Droplet Formation and Dripping Behavior during the Electroslag Remelting Process with Two Series-Connected Electrodes

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Abstract: The formation and dripping behavior of droplets in the process of the electroslag remelting with two series-connected electrodes (TSCE-ESR) has an important influence on the optimization of power supply parameters and the purity of the electroslag ingot. In this article, through numerical simulation based on the VOF (volume of fluid) model, combined with the transparent experimental device for physical simulation, the mechanism of metal droplet formation and the effect of the filling rate on its droplet behavior were studied. The results showed that the proximity effect, instead of the skin effect, is a major factor influencing droplet formation in TSCE-ESR process. The proximity effect makes the region inside the two electrode tip melt first, and the molten steel converges at the electrode tips to form a droplet source. The process of droplet formation and dropping can be divided into three stages: formation of molten layer, droplet stretching and necking, and detachment. In the stage of droplet stretching and necking, the increase in the contact area between the droplet and the slag and the instantaneous increase of the current provide good thermodynamic and dynamic conditions for the removal of non-metallic inclusions. After the droplet drops into the slag pool, it promotes the flow of slag and improves the heat and mass transfer efficiency of the slag/metal interface. The relatively large filling rate can form smaller and dispersed droplets, which improves the refining effect. At the same time, the increase of the filling rate can improve the input power and the electrode remelting rate.

Keywords: two series-connected electrodes; electroslag remelting process; droplet; numerical simulation; physical simulation

1. Introduction

Electroslag remelting (ESR) can effectively improve the cleanliness and compactness of steel and is widely used in the production of high-quality steel and alloys. The quantity, distribution, and size of non-metallic inclusions in steel are the standards in which to measure their purity. In the process of ESR, consumable electrodes are melted and converged, then separated from the electrodes, and enter the slag pool. In the process of droplet formation and dripping, the molten metal and the slag are fully contacted, and the contact area and time are much larger than the traveling time of the droplet in the slag pool, so the electrode tip is the main area for slag/metal reaction and non-metallic inclusion removal [1]. However, due to the high temperature and the opacity of the metal phase, it is difficult to observe the phenomenon of metal droplets in the slag in the actual process of ESR, so only numerical simulation or physical simulation can be used for research. In the electroslag remelting process with two series-connected electrodes (TSCE-ESR), the heating area is mainly located between the two
electrodes, thus making the metal bath shallower and improving the quality of the steel ingot [2]. Meanwhile, compared with the traditional one-electrode electroslag remelting (OE-ESR) system, the TSCE-ESR system adds an electrode, thus changing the current flow direction. Due to the cancellation of the magnetic field, the inductance of the short net is reduced, the power factor can be increased by about 0.9, and the working efficiency is further improved [3]. However, in the current work, there has been little research on droplet formation, dropping behavior, and its electrical parameters in the process of TSCE-ESR.

In recent years, researchers have established mathematical models to study the droplet behavior of the ESR process. Kharicha et al. [4–6] studied the droplet behavior in the process of OE-ESR by applying the multiphase flow model. Wang [7] studied droplet dropping behavior by coupling the velocity field and temperature field of the process of ESR. Liu [8] established a mathematical model of droplet behavior for OE-ESR based on MHD (magneto-hydro-dynamical), and the calculated values were consistent with the predicted values. In the above work, the dropping behavior of droplets was studied by applying a constant mass flow. In the process of droplet formation, it is affected by slag temperature, which further affects the droplet size and droplet frequency. However, the application of constant mass does not take into account the influence of slag temperature on droplet formation, thus resulting in inaccurate calculation results. Furthermore, the changes in electrical parameters during the process of ESR will affect the electrical power consumption, but the current numerical simulation methods cannot reflect those changes in electrical parameters during droplet formation and dripping behavior.

Physical simulation is also an important research method in the study of droplet behavior during the process of ESR. Campbell [9] and Makropoulos [10] used a transparent eutectic LiCl-KCl alloy as slag for remelting low melting point alloys. By using an oscilloscope to detect the slag voltage curve, the droplet separation frequency can be obtained. ElGamal [11] used NaCl solution to remelt the low melting point alloy. All these works studied the influence of slag composition and height [12], interfacial tension [5], current density [13,14], consumable electrode shape [15], current frequency [9,16], and other factors on droplet formation. Cao [17] used a visual device to study the relationship between droplet diameter and filling rate in the process of OE-ESR. However, there is still little research on the physical simulation of droplet formation and dropping behavior in the process of TSCE-ESR. In addition, the methods of physical simulation still have limitations. For example, in this work, the current used was small, and the electromagnetic force generated was far from the electromagnetic conditions in the real process of ESR. The movement and thermal state of the slag pool will affect the production efficiency. Furthermore, the physical simulation method cannot reflect the flow and heat transfer of slag when the drops fall. Therefore, under the condition of satisfying the electromagnetic effect, the change of velocity field and temperature field in the slag pool can be studied by the method of numerical simulation when the drops fall.

