Numerical simulation of the initial plasma formation and current transfer in single-wire electrical explosion in vacuum*

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In this paper, a computational model is constructed to investigate the phenomenon of the initial plasma formation and current transfer in the single-wire electrical explosion in a vacuum. The process of the single-wire electrical explosion is divided into four stages. Stage I: the wire is in solid state. Stage II: the melting stage. Stage III: the wire melts completely and the initial plasma forms. Stage IV: the core and corona expand separately. The thermodynamic calculation is applied before the wire melts completely in stages I and II. In stage III, a one-dimensional magnetohydrodynamics model comes into play until the instant when the voltage collapse occurs. The temperature, density, and velocity, which are derived from the magnetohydrodynamics calculation, are averaged over the distribution area. The averaged parameters are taken as the initial conditions for stage IV in which a simplified magnetohydrodynamics model is applied. A wide-range semi-empirical equation of state, which is established based on the Thomas–Fermi–Kirzhnits model, is constructed to describe the phase transition from solid state to plasma state. The initial plasma formation and the phenomenon of current transfer in the electrical explosion of aluminum wire are investigated using the computational model. Experiments of electrical explosion of aluminum wires are carried out to verify this model. Simulation results are also compared with experimental results of the electrical explosion of copper wire.

Keywords: single-wire electrical explosion, plasma formation, current transfer

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1. Introduction

Single-wire electrical explosion has been encountered in many physical fields, such as material property study under extreme conditions,[1] dense plasma generation,[2] and synthesis of nanopowder.[3] A better understanding of the physics of the single-wire electrical explosion is important for its effective utilization. In the experiments of the single-wire electrical explosion, a binary structure has been observed, i.e., a high-density, low-temperature core which exists until late into the discharge, surrounded by a low-density, high-temperature corona.[4] The core–corona structure is formed due to voltage breakdown of the metal vapor. The energy deposition into the wire terminates or is substantially suppressed at the moment of the voltage collapse with the current switching from the core to the conductive plasma.[5] The metal wire experiences severe phase transition from solid state to plasma state in the process of single-wire electrical explosion under the intense action of the pulsed current. A number of experimental investigations on the exploding wires have been carried out to study the factors affecting the energy deposition during the resistive stage.[6] The optical diagnostics with high spatial and temporal resolution are used to investigate the characteristics of the exploding products.[7,8] Numerical investigation is an essential approach to gain in-depth insight into the dynamics of the single-wire electrical explosion. The magnetohydrodynamics (MHD) simulation of electrical explosion of aluminum (Al) wire has been reported by Sarkisov.[9] An MHD simulation of fast exploding tungsten wire was presented by Tkachenko with the metastable state of the liquid metal taken into consideration.[10] A simplified MHD model has been proposed by Beilis to investigate the shunting discharge of the electrical explosion of tungsten wire.[11] Although the simplified model for electrical explosion of tungsten wire has the advantage of less calculation, several elements of experimental data are introduced as empirical parameters. The complete MHD models are more accurate, however, the algorithm is complicated and the calculation is time consuming, even for a one-dimensional MHD model. Therefore, the computational model with accuracy and amount of calculation taken into consideration is useful and necessary for investigating the specific phenomena in the single-wire electrical explosion.

In this paper, a computational model is constructed to investigate the initial plasma formation and the phenomenon of current switching from the core to corona with "cold start" conditions. The process of the single-wire electrical explo-

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sion is divided into four stages according to the state of the wire. A wide-range semi-empirical equation of state based on the Thomas–Fermi–Kirzhnits (TFK) model is constructed to describe the phase transition from solid state to plasma state. The conductivity is calculated by Lee–More–Desjarlais model combined with non-ideal Saha equation. The simulated results of the electrical explosion of aluminum wire are presented and compared with the relevant experimental results, which are conducted on a current pulse generator. This model is also verified by the experimental data of the electrical explosion of copper (Cu) wire.

