Numerical Simulations of the Molten Metal Droplet Formation in the Electroslag Remelting Process with a Rotating Electrode

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Electroslag remelting (ESR) is a well-known process widely used in the production chain of high-quality alloys. Herein, numerical investigations of the implementation of a rotating-electrode (low rotation speed) modification to the flow behavior inside the slag area of a lab-sized ESR process are shown. Therefore, a coupled simulation approach between a commercial CFD (FVM) and electromagnetics (FEM) software is used. Comparative results for the simulated droplet formation between a stationary and a rotating electrode are shown. The results show a strong effect on the local shaping of the liquid metal film below the electrode and consequently a radial shift of the droplet incidence into the metal pool under electrode rotation. There are no observable positive effects on mean metal film thickness, droplet trajectory, or droplet size, which are suspected as possible explanations for observed material improvements in small-scale rotating electrode ESR processes. In addition, an overview of current bottlenecks, restrictions, and possible strategies for improved ESR process simulations is given.

1. Introduction

Electroslag remelting (ESR) respectively electroslag refining or electroflux remelting is a method to refine and enhance the properties of alloys and metals. Due to its outstanding chemical purification capabilities, it is vital to produce certain kinds of highly stressed materials, especially those with aerospace, deep sea, or reactor technology applications. Several process variants based upon the ESR process, for different manufacturing purposes, exist.¹,² The basic process design is mainly unaltered since several decades. There only have been improvements regarding the process control and the input materials, as well as some developed derivatives of the process. Two ideas are currently discussed in the scientific community, of how to improve the ESR process, namely, the use of a rotating or respectively a vibrating electrode. This article focuses on numerical investigations of the influence of low-speed electrode rotation, applied in the ESR process, to the liquid metal film below the electrode, the droplet detachment, and the droplets’ movement through the slag phase.

1.1. Process Description

Figure 1 shows a schematic diagram of the advanced stage of an exemplary regular ESR process. The electrode is attached to a rod. Through a lifting vertical mechanism, the electrode is immersed in-/onto the slag phase. The slag, due to its higher resistance, heats up and further is molten, when the electric current is applied. The electrode, in contact with the hot slag, begins to melt. This leads to a film of molten metal at the bottom of the electrode, which then continuously forms into droplets. The droplets, when detachment from the film, fall through the slag layer, starting to form a liquid metal pool below the slag phase. Due to the cooling of the mold, the liquid metal starts to solidify directed from the outside to inside, while the liquid metal pool sustains till the power supply is terminated. The zone in between the liquid metal and the already solidified metal, where solidified dendrites start to form, is called mushy zone.

Due to the solidification of the final ingot, an air gap is formed between electrode and mold. Furthermore, a solidified slag skin surrounds the ingot; this is a remnant of the slag phase, which moves upward with the growing ingot. Both phenomena have a critical impact on the heat transfer and the resulting current paths.

During the processing, the ESR process should reach some kind of a (quasi)-stationary state, where the influence of the lower ingot on the thermals can be neglected. During this stationary phase, many process parameters of the process are held constant (within the range of process control deviations), for example, the electrode is generally controlled to hold a constant immersion depth in the slag. Due to the more stable conditions and its critical implication to the quality for a large part of the ingot, this phase is the subject of the many ESR simulations.
1.2. Electrode Rotation

To further enhance the economy efficiency of the ESR process, a rotational electrode movement was suggested by Chumanov and Chumanov. Furthermore, Schwenk et al. showed a design for retrofitting an existing ESR experimental plant and the results of initial preliminary tests, where positive aspects as higher melt rate, a shallower melting pool, and less influence of melting on feed control were observed. Demirci et al. describes trials where 500% shallower melt pools were reached with electrode rotation. According to different publications by Chumanov and others, an increase in about 25% in productivity can be reached. Schlüter et al. describe slightly lower increase within 5–16%, for lower rotations speeds, but slightly higher electrode diameters are used. Furthermore, the authors observed the positive effects of electrode rotation in initial experiments, like reduction of necessary slag amount (10–15%), higher ingot density, and overall, more regular distributed ingot properties. It was suggested that these improvements can be related to the following effects: 1) flattening of the electrode, 2) changes to the flow field as indicated by Figure 2, 3) significant reduction of the liquid metal film thickness below the electrode, 4) a wider distribution of droplets over the ingot diameter, and 5) increase in the length of the droplet trajectory due to a longer fall path.