In light of the above analysis, this paper combined numerical simulation with physical simulation to study the droplet formation and dropping mechanism in the process of TSCE-ESR. The distribution of the flow field and temperature field in the slag pool was obtained through steady state calculation as the initial condition of the electrode melting model in the numerical simulation. The VOF method, coupled with an energy equation and fluid flow equation, was used to track the distribution of the two phases, the electromagnetic phenomenon solved by user define functions (UDF) to study the change in the velocity field and temperature field in the slag pool during droplet dropping. By remelting a wood-alloy rod with a NaCl solution, the electrical parameters, droplet frequency, and droplet weight of the dropping process were studied. In addition, the influence of filling rate on droplet formation and the dropping process was also studied, which provided a theoretical basis for improving the quality of ingot in TSCE-ESR.
2. Numerical Model

2.1. Mathematical Modeling

The research of numerical simulation was based on the VOF and MHD models, and their calculation domains are shown in Figure 1. As shown in the figure, a 2D model was used in the simulation process. The r axis represents the radial distance of the model, and the z axis represents the axial distance of the model. The melting of the electrode is only related to the joule heat and electromagnetic force of the slag pool, and the temperature field in the slag pool is affected by the radiation and convection in the air, so the calculation field includes the air, electrode, and slag pool. In order to simplify the calculation, we put forward the following important assumptions [18]: (1) Due to the existence of self-inductance and mutual inductance, it is necessary to ignore the induced magnetic field in the system; (2) the fluid density does not change during the simulation, so the slag and molten steel can be considered as uncompressed Newtonian fluids; and (3) heat and mass transfer were studied in this paper, so the physical and chemical properties of the steel slag were only related to temperature.

![Figure 1. Calculation domains of electroslag remelting (ESR). (1) Electrode. (2) Air. (3) Slag pool.](image_url)

2.1.1. Electromagnetic Field Control Equation

The electromagnetic field follows the Maxwell equations and is expressed as follows:

\[
\nabla \times E = \frac{-\partial B}{\partial t} \\
\n\nabla \times H = J \\
\n\n\nabla \cdot B = 0 \\
\n\n\n\nabla \cdot J = 0
\]

where \(E\) is the electric field intensity; \(H\) is the magnetic field intensity; \(J\) is the current density; \(B\) is the magnetic flux density; and \(t\) is the time.

2.1.2. Fluid Control Equation

During the process of ESR, fluid flow is driven by electromagnetic force and buoyancy, which can be described by the continuity equation and Neville-Stokes equation:

\[
\frac{\partial p}{\partial \tau} + \nabla \cdot \nu = 0
\]
\[
\frac{\partial \rho v}{\partial \tau} + \rho (v \cdot \nabla) v = -\nabla P + \nabla \cdot (\mu_{\text{eff}} \nabla v) + \rho g + S_S
\]  

(6)

Here, \(\rho\) is the density; \(v\) is the velocity vector; \(P\) is the pressure; \(\mu_{\text{eff}}\) is the effective viscosity; \(g\) is the acceleration of gravity; and \(S_S\) is the source term including electromagnetic force, buoyancy, and interfacial tension. The electromagnetic force expression is as follows:

\[
F_{\text{loc}} = \mu_0 \mathbf{j} \times \mathbf{H}
\]

(7)

\[
Q_j = \mathbf{j} \times \mathbf{j} \sigma
\]

(8)

where \(F_{\text{loc}}\) is electromagnetic force; \(\mu_0\) denotes vacuum permeability; \(Q_j\) is the Joule heat per unit volume; and \(\sigma\) is the conductivity.

2.1.3. Multiphase Flow

In the VOF model, different phases are calculated as continuous fluids, which can be used to deal with the flow phenomena of two or more incompatible fluids and track the interface of incompatible fluids by using the volume fraction of different fluids. The volume fraction of each phase is calculated by the continuity equation:

\[
\frac{1}{\rho_q} \left[ \frac{\partial}{\partial \tau} (\alpha_q \rho_q) + \nabla \cdot (\alpha_q \rho_q v_q) \right] = \sum_{p=1}^{n} \left( \dot{m}_{pq} - \dot{m}_{qp} \right)
\]

(9)

Here, \(\rho_q\) is the density of the \(q\)th phase in the solution domains; \(\alpha_q\) denotes the fraction of the \(q\)th phase; \(v_q\) represents the velocity vector of the \(q\)th phase; and \(\dot{m}_{pq}\) is the mass transfer from the \(q\)th to the \(p\)th phase. In the VOF method, the interfacial tension between phases is 1.2 N/m [19].