2. The physical model

The metal wire experiences severe phase transition from solid state to exploding plasma in the process of single-wire electrical explosion. Four stages are proposed in this model to describe the behavior of the exploding wires. The solid wire and the melting stage correspond to stage I and stage II, respectively. In stages I and II, the thermodynamic calculation is adopted. After the wire is melted completely, stage III begins until the moment of the voltage breakdown on the wire surface, during which a one-dimensional MHD model is applied to describe the behavior of liquid metal and the formation of the initial metal vapor. Subsequently, the core and corona expand separately in stage IV, in which the phenomenon of the current transfer with the development of the corona is calculated by a simplified MHD model.

The wire is in stage I when it is in solid state. The stage II is the melting stage which corresponds to the transition from solid to liquid state. The thermal expansion of the wire is ignored in stages I and II. The thermodynamic calculation, which is accurate at least up to the instant when the wire melts completely, is applied to describe the heating of the metallic wire. The energy deposition $\mathrm{d}E$ within the time duration $\mathrm{d}t$ can be expressed by[12]

$$\mathrm{d}E = I^2 R \mathrm{d}t, \tag{1}$$

where I is the current, R is the resistance, and $R = 4L/\sigma\pi d^2$ where σ, L, and d are the conductivity, length, and diameter of the wire, respectively. The dependence of the temperature rise $\mathrm{d}T$ and energy deposition in stages I and II is denoted by

$$\mathrm{d}T = \frac{\mathrm{d}E}{mC}, \tag{2}$$

where m is the total mass and C is the heat capacity.

Once the wire is melted completely, the wire comes into stage III. The radial distribution of the density and velocity are calculated using the following set of one-dimensional MHD equations under the cylindrical coordinate with one temperature approximation:[13]

$$\frac{\partial \rho}{\partial t} + \frac{1}{r}\frac{\partial (r\rho u)}{\partial r} = 0, \tag{3}$$

$$\frac{\partial (\rho u)}{\partial t} + \frac{1}{r}\frac{\partial \left(r\rho u^2\right)}{\partial r} = -\frac{\partial p}{\partial r} - j_z B_\varphi, \tag{4}$$

where ρ, u, j_z, and p are the density, velocity, current density, and pressure, respectively. B_φ is the magnetic induction which is derived by the magnetic field diffusion equation

$$\frac{\partial B_\varphi}{\partial t} + \frac{\partial \left(uB_\varphi\right)}{\partial r} = \frac{\partial}{\partial r}\left(\frac{1}{\mu_0 \sigma r}\frac{\partial \left(rB_\varphi\right)}{\partial r}\right). \tag{5}$$

The temperature rise of the uniform liquid wire is calculated by Eq. (2). The metal vapor expands freely into the vacuum and the Joule heating is negligible before the voltage breakdown in the region of the low-density metal vapor.

Equations (3) and (4) are solved explicitly with NND method.[14] The magnetic field diffusion equation is backwards differenced and solved implicitly with chasing method. The one-dimensional MHD calculation is carried out until the instant when the voltage breakdown happens. This point is determined by the critical temperature.[15] Then, the conductive plasma plays a significant role in the subsequent period of the discharge.

The main purpose of this paper is to construct a computational model without introducing much experimental and semi-empirical data for predicting the initial plasma formation and the phenomenon of current transfer from the wire core to plasma with a relative accuracy and less calculation. Therefore, a simplified MHD model is adopted in the following stage IV. Beilis proposed several treatments to the MHD equations to investigate the dynamics of the plasma layer for exploding pre-heated tungsten wire, which greatly reduced the computations.[11] The initial vapor density was estimated by a temperature-dependent saturated tungsten vapor in their calculation. The expansion velocity of the tungsten plasma was derived based on the thermal velocity of the tungsten ions. The initial corona plasma radius was calculated through the assumption that the plasma expanded 10 ns with the thermal velocity before coming into play.