However, if we consider the resulting centrifugal accelerations in the electrode radii and rotational velocities given by the experimental descriptions of Chumanov and others, they are still a factor of 2–3 below the Earth’s acceleration, which raises doubts about some of the described causes. Understanding the exact causes of potential enhancements of this rotating electrode technology, however, is crucial, for example, to prognose a potential scaling applicability to industrial ESR processes. Therefore, to better investigate the effect of rotation, on flow field, droplet formation, and film thickness, a detailed simulation model was used.

1.3. Modeling Approaches

The simulation of the ESR process has quite a long history; a recent review of the literature was given by Kharicha et al. Usually, a 2D axisymmetric simulation approach is used to model the ESR process. However, in the region of the slag, according to Giesselmann or Karimi-Sibaki et al., this approach is only appropriate to model the droplet behavior in small lab-scale-sized electrodes with electrode diameters of a few centimeters. A 2D approach to model the electrode melting inside the slag region is not valid for industrial-scale-sized processes, as shown by Kharicha et al. Then again, Karimi-Sibaki et al. showed that a 2D axisymmetric approach will be sufficient to model the solidification of larger ingot sizes. These findings are quite relevant as a full transient 3D simulation of the whole process, which resolved all the relevant phenomena, will be quite unrealistic soon. A multizone approach as described by Giesselmann et al. can reduce computational demands while still delivering relatively good model representation. In conclusion, working out the right simplifications will still have a lot of impact on quality and results of future ESR simulations. However, it is likely that for the solidification in an ESR process with a rotational electrode, at least an axisymmetric 3D geometry must be used, to account for the swirling flow, which may be introduced to the pool area, due to the rotation of the electrode. A 3D simulation of the slag phase itself is most likely inevitable.

Apart from research activities to set up fast and accurate modeling approaches, the accuracy of the available material data is still bad for most metals, alloys, or slags, close and above liquidus temperature. Furthermore, especially properties of slag and slag skin may change over the time of the process. This is problematic as some of these properties have a high influence on the simulation as well as general process management. Additional parameters, such as slag skin thickness, are highly important for ESR simulations. However, modeling the exact expression and development of slag skin is difficult, and there exist some approaches made by Yanke et al., but they are computational expensive and not reliable enough to be used for general modeling of the process. Therefore, simplifications and assumptions in critical parts of the model are still common. Until today, there have been no extensive experimental measurements of flow or temperature field within the liquid metal or slag phase. Therefore, usually the solidification lines are used for indirect validation of the process. There are many different uncertainty parameters influencing the simulated solidification
lines, however, that is, process control, thermophysical properties, slag skin formation, dendrite growth, porous flow inside the mushy zone, change of electrode shape, air gap formation, or ion transport, to name a few. There at least exist some modeling approaches for all of these, but most of these lack validation and/or are comprehensive enough to be used for the modeling of the whole process. Due to the many uncertainties and the connection of many nonlinear correlations, until today, there has been no evidence that a temperature profile well diagnosed by a simulation also guarantees the correctness of the simulation in other areas, that is, of the flow field in the slag phase. As stated by Plotkowski and Krane, the fidelity of the physics-based numerical models for ESR surpassed the precision of the required input data. Nevertheless, till these uncertainties can be overcome, the models itself will still prove their usefulness for a better understanding of certain phenomena and trends.

In this article, we will describe the modeling results of a variant of the ESR process, utilizing a rotating electrode based on the concepts of Chuman and Chuman.[4] There have been attempts for modeling the whole process of the rotating-electrode ESR by Wang et al.[22] Here, they simulated a small-scale ESR lab process with electrode rotation speeds between 120 rpm and 160 rpm and confirmed phenomena like the typical change of the velocity field or the shallowing of the pool. More recent numerical investigations from Huang et al. observed increased melt rates (16–22%) and therefore, by implication, a lower and more uniform slag temperature. Furthermore, they reported shifting of droplet detachment to the outer radius of the electrode bottom, decrement of inclusions, and the influence on the pool profiles of different rotation speeds.[23,24]

In this article, we will focus on the modeling and evaluation of the dripping behavior inside the slag phase. From the observations made, we will try to propose a strategy on how to further improve the technology of a rotating electrode in the ESR process. Furthermore, we present a new modified concept to evaluate the varied droplet behavior introduced by the rotational movement by the electrode.