2.1.4. Governing Equation for Droplet

Assuming that the droplet is spherical, the motion of the droplet can be expressed as follows:

\[
\frac{4}{3} \pi r_d^3 (\rho_d + \rho) \frac{dU}{dt} = \frac{4}{3} \pi r_d^3 \Delta \rho g - C_D \pi r_d^2 \rho U^2
\]

(10)

where \(\rho\) is the density of molten slag; \(U\) denotes the droplet velocity; \(r_d\) and \(q_d\) represent the radius and density of droplet, respectively; and \(C_D\) is the resistance coefficient, as follows:

\[
C_D = \frac{4}{3} \left( \frac{\rho_d - \rho}{\rho} \right) \frac{gr_d}{U^2}
\]

(11)

The heat transfer between the slag/droplet interface is described by the heat transfer coefficient and the average temperature of the slag/metal interface at the tip of the electrode. The heat balance of the droplet is:

\[
\frac{4}{3} \pi r_d^3 C_{p,d} \frac{dT_S}{dt} = 4 \pi r_d^2 h(T_B - T_d)
\]

(12)

Here, \(T_B\) is the average temperature between the slag/metal interface at the tip of the electrode and \(C_{p,d}\) is the heat capacity of the droplet. The heat transfer equation can be calculated by the following equation:

\[
\frac{hr_d}{\lambda} = 0.8 (r_d U_{av} \rho / \mu)^{1/2} (C_p L / \lambda)^{1/3}
\]

(13)

where \(\lambda\) is the conductivity of the molten slag; \(U_{av}\) represents the average velocity of droplet in slag pool; and \(L\) is the distance between the two electrodes.
When a droplet drops to the slag/metal interface, the temperature can be expressed as:

\[ T_{dp} = T_B - (T_B - T_{me})e^{-st} \]  \hspace{1cm} (14)

\[ s = \frac{3h}{r_d \rho_d \cdot C_{p,d}} \]  \hspace{1cm} (15)

The amount of heat when a droplet falls can be expressed as:

\[ Q = m_e C_p (T_{dp} - T_L) \]  \hspace{1cm} (16)

where \( Q \) represents the heat absorbed by the droplet; \( m_e \) indicates the electrode melting rate; \( C_p \) denotes the heat capacity of liquid steel; \( T_{dp} \) is the temperature of the droplet; \( T_L \) represents the liquidus temperature; and \( T_{me} \) represents the melting temperature of the electrode.

### 2.1.5. Boundary Condition

Figure 2 is the physical concept of the TSCE-ESR. In the process of TSCE-ESR, current flows from one electrode, passes through the slag pool, and flows out from the other electrode. Hence, there is only a radial component of the current at the slag/air interface and at the bottom of the slag pool. Therefore, the magnetic field on the slag/air interface only has an axial component [20], and the expression of the current and magnetic field is:

\[ H_r = 0, \]
\[ H_z = \frac{l_0}{2 \pi r_t} \]  \hspace{1cm} (17)

**Figure 2.** Physical concept of the electroslag remelting with two series-connected electrodes (TSCE-ESR).

At the slag pool/crystallizer interface, the current flowing into the side wall of the crystallizer is not considered in this model, so the current only flows along the axial direction on the two contact surfaces, and the magnetic field only has a radial component [21]. The expression between the current and the magnetic field is:

\[ H_r = \frac{l_0}{2 \pi r_t}, \]
\[ H_z = 0 \]  \hspace{1cm} (18)

Here, \( l_0 \) is the initial current fed into the electrode at its upper side, which will vary in the following iterative procedure.

The temperature at the tip of the electrode is the metal liquidus temperature, and the heat flux at the slag/electrode interface is calculated as follows:
Due to the high temperature in the slag pool, the heat exchange is complicated. Considering all things, the total heat transfer at the slag/air interface can be expressed as:

$$Q = Q_c + Q_r = h(t_w - t_{\infty})A$$

Here, $Q_c$ is the heat of convection heat transfer; $Q_r$ the heat transfer heat of the radiation; $A$ is the heat exchange area; and $h$ is the comprehensive convective heat transfer coefficient.

In this model, the free sliding boundary condition is adopted at the slag surface, and the other conditions are all non-sliding. Zero shear force is applied to the free surface of slag.

2.1.6. Calculation Strategy

Using the VOF method, the electromagnetic field equation, energy equation, and flow equation were coupled to track the interaction between the slag and droplet in the slag pool. Figure 3 is a flow chart of a numerical simulation scheme. A quadrilateral grid is used in the model, and the computational domain contains 130,166 elements. Table 1 shows the process parameters and physical parameters used in the numerical simulation part. The 2D model was used in this article, so the filling rate represents the ratio of the electrode to mold diameter. The research has mainly studied the effect of the filling rate on the droplet behavior, so it is necessary to ensure that the distance between the two electrodes is fixed. The distance between the two electrodes is provided by the actual TSCE-ESR process to ensure the reasonableness of the parameters. After the residual error is less than $10^{-6}$, the calculation stops.

![Figure 3. Flow diagram of the numerical simulation.](image)

Table 1. Parameters of the numerical simulation.

| Parameter                        | Value  |
|----------------------------------|--------|
| Density, kg·m⁻³                  | 2850   |
| Specific capacity, J·kg⁻¹·K⁻¹    | 1404   |
| Thermal conductivity, W·m⁻¹·K⁻¹  | 10.45  |
| Viscosity, kg·m⁻¹·π⁻¹            | 0.01   |
| Emissivity                      | 0.6    |
| Expansion coefficient, K⁻¹       | 0.0001 |
According to Chen’s calculation results [27], the conductivity of the 0.1221 mol/L NaCl solution was very similar to that of slag. The wood alloy had a melting point of 70 °C, and its density and viscosity were similar to those of molten steel. The matching process parameters of the numerical simulation and physical simulation models were calculated respectively through the geometric similarity rate. Table 2 shows the parameters used in the physical simulation.