In the present work, the plasma parameters at the end of stage III are averaged over the computational region. Those averaged values, e.g., density, velocity, and temperature, are taken as the initial conditions for the following stage IV. The simplified MHD model is with two temperature approximation.[11] In order to deduce the simplified MHD equations, the momentum conservation equation and the energy conservation equation are treated by differential operation combined with Eq. (3) as follows:[11,13]

$$\rho\frac{\partial u}{\partial t} + \rho u\frac{\partial u}{\partial r} = -\frac{\partial p}{\partial r} - j_z B_\varphi, \tag{6}$$

$$\rho\frac{\partial e_\mathrm{e}}{\partial t} + \rho u\frac{\partial e_\mathrm{e}}{\partial r} = -p_\mathrm{e}\left(\frac{\partial u}{\partial r} + \frac{u}{r}\right) + \frac{j^2}{\sigma} - Q, \tag{7}$$

$$\rho\frac{\partial e_\mathrm{i}}{\partial t} + \rho u\frac{\partial e_\mathrm{i}}{\partial r} = -p_\mathrm{i}\left(\frac{\partial u}{\partial r} + \frac{\rho u}{r}\right) + Q, \tag{8}$$

where $e_e = 3/2zk_bT_e/m_i + \varepsilon_{ion}$ and $e_i = 3/2k_bT_i/m_i$. ε_{ion} is the sum of the ionization potential per unit mass. m_i is the mass of the Al ion. z is the average ionization degree. T_i and T_e are the temperatures of the ion and electron, respectively. k_b is the Boltzmann constant. p_e and p_i are the pressures released by electron and ion, and $p = p_e + p_i$. Q is the energy exchange between the electrons and ions. $Q = 3m_e n_e \nu_{ei} k_b (T_e - T_i)/m_i$, in which n_e and m_e are the electron number density and electron mass respectively, and ν_{ei} is the collision frequency between the electron and ion. It is assumed that the expanding velocity of the plasma increases monotonically with the position r and the current has a uniform distribution in core and corona. The magnetic field in stage IV is calculated by Ampere's circulation theorem.

Thus, equations (6)–(8) can be changed to the following forms by integration in cylindrical coordinate within the section of the corona:[11]

$$\frac{m_i N_i}{R_c}\frac{dV}{dt} = \frac{2N_i(zk_bT_e + kT_i)}{R_c^2 - R_w^2} - \frac{\mu_0}{2\pi}\frac{(I - I_w)^2}{R_c^2 - R_w^2} - \frac{\mu_0 (I - I_w)(I_w R_c^2 - I R_w^2)}{\pi (R_c^2 - R_w^2)^2}\ln\frac{R_c}{R_w}, \quad (9)$$

$$\frac{3}{2}k_b\frac{\partial T_i}{\partial t} = -\frac{kT_i V R_c}{R_c^2 - R_w^2} + \frac{3m_e}{m_i} z\nu_{ie} k_b (T_e - T_i), \quad (10)$$

$$\left(\frac{3}{2}k_b z + \frac{3}{2}k_b T_e\frac{\partial z}{\partial T_e} + m_i\frac{\partial \varepsilon_{ion}}{\partial T_e}\right)\frac{\partial T_e}{\partial t} = -\frac{zk_bT_eVR_c}{R_c^2 - R_w^2} + \frac{(I - I_w)^2}{\pi N_i \sigma (R_c^2 - R_w^2)} - \frac{3m_e}{m_i} z\nu_{ei} k_b (T_e - T_i), \quad (11)$$

where I_w is the current remaining in the core; R_c and R_w are the radius of corona and core, respectively; N_i is the number of ions per unit length of the corona; V is the velocity in the corona boundary. When the wire reaches stage IV, the one-dimensional MHD calculation in stage III terminates. From the numerical and experimental investigation of the single-wire electrical explosion,[9] it is phenomenologically acceptable that the core expands with a constant velocity approximately. Therefore, we assumed that the core expands with a constant velocity, which is calculated by the one-dimensional MHD model in stage III.

3. Equation of state and conductivity

In the numerical simulation of the single-wire electrical explosion, the equation of state and transport coefficients play a very crucial role in simulating the behavior of the exploding wires.