2. Modeling

For this experiment, we used a 3D model, which is a coupled model between multiphase flow (FVM) and electromagnetics (FEM) simulation, considering the slag/phase area shown in Figure 3.

2.1. Theoretical Foundation

To start with, we will introduce the basic modeling equations to describe the multiphase magneto hydrodynamic flow and energy transfer, building the theoretical foundation for the used commercial computational fluid dynamics (ANSYS Fluent 19.2) and electromagnetic capable finite-element (ANSYS Mechanical APDL 19.2, EMAG capabilities) software. These will further on be abbreviated with CFD of EMAG software, respectively.

2.1.1. Fluid Flow

The incompressible fluid flow can be modeled using the Navier–Stokes equations consisting of continuity Equation (1) and momentum Equation (2).

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \tag{1}
\]

\[
\frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) = -\nabla p + \nabla \cdot \mathbf{t} + \rho \mathbf{g} + F_L \tag{2}
\]

Within these equations, \( \mathbf{u} \) is velocity, \( t \) time, \( p \) pressure, and \( \mathbf{g} \) gravity acceleration vector. Forces induced by the electromagnetic field are modeled using the volume-specific Lorentz force source term \( F_L \). Coupling the flow velocities with the electromagnetic equations is not necessary, due to the low flow velocities. The shear stress tensor \( \mathbf{t} \) can be described using Equation (3), \( \mu_D \) is dynamic viscosity, and \( \mathbf{I} \) the identity matrix.

\[
\mathbf{t} = \mu_D \left( (\nabla \mathbf{u} + (\nabla \mathbf{u})^T) - \frac{2}{3} \nabla \cdot (\mathbf{u} \cdot \mathbf{I}) \right) \tag{3}
\]

To describe the interaction of the liquid metal and the slag phase, the volume of fluid (VOF) method is used. The VOF technique considers a single momentum equation but solves these for each phase’s volume fraction \( \alpha \) of an adapted continuity Equation (4), and \( \rho_i \) the density of the phase. The sum of the volume fractions of all phases \( \alpha_p \) must be equal to unity, as shown by Equation (5).

\[
\frac{1}{\rho_i} \left( \frac{\partial (\rho_i \alpha)}{\partial t} + \nabla \cdot (\rho_i \alpha \mathbf{u}) \right) = 0 \tag{4}
\]

\[
\sum_{i=1}^{n_p} \alpha_i = 1 \tag{5}
\]

The interface between the different phases of the VOF cells can be tracked via interface reconstruction schemes.[27] In particular, the “geometric reconstruct” method derived after Young’s method according to the ANSYS Theory Guide is used.[28,29]

A turbulence model should be used to account for the wake flow of liquid metal droplets inside the slag area. To account for turbulent movements, the Reynolds averaged Navier Stokes (RANS) approach is used. Therefore, all velocities in the momentum or continuum equations are expressed as a combination of mean average velocities and their fluctuations. While the time-averaged fluctuations of linear terms become zero, all nonlinear terms must account for these fluctuations, which lead to a modified version of Equation (2). This equation can be expressed using the tensor notation, see Equation (6) and (7).[30]
\[
\rho \frac{\partial u_i}{\partial t} + \frac{\partial}{\partial x_j} (\rho u_i u_j) = - \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \tau_{ij} + \rho g_i + F_i \tag{6}
\]

\[
\tau_{ij} = \mu \frac{\partial u_i}{\partial x_j} + \left( \mu_1 \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} \rho \kappa \Delta u \tag{7}
\]

Here, \( k \) is the turbulent kinetic energy and \( \mu \) the turbulent viscosity. The calculation of these additional parameters depends on the selected turbulence model. In particular, the RNG \( k \)-epsilon model from Yakhot et al. was used for the simulations.\(^{[29]}\)

2.1.2. Energy Conservation

With the use of a RANS turbulence model, the energy conservation can be described via Equation (8) additionally defining the Joule heating \( Q_l \).