### Table 1. Cont.

| Parameter                             | Value   |
|---------------------------------------|---------|
| Physical properties of steel          |         |
| Density, kg m\(^{-3}\)                | 7200    |
| Specific capacity, J·kg\(^{-1}\)·K\(^{-1}\) | 502     |
| Thermal conductivity, W·m\(^{-1}\)·K\(^{-1}\) | 31.9    |
| Steel solidus temperature, K          | 1723    |
| Steel liquidus temperature, K         | 1693    |
| Latent heat of solidification, J·kg\(^{-1}\) | 247,000|
| Process parameters                    |         |
| Immersion depth of electrode, m       | 0.02    |
| Mold diameter, m                      | 0.14    |
| Length of electrode, m                | 0.32    |
| Voltage, V                            | 35      |
| Height of slag, m                     | 0.07    |
| Filling rate                          | 0.5, 0.6, 0.7, 0.8 |
| Distance between the two electrodes, m| 0.0265  |

### 3. Experimental Setup

In the physical simulation, a wood-alloy rod was used to simulate the consumable electrode and the composition of wood alloy (2.5% Cd, 12.5% Sn, 50% Bi, 25% Pb), beaker simulating crystallizer, and 0.1221 mol/L NaCl solution was used to simulate slag. The quartz beaker was used as a mold to simulate the ESR process. An induction cooker and 3D printing mold were used to remelt the alloy and make electrodes with different filling rates, wherein the filling rates (defined as the rate of electrode diameter to mold diameter in this experiment) were 0.5, 0.6, 0.7 and 0.8, respectively. A high-speed camera and a computer with a frame number of 200 frames/s recorded the droplet dropping process; after the droplet was taken out by the spoon taking method, the weight of the droplet was recorded by an electronic balance. A clamp multimeter recorded changes in the electrical parameters. Figure 4 shows a schematic diagram of the TSCE-ESR in the physical simulation.

**Figure 4.** Schematic diagram of the physical simulation apparatus. 1—insulation support; 2—thermometer; 3—graduated scale; 4—electrode; 5—quartz beaker; 6—slag pool; 7—electronic balance; 8—automatic coupling voltage regulator; 9—tong-type ammeter; 10—high speed camera; 11—computer.
Table 2. Parameters of physical simulation.

| Parameter                      | Value |
|--------------------------------|-------|
| Length of electrode, m         | 0.07  |
| Inner diameter of beaker, m    | 0.085 |
| Resistance of resistor, Ω      | 5     |
| Depth of electrode immersion, m| 0.007 |
| Height of slag, m              | 0.056 |
| Viscosity of wood alloy, kg·m⁻¹·s⁻¹| 0.0042 |
| Distance between the two electrodes, m | 0.001 |

4. Results and Discussion

4.1. Validation of Mathematical Model

In order to verify the accuracy of the numerical model, some experiments were carried out. In the experiment, the current was 4000 A and the current frequency was 50 Hz. The mold diameter was 140 mm and the height was 360 mm. The electrode filling rates were 0.5, 0.6, and 0.7, and the electrode insertion depth was 20 mm. The slag system consisted of CaF₂ (30%), CaO (35%), Al₂O₃ (20%), and MgO (15%). Figure 5 shows the in situ experiment of the TSCE-ESR process. Figure 5b shows that the results were basically consistent with the tip shape of the consumable electrode, which was obtained by numerical simulation (Figure 7). As can be seen from Figure 5b, the melting speed on the inner sides of the electrode was much higher than that on the outer sides of the electrode, so the droplet dropping position was close to the outer side of the electrode. This is due to the proximity effect between the electrodes, which was much greater than the skin effect. This results in the Joule heat being mainly concentrated in the slag pool area between the two electrodes, making the inside of the electrodes melt first, and the temperature of the slag pool in this area is much higher than that of the slag pool area outside the electrodes. Therefore, we can come to the conclusion that the proximity effect plays a chief role in the process of TSCE-ESR. According to Equation (21), we obtained the remelting rate of the TSCE-ESR process under laboratory conditions.

\[
u = \frac{\rho \left( L + \frac{Lr_e^2}{(R^2 - r_e^2)} \right) \pi r_e^2}{\Delta t}
\]