A wide-range semi-empirical equation of state, consisting of three terms, i.e., the cold term, the thermal contributions of electrons and ions, is constructed. For the cold term, the polynomial expression[16] is adopted. Thomas–Fermi (TF) model is widely used in the equation of state computations. However, TF model yields a very high pressure in the region of sub-solid density at low temperature. In order to describe the behavior of the condensed state, Kirzhnits introduced the quantum and exchange corrections into the TF model to reduce the pressure released by electrons, leading to the Thomas–Fermi–Kirzhnits (TFK) model.[17] The TFK model makes it possible to describe the phase transition from solid state to plasma state to be approximated. Thus, the TFK model is applied to calculate the thermal contribution of electrons. The thermal contribution of ions is derived from a kind of quasi-harmonic model.[18] The pressure of Al generated by the semi-empirical equation of state is shown in Fig. 1. The dashed line illustrates the trajectory of the pressure from the degenerate state to the ideal gas state in the process of electrical explosion of Al wire.

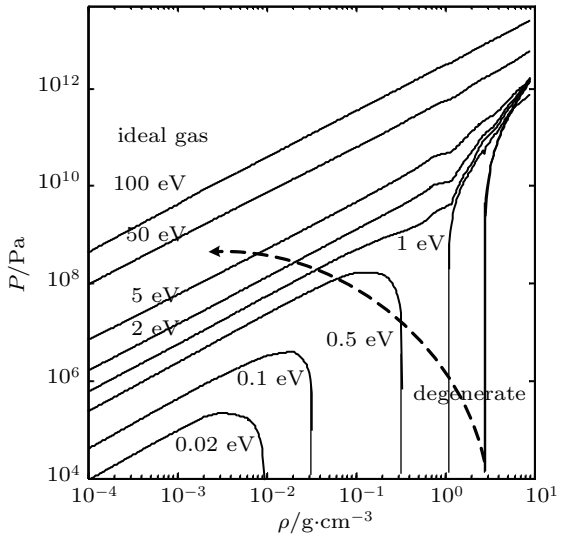


Fig. 1. The pressure of Al as a function of density at different temperatures.

The conductivity is determined by the Lee–More–Desjarlais model.[19,20] The ionization equilibrium is calculated by non-ideal Saha equation which is derived by the ideal free energy with the non-ideal effects taken into consideration.[21] The Coulomb interaction between charged particles, e.g., electron–electron, electron–ion, and ion–ion, are calculated by Padé approximation.[22] The hard-sphere model is used to describe the excluded volume effect induced by the high density. The polarization contribution from the interaction between the atoms and charged particles is also added to the non-ideal effects in the regime of partially ionized plasma.[23]

It is convenient to apply the semi-empirical equation of state and the conductivity model for other metal materials.

4. Simulation results and comparison with experimental data

A set of experiments are conducted on a pulsed current generator to verify the model discussed above. The electrical schematic diagram of the experimental setup is presented in Fig. 2. $C_p = 17$ nF is the primary energy-storage capacitor and $C_s = 150$ pF is the secondary energy-storage capacitor. A self-breakdown nitrogen-charged switch S is adopted in the secondary discharge circuit. It is convenient to control the breakdown voltage by adjusting the nitrogen pressure. PT is a pulse transformer with a ratio of 1:4. H is a hydrogen thyratron which is controlled by a trigger module. A negative discharging current is delivered to the load when H is switched on. The experimental setup can be operated to generate the pulsed current with magnitude of ~ 1 kA and rising rate of 80–170 A/ns. The current flowing through the wire and the voltage across the anode and cathode are measured with Rogowski coil and resistive divider, respectively.

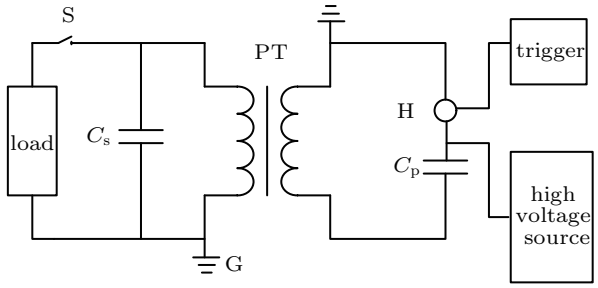


Fig. 2. The electrical schematic diagram of the experimental setup.

