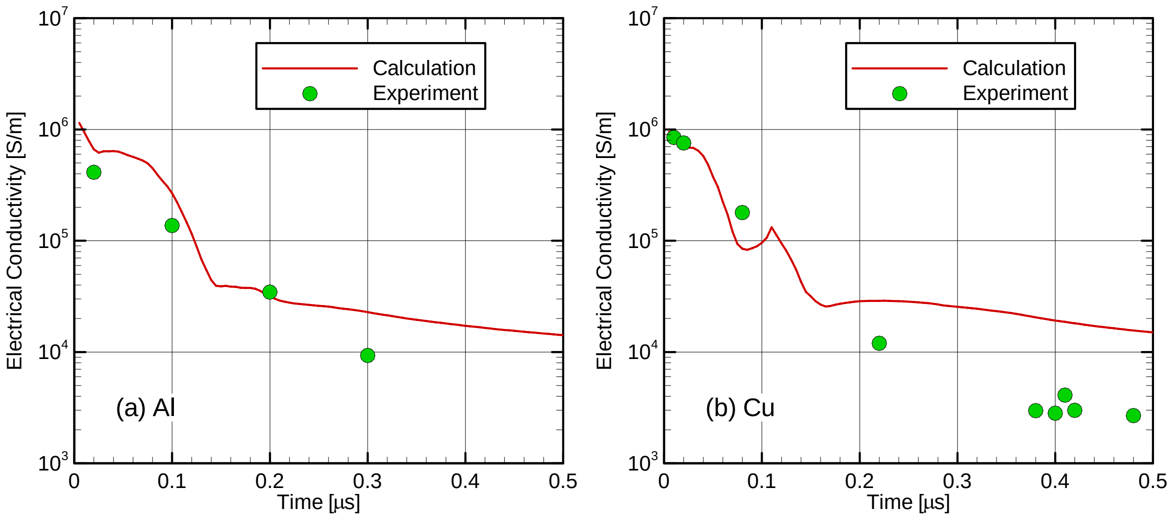

FIG. 3. Electrical conductivities of (a) aluminum and (b) copper plasmas during the Joule heating stages.

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