(21)

where \( u \) is the melting rate of the electrode; \( L \) is the electrode falling speed in a certain period of time; \( r_e \) is the radius of the electrode; \( R \) is the radius of the mold; \( \rho \) is the density of steel; and \( \Delta t \) is the time difference. Figure 6 reveals the comparison between the measured remelting rate and the calculated value by the mathematical model. It can be seen from the figure that the numerical simulation results were in good agreement with the experimental results. In the empirical Equation (21), the melting rate is calculated by the parameters of the electrode lowering rate, process size, and ingot specific heat capacity in the in situ experiments. However, in our numerical simulation, the melting rate was calculated with full consideration of the heat flux density at the slag/metal interface and the influence of the electromagnetic field, flow field, and buoyancy of the slag pool. The correspondence between the two calculation results is very significant, because it fully shows that our numerical simulation results can more accurately reflect the actual electroslag remelting process. The reason why our calculation results can be more accurate is that the influence of multiple physical fields on droplet formation and dripping is fully considered, which makes the melting of the slag/metal interface and droplet formation dependent on the thermal state in the slag pool instead of setting a constant mass flow. Therefore, it is very necessary to consider multiple physical effects when studying the droplet behavior of ESR.
Therefore, we can come to the conclusion that the proximity effect plays a chief role in the process of TSCE-ESR. According to Equation (21), we obtained the remelting rate is calculated by the parameters of the electrical conductivity and the specific heat capacity in the in situ experiments. However, in our numerical simulation, the melting rate was calculated with full consideration of the heat flux density at the slag/metal interface and the heat capacity of the metal. It can be seen from the figure that the numerical simulation results were in good agreement with the experimental results. In the empirical Equation (21), the melting rate is calculated by the parameters of the electrical conductivity, the specific heat capacity, and the mass of the molten steel. The in situ experiment of the TSCE-ESR process under laboratory conditions.

4.2. Droplet Formation and Dripping Process

Figure 7 is the droplet formation and dropping process of TSCE-ESR with a filling rate of 0.5 under numerical simulation. The formation and dropping of droplets can be roughly divided into three stages. In Figure 7, from the \( t_a \) to \( t_c \) period, due to the proximity effect [28], the inner sides of the two electrode tips started to melt first, forming a molten layer with a certain thickness. With the increase in molten steel, the molten steel in the molten layer gradually slides to the tip of the two electrodes and forms two larger droplet sources. During the period from \( t_d \) to \( t_e \), when the resultant force of gravity, buoyancy, and electromagnetic force counteracts the interfacial tension, the droplet starts to move downward under the downward force, and necking occurs. At this time, the droplet is mainly divided into two parts. The first part is the downward movement of the main droplet. The other part is connected with the main liquid drop and the electrode and is gradually elongated until the main liquid drop is separated from the electrode. During the period from \( t_f \) to \( t_h \), part of the elongated droplet moves downward, separated from the electrode, and gradually changes from a linear shape to a circular shape. The other part rapidly shrinks back to the surface of the electrode under the action of surface tension, while oscillating to form numerous small suspended droplets. Figure 8 shows the droplet dropping process captured by a high-speed camera under the physical simulation experiment. However, due to the influence of the experimental environment, where it is impossible to ensure that two electrode droplets simultaneously drop in the physical simulation experiment, the results obtained by the physical simulation and the numerical simulation were basically consistent.
Figure 7. Formation and dripping process of the droplet with the filling rate of 0.5 in the numerical simulation. $t_a = 0.27$ s; $t_b = 0.39$ s; $t_c = 0.56$ s; $t_d = 0.74$ s; $t_e = 0.83$ s; $t_f = 0.92$ s; $t_g = 1.16$ s; $t_h = 1.31$ s.

Figure 8. Formation and dripping process of droplet in physical simulation. (a) 0.31 s; (b) 0.49 s; (c) 0.77 s; (d) 0.87 s; (e) 0.93 s; (f) 1.01 s.
4.3. Velocity Field and Temperature Field

Figure 9 is a graph showing the velocity field and temperature field distribution of the slag pool at time \( t_d \). As can be seen from the figure, the slag velocity near the melting region of the electrode tip was significantly higher, which improved the eddy current flow velocity near the electrode tip. Therefore, melting at the tip of the electrode promotes the flow intensity of the vortex, which not only promotes the heat and mass transfer efficiency of the slag/metal interface, but also improves the stirring effect of the slag pool. The blue line in Figure 9a shows the outline of the droplet. The speed of slag in the droplet and its vicinity is significantly higher than that in other areas, reaching about 0.13 m/s, which is due to the viscous force generated during droplet dropping, which caused an increase in slag velocity nearby. At the bottom of the droplet, due to the driving effect of the droplet, part of the slag flows to the edge of the crystallizer for heat exchange, and the other part of the slag flows to the surface of the slag pool for heat exchange through the centerline position. Therefore, droplet dripping plays a positive role in the heat transfer of the slag pool. In the process of ESR, temperature distribution plays an important role in the structure and quality of the ingot. The temperature of the slag pool is a result of the joint action of Joule heat and slag pool flow. It can be seen from Figure 9b that the temperature of the slag pool between the electrodes is the highest due to the proximity effect, which reached 2130 K, while the temperature distribution was relatively uniform in other areas of the slag pool. Therefore, at the location where the droplet is located, the temperature was obviously lower than the temperature of the high-temperature region between the electrodes, and the temperature of the high-temperature region was transferred to other regions with lower temperature, resulting in an obvious temperature gradient.