The typical experimental waveforms of the voltage and current for the electrical explosion of 20-μm-diameter, 2-cm-long Al wire are shown in Fig. 3. The inner pressure of S and the voltage of C_p are charged to 4 atm and 16 kV, respectively. The simulated voltage waveform, which is calculated by the computational model with the experimental current waveform as the input parameter, is presented for comparison.

It can be seen from Fig. 3 that the simulated voltage fits the experimental data relatively well. The maximum of the simulated voltage is somewhat lower than the experimental result. The poor contact between the wire end and the electrodes leading to an increase in resistance should be responsible for this discrepancy.

As described above, in stage III, the density, temperature, and velocity are solved by the one-dimensional MHD model. Those parameters are averaged over the core and corona regions. Then, the averaged values are taken as the input parameters for stage IV. For instance, the density distribution at the end of stage III and the averaged density used in stage IV are shown in Fig. 4. If the density is lower than 1% of the density of the core in the axis, the region is recognized as corona. The radius of the initial corona plasma is 30 μm which is three times the initial wire radius. The number of ions per unit length of the corona $N_i = 4 \times 10^{15}$ m^{-1}. The expanding velocity of the plasma for the initial conditions of stage IV is 3.7 km/s with the temperature $T_i = T_e = 4500$ K. The thermal expansion velocity of the core is about 1 km/s at this moment.

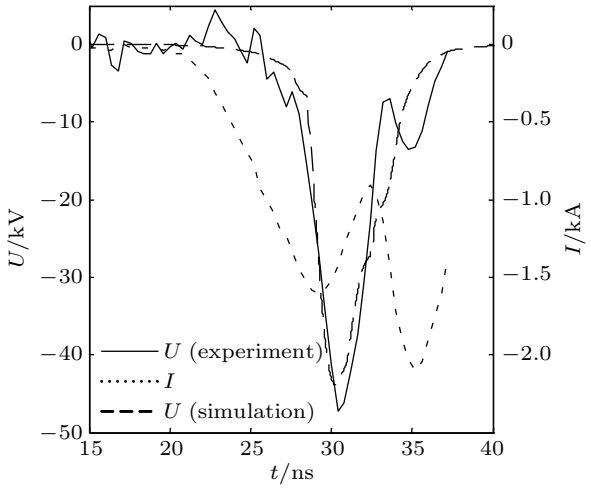


Fig. 3. The typical waveforms of the current and voltage for the electrical explosion of 20-μm-diameter, 2-cm-long Al wire.

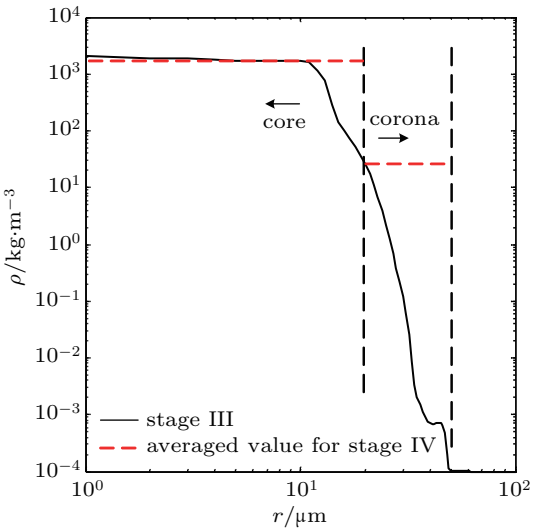


Fig. 4. (color online) The density distribution calculated by stage III and the averaged value for stage IV.

The simplified MHD calculation in stage IV is carried out based on the results from the stage III. The evolution of the velocity in the corona boundary and the temperatures of electron and ion are shown in Fig. 5. One can see that the maximum temperatures are about 45 eV and 22 eV for electron and ion, respectively.