![Velocity and Temperature Fields](image)

**Figure 9.** Distribution of velocity field and temperature field of numerical simulation at \( t_d \). (a) velocity field. Blue line represents the outline of droplet. Black line represents flow stream line. (b) temperature field.

4.4. Variation of Electrical Parameters

Figure 10 is a graph of the input current and output current versus temperature. The current increased with the increase in the solution temperature, revealing that the resistance of the solution decreased with the increase in temperature, which is similar to liquid slag in the ESR process. In this experiment, the current flowed in from one electrode, flowed through the NaCl solution, and then flowed back to the short net system from the other electrode. Therefore, in the electrode process, AC impedance controlled by a mixture of charge transfer and diffusion processes is formed. From the meaning of electrochemical AC impedance, the relationship between input voltage \( Y \) and output current \( X \) can be expressed by transfer function \( G(w) \):

\[
Y = G(w)X \tag{22}
\]

where \( G(w) \) is influenced by state factors such as adsorption on the electrode surface or coverage of oxide, the activity of particles participating in electrode reaction, etc. Therefore, after the current passes through
the NaCl solution, its current value is determined by the linear response relation of Equation (22), thus causing the input current to be greater than the output current in the short-network system.

\[ U = \frac{I_d}{A\kappa} \]  

where \( U \) is the voltage; \( I \) represents the electric current; \( A \) represents the contact area between the electrode and the slag, and \( \kappa \) represents the conductivity of the slag. Figure 11 shows the change of the electrical current before and after dropping droplets, which was mostly consistent with the change trend of the electrical parameters before and after dropping droplets in OE-ESR [17]. In the process of OE-ESR, \( d \) represents the distance between the electrode and the metal bath. Therefore, it can be inferred that in the process of TSCE-ESR, \( d \) is the distance between the two electrodes. In the process of droplet dropping and stretching, the interfacial area of the effective conductor increases, making the current reach a peak before droplet separation. Unlike OE-ESR, in the process of TSCE-ESR when the droplet falls behind, the effective conductor decreases. As shown in Figure 11, the distance between the electrodes increases, which prevents the current from reaching the level before the droplet drops. Thus, the current will eventually show a decreasing trend, despite the occurrence of the peak value along with the droplet drops. The current was reduced by 0.02 A compared with that before the droplet dropped. It is worth noting that the current used in the actual electroslag remelting process is up to 4000 A, and the process parameters are much larger than those in the laboratory. The change of electrical parameters is important for the adjustment of melting rate and power.

Figure 10. Relationship between current and temperature in physical simulation.

In the process of OE-ESR, an equilibrium equation can be derived from the voltage in the furnace and the immersion depth as follows [29]:

\[ U = \frac{I_d}{A\kappa} \]  

Figure 11. Variation of electric current with time, before and after droplet detachment.
4.5. Effects of Filling Rate on the Droplet Behavior

In actual industrial production, the filling rate is generally greater than 0.5, so four groups of models with filling rates of 0.5, 0.6, 0.7, and 0.8 were selected for comparison in this experiment. When the system loop voltage is constant, the current will change with the change in the fill rate. Figure 12 shows the relationship between the current and fill rate in the physical simulation experiment. It can be seen from the figure that the current in TSCE-ESR increases with the increase in the filling rate, which corresponds to Equation (23). When other parameters are unchanged, the contact area between the electrode and the solution increases due to the increase in the filling rate, and the increase of the effective conductor is equivalent to the decrease of the resistance in the system. Therefore, the current increases with an increase of the filling rate. Figure 13 reflects the relationship between the filling rate and the current density. Although the voltage is constant, the current increases with the increase in the filling rate. However, the current density in the system is determined by the current and the cross-sectional area of the electrode. It can be seen from the figure that the current density decreases with the increase in the filling rate, because the increase amplitude of the current is smaller than the corresponding increase amplitude of the cross-sectional area of the electrode.

Figure 12. Relationship between the current and filling rate in the physical simulation.

Figure 13. Variation of the current density and electric current at different filling rates in the physical simulation.

When the diameter of the mold is constant, the increase in the filling rate means an increase in the consumable electrode diameter. The increase in the electrode diameter will reduce the area of the
slag/air interface, thus affecting radiant heat. The relationship between radiant heat loss on the slag pool surface and filling rate is given by the following Equation (24) [30]:

\[
P_{em} = 4.5 \times 10^{-3} \epsilon D_m^2 (1 - K^2) \left( \frac{T_s}{100} \right)^4
\]

(24)

where \(P_{em}\) is the radiant heat loss and \(\epsilon\) represents the emissivity of slag. \(D_m\) is the diameter of the mold; \(K\) is the filling rate; and \(T_s\) is the surface temperature of the slag. Therefore, as the filling rate increases, the radiant heat area on the slag pool surface decreases, thus reducing the radiant heat loss. At the same time, increasing the diameter of the electrode will increase the current, which can effectively improve the thermal power and the \(UI\) of the short network system. This will further affect the generation of Joule heat and increase the temperature of the electrolyte between the two electrodes. The electrolyte temperature increases, the viscosity is lower, the droplet growth is faster, and the stretching period is relatively shorter. Therefore, an increase in the filling rate will reduce the formation time of liquid droplets, thus increasing the drop frequency of the liquid droplets. Figure 14 shows the relationship between droplet dropping frequency and filling rate.