The current rising rate exerts strong influence on the state of the core. The rising rate of the experimental current of about 150 A/ns, which is relatively fast, makes the metal wire experience severe overheated state. The current begins to switch

from the wire core to the plasma at the instant of the voltage breakdown. The evolution of the current flowing through the core and corona plasma and the temperature of the core are shown in Fig. 6.

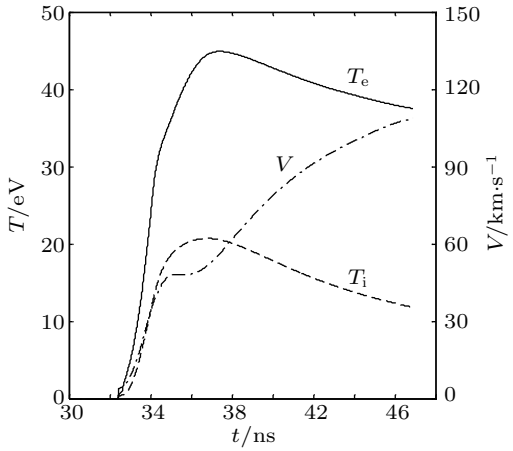


Fig. 5. Simulated results of the velocity in the corona boundary and temperatures of the electron and ion.

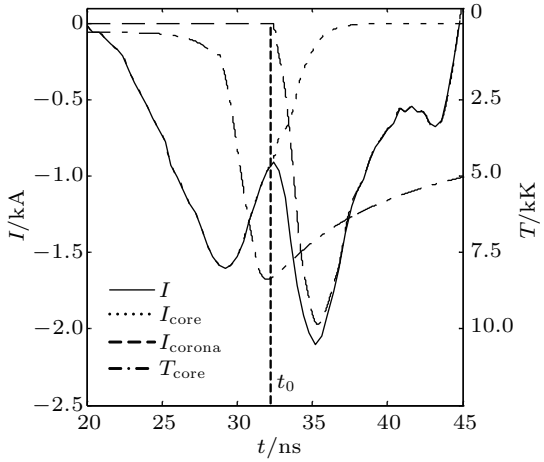


Fig. 6. The evolution of the current flowing through the core and corona and temperature of the core.

It can be seen from Fig. 6 that the current begins to switch from the core to the corona at the instant t_0. Almost all the current switches to the corona plasma within 4 ns. The temperature of the core begins to decrease at the point of the voltage breakdown. From Fig. 3 one can estimate the conductivity of the wire $\sigma = 2 \times 10^6$ S·m^{-1} at the instant t_0. The temperature, which is derived by Lee–More–Desjarlais conductivity model with the conductivity $\sigma = 2 \times 10^6$ S·m^{-1} at the density of $\rho = 2.7$ g/cm^3, is 8000 K. It is very close to the critical temperature of Al.

In Ref. [5], special electrodes were designed to investigate the phenomenon of current transfer in the electrical explosion of Cu wire. The cathode consists of two stacked plates that were separated by insulation. The upper plate has a 740-μm-diameter hole lined with a 130 μm insulator. It was supposed that the current flowing through the core was collected by the lower plate of the cathode. A 25-μm-diameter, 3-cm-long Cu wire was driven by the experimental setup. We also conducted simulation with the same experimental current configuration to validate this model. The comparison of the simulated voltage and experimental result is shown in Fig. 7. The simulated voltage is in reasonably good agreement with the experimental measurement.

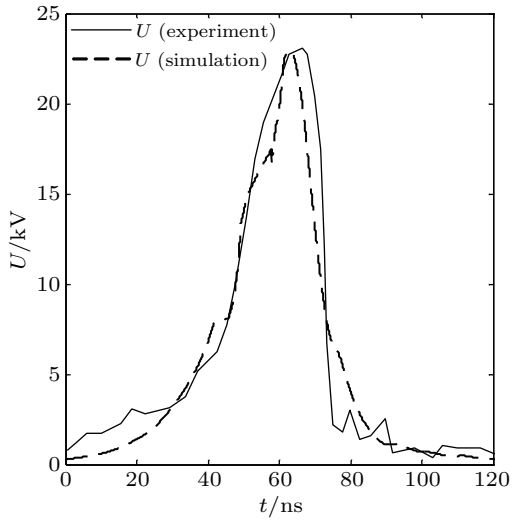


Fig. 7. The comparison of the simulated voltage with the experimental voltage for electrical explosion of Cu wire.