![Figure 14](image_url)

**Figure 14.** Relationship between droplet dropping frequency and filling rate in the physical simulation.

The heat distribution and state of the consumable electrode affect its melted shape [6,14]. Given that the high-temperature region is mainly concentrated between the two electrodes, and the electrolyte temperature at the lower part of the electrode tip is relatively low, this made the adjacent inner sides of the two electrodes melt first to generate sag. The molten layer slides down and collects along the sag, eventually forming the dripping droplet. This is different from the droplet dropping mechanism in the process of OE-ESR. Due to the skin effect, the periphery of the electrode melts first in the process of OE-ESR. With the increase in the filling rate, the shape of the electrode tip will change from a cone to flat surface, and the droplet source will also change from one to multiple. However, in the process of TSCE-ESR, the proximity effect makes the electrode tip form a smooth slope on one side of the symmetry axis. At the intersection of the inclined plane and the plane at the tip of the electrode, the droplet sources converge. At the same time, due to the maximum curvature at the intersection of the inclined plane and the plane and the maximum Laplace pressure value, a liquid dripping head will be formed. As can be seen from Figure 15, compared with OE-ESR, the skin effect does not make the electrode tip appear tapered [17]. Therefore, the shape of the consumable electrode tip does not change obviously with the increase in the filling rate during the process of TSCE-ESR.
In previous studies, surface tension and droplet gravity, etc. established the dynamic equilibrium relationship during droplet dropping. Therefore, droplet diameter ($d_e$) was estimated based on the empirical formula of interfacial tension between molten metal and slag, which is as follows [31]:

$$
\begin{align}
    d_e &= \left[ \frac{\sigma \times H}{(\rho_m - \rho_s) \times g} \right]^{\frac{1}{2}} \\
\end{align}
$$

where $\sigma$ is the surface tension of the wood alloy in NaCl solution. $\rho_m$ and $\rho_s$ represent the density of metal droplets and NaCl solution, respectively. $g$ is the gravitational acceleration and $H$ is the correction coefficient determined by the consumable electrode position. According to Equation (25), the equivalent diameter of the droplet mainly depends on the difference between interfacial tension and density. When the system voltage is constant, with the increase in the filling rate, the temperature of the solution increases, and the temperature of the droplet formation and separation region also increases. Therefore, the interfacial tension of the droplet/solution decreases with the increase in temperature, resulting in faster droplet growth. However, in the process of TSCE-ESR, in addition to the two factors of interfacial tension and density difference, the effective conductor decreases and the distance between the two consumable electrodes increased with the droplets dropping, which is equivalent to the increase of resistance in the system. Thus the increase in electrode spacing will also affect the droplet diameter with the passage of time in the TSCE-ESR process. Therefore, in the physical simulation, the relationship between filling rate and droplet diameter can be equivalently studied by measuring the droplet weight with the spoon sampling method. Figure 16 shows the collected droplet at different filling rates.

Figure 16. Droplets collected from the physical simulation at different filling rates. (a) filling rate = 0.5; (b) filling rate = 0.6; (c) filling rate = 0.7; (d) filling rate = 0.8.
Figure 17 shows the relationship between the filling rate and the droplet weight. The continuous dropping of molten drops led to the increase in electrode spacing and system resistance, which led to an increase first in the solution temperature and then a decrease. Therefore, the change trend of droplet weight under different filling rates is roughly the same. Both are divided into two stages, the rising stage and the falling stage. During the rising stage of droplet weight, the electrolyte temperature is higher, the interfacial tension is lower, and the droplet formation and dropping speed are faster, thus the droplet weight dropped at the beginning is smaller. With the dropping of the droplet, the effective conductor decreases, the electrolyte temperature decreases, the interfacial tension increases, and the droplet forming and dropping time becomes longer, which will lead to a peak in droplet weight. After the droplet weight reaches the peak value, the consumable electrode immersed in the electrolyte loses more, and the morphology of the consumable electrode changes to a certain extent, causing the droplet weight to begin to show a downward trend, while the temperature of the electrolyte decreases, causing the droplet dropping frequency to decrease. When the filling rate increases, the current increases and the electrolyte temperature increases. Although the density difference changes with the change in temperature, the viscosity decreases, the interfacial tension decreases, and the droplet formation to droplet dropping time decreases. Therefore, the droplet weight decreases with the increase in the filling rate in the rising stage. Due to the increase in the filling rate, the temperature drop trend of the electrolyte slows down, delaying the appearance of the peak value of the droplet weight. In the drop phase, when the filling rate is greater than 0.6, the drop trend of the drop weight increases. This is because as the filling rate increases, the flow of the solution becomes more intense and will form smaller and more irregular droplets. Although the electromagnetic effect produced by physical simulation is far from the actual ESR, it can be seen from Figure 16 that when the filling rate is 0.8, the solution movement becomes intense, making the droplet shape more irregular and producing more dispersed droplets, increasing the contact area between the droplets and slag. Therefore, we can draw a conclusion that a larger filling rate will produce more smaller droplets and increase the specific surface area of the droplets, making the contact between the droplets and slag more sufficient, which is beneficial to the removal of inclusions.

![Figure 17](image_url)

**Figure 17.** Variation of droplet weight at different filling rates in the physical simulation.

In a stable process of TSCE-ESR, the input power is determined by the voltage and system current. When the voltage is constant, a larger fill rate will increase the system current and increase the input power of the system. The increase in input power will lead to an increase in the droplet dropping frequency and melting rate. Figure 18 is a graph showing the changes in melting rate and input power at different filling rates. Therefore, we can conclude that when the filling rate increases, the droplet rate and input power in the system can be effectively increased.
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5. Conclusions

This article studied the behavior of droplet formation and dripping in the process of TSCE-ESR by combining numerical simulation with physical simulation, and discussed the influence of the electrodes’ filling rate on droplets.

(1) Proximity effect instead of skin effect has become a major factor influencing droplet formation in the TSCE-ESR process. The proximity effect makes the region inside the two electrode tip melt first, and the molten steel converges at the electrode tip to form a droplet source. The process of droplet formation and dropping can be divided into three stages: formation of the molten layer, droplet stretching and necking, and detachment.

(2) After the droplet drops into the slag pool, the slag flow and heat transfer are effectively promoted. Therefore, the efficiency of mass transfer and heat transfer at the slag/metal interface is improved, which is beneficial to the solidification of the ingot.

(3) Due to the existence of AC impedance, the input current in the system is larger than the output current. As the slag temperature increases continuously, the current in the system gradually increases. In the stage of droplet stretching and necking, the increase in the contact area between the droplet and the slag and the instantaneous increase of the current provide good thermodynamic and dynamic conditions for the removal of non-metallic inclusions. The current was reduced by 0.02 A compared with that before the droplet dropped.

(4) With the increase in the filling rate, the radiant heat loss at the slag pool decreases and the thermal state changes, but the shape of the electrode tip showed no obvious change. Larger filling rate makes it easier to form smaller and more dispersed droplets. A relatively large filling rate can increase the input power and the electrode remelting rate.

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Abbreviations

| Symbol | Description |
|--------|-------------|
| E      | Electric field (V·m\(^{-1}\)) |
| H      | Magnetic field intensity (A·m\(^{-1}\)) |
| J      | Current density (A·m\(^{-2}\)) |
| B      | Magnetic flux density (T) |
| t      | Time (s) |
| ρ      | Density of fluid (kg·m\(^{-3}\)) |
| v      | Velocity (m·s\(^{-1}\)) |
| p      | Pressure (Pa) |
| µ\(_{\text{eff}}\) | Effective viscosity of the fluid (Pa·s) |
| F\(_{\text{loc}}\) | Electromagnetic force (N·m\(^{-3}\)) |
| µ\(_0\) | Vacuum permeability (H·m\(^{-1}\)) |
| Q\(_J\) | Joule heat per unit volume (W·m\(^{-3}\)) |
| σ      | Electroconductibility (S·m\(^{-1}\)) |
| U      | Velocity of droplet (m·s\(^{-1}\)) |
| r\(_d\) | Radius of droplet (m) |
| q\(_d\) | Density of droplet (kg·m\(^{-3}\)) |
| C\(_d\) | Resistance coefficient |
| λ      | Conductivity of slag (S·m\(^{-1}\)) |
| C\(_p\) | Heat capacity of liquid steel (J·kg·K\(^{-1}\)) |
| T\(_{dp}\) | Temperature of droplet (K) |
| T\(_L\) | Liquidus temperature (K) |
| T\(_{me}\) | Melting point of electrode (K) |
| I\(_0\) | Current (A) |
| Q\(_c\) | Heat of convection heat transfer (W·m\(^{-2}\)·K\(^{-1}\)) |
| Q\(_r\) | Heat transfer heat of the radiation (W·m\(^{-2}\)·K\(^{-1}\)) |
| A      | Heat exchange area (m\(^2\)) |
| h      | Heat transfer coefficient (W·m\(^{-2}\)·K\(^{-1}\)) |
| T\(_B\) | Average temperature of slag/metal interface (K) |
| C\(_{p,d}\) | Heat capacity of the droplet (J·kg\(^{-1}\)·K\(^{-1}\)) |
| C\(_{p,l}\) | Liquid heat capacity of steel (J·kg\(^{-1}\)·K\(^{-1}\)) |
| m\(_e\) | Melt rate (kg·s\(^{-1}\)) |
| D\(_m\) | Diameter of the mold (m) |
| K      | Filling rate |
| T\(_s\) | Surface temperature of slag (K) |
| r\(_e\) | Radius of electrode (m) |
| R      | Radius of mold (m) |
| u      | Melting rate of electrode (kg·s\(^{-1}\)) |
| L      | Electrode filling rate (m·s\(^{-1}\)) |

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