Simulations are carried out with and without an artificial hole in the cathode. The experimental and simulated results of the current redistribution are shown in Fig. 8. The experimental results indicate that the current flowing through the core begins to decrease at the instant $t_2 \approx 73$ ns which delays about 10 ns compared with the instant of voltage breakdown shown in Fig. 7. The simulation result without the cathode hole taken into consideration shows that the current begins to switch to plasma at the instant $t_1 \approx 61$ ns. This result is very close to the instant of voltage collapse in the experiment. It should be noted that the current measured in the lower plate is in fact the current flowing within the hole with the radius of 370 μm.[5] Therefore, part of the current flowing through the corona plasma is included in the measurement, resulting in the current switching to the plasma earlier in simulation than that in the experiments. It can be seen from Fig. 8 that the simulated current switches from core to plasma at $t_3 \approx 90$ ns with the hole configuration taken into consideration. Actually, it is very difficult to make sure that the wire is perfectly centered in the hole in the experimental operation. Therefore, this might be responsible for the result of $t_3 > t_2$. If the wire was close to the edge of the hole, the plasma just needed to travel 130 μm to contact with the upper cathode plate. The average expanding velocity of the plasma can be estimated by $V \approx 370$ μm/29 ns= 12.8 μm/ns, which fits well with the experimental expanding velocity of 14 μm/ns.

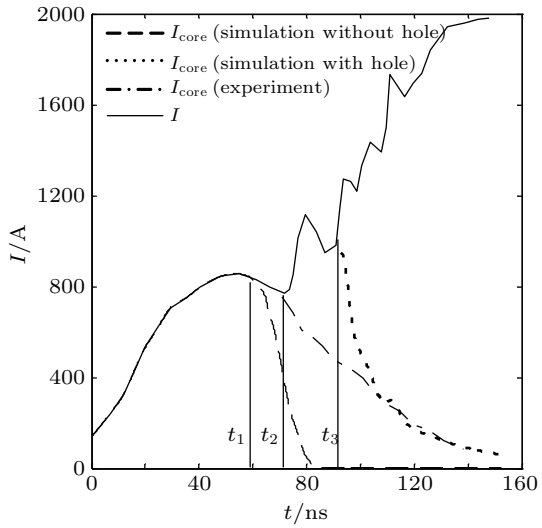


Fig. 8. The experimental and simulation results of the current transfer from the core to corona.

5. Conclusion

In this paper, the initial plasma formation and the phenomenon of the current switching from the wire core to the surrounding corona plasma in the electrical explosion of Al and Cu wires are investigated. The process of the single-wire electrical explosion is divided into four stages. The thermodynamic calculation is applied in stages I and II before the wire melts completely. The distribution of the density, velocity, and temperature are calculated by a one-dimensional MHD model in stage III up to the instant of voltage breakdown. Those results are averaged within the regions of the core and corona, providing the initial conditions for the following stage IV, in which a simplified MHD model is adopted. A wide-range semi-empirical equation of state is constructed based on the TFK model to describe the phase transition of the wire from solid state to plasma state.

The simulation results of the plasma formation induced by the voltage breakdown are in good agreement with experimental data in exploding Al wire. The process of the current transfer from core to the corona plasma for Cu wire coincides reasonably well with corresponding experimental data as well. Besides, the evolution of the temperature for electron and ion and the expanding velocity in the corona boundary can be obtained by the proposed model. In general, the model provides an efficient approach to investigate the plasma formation and current transfer of the single-wire electrical explosion in vacuum with acceptable accuracy. In the future work, much endeavor will be devoted to construct the two-dimensional computational model for investigating the morphology of the exploding products.

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