\[
\frac{\partial (\rho E)}{\partial t} + \nabla \cdot (\rho E + \rho E + p) = \nabla \cdot (\lambda_{\text{eff}} \cdot \nabla T + \tau_{\text{eff}} \cdot u) + Q_l \tag{8}
\]

In this equation, \( \lambda_{\text{eff}} \) and \( \tau_{\text{eff}} \) are so-called effective quantities, whose calculation depends on the chosen turbulence model.\(^{[29]}\)

2.1.3. Electromagnetics

The electromagnetic field during the ESR process can be described using macroscopic Maxwell’s equations (9)–(12).\(^{[32]}\)

\[
\nabla \times H = J + \frac{\partial D}{\partial t} \tag{9}
\]

\[
\nabla \times E = -\frac{\partial B}{\partial t} \tag{10}
\]

\[
\nabla \cdot B = 0 \tag{11}
\]

\[
\nabla \cdot D = 0 \tag{12}
\]

\( B \) is the magnetic flux density, \( D \) is the electric displacement field, \( E \) is the electric flux, \( H \) is the magnetic field intensity, and \( J \) is the electric current density. According to Henke displacement, currents can be neglected in most cases for current conduction at main frequency (50–60 Hz) \((\partial D/\partial t = 0)^{[33]}\). Furthermore, neglecting magnetization and polarization effects and assuming isotropic material behavior, the Maxwell equations can be complemented with the following material equations, Equation (13)–(15).

\[
B = \mu H \tag{13}
\]

\[
D = \varepsilon E \tag{14}
\]

\[
J = \sigma (E + u \times B) \tag{15}
\]

Here, \( \mu \) is the magnetic permeability, \( \varepsilon \) is the permittivity, and \( \sigma \) is the electrical conductivity. All those material properties can be third-level tensors, but they are assumed to be constant within this work.

To describe the electrodynamic phenomena the magnetic vector potential \( (A - \phi) \) method is used. The \( A - \phi \) method states that due to Equation (11) the magnetic field can be purely described with the rotation of the magnetic vector potential \( A \) (Equation (16)). Introducing this approach leads to another degree of freedom, which can be dealt with by introducing the gradient of a scalar function \( \phi \), the so-called electric potential; this allows the electric field \( E \) to be described by Equation (17).\(^{[32]}\)

\[
B = \nabla \times A \tag{16}
\]

\[
E = -\frac{\partial A}{\partial t} - \nabla \phi \tag{17}
\]

Using these equations, the Maxwell and material equations are put to Equation (18). As described by Kost, the Maxwell equations can then be solved numerically, utilizing a suitable gauge condition for the divergence of \( A \).\(^{[32]}\)

\[
\nabla \times \frac{1}{\mu} \nabla \times A + \sigma \left( \frac{\partial A}{\partial t} + \nabla \phi \right) - u \times \sigma \nabla \times A = 0 \tag{18}
\]

The time step size for the calculation of changing electromagnetic fields is usually significantly smaller than the time step size necessary for the solution of the multiphase flow. Therefore, the magnetic vector potential equation should be simplified in case of stationary DC current or be solved in a harmonic manner in case of applied AC current, a usual approach is described in the ANSYS Mechanical APDL Theory Guide.\(^{[34]}\)

The resulting quantities of the Lorentz force \( F_l \) used in the momentum equation as well as the Joule heating \( Q_l \) term used in the energy conservation equation can be derived using the general equations, Equations (19) and (20).

\[
F_l = J \times B \tag{19}
\]

\[
Q_l = \frac{J \cdot J}{\sigma} \tag{20}
\]

2.2. Geometry

The geometry for the CFD and EMAG simulation is slightly different, as shown in Figure 6. The geometry parameters shown in Table 1 were used.

2.3. Mesh

The mesh is the critical point for our simulations, especially for the multiphase flow simulation. If we look at Equation (21), given by Hoyle, to determine the influence of droplet size on residence time, we can see that the increase in residence time with decreasing droplet radius is proportional to \( 2/r^3 \).\(^{[3]}\) This means that a slight decrease in droplet size should lead to a relatively large increase in residence time.

\[
t = \frac{k \cdot \mu_s}{r^2 \cdot (\rho_m - \rho_s)} \text{ with } k = \frac{9 \cdot \Delta h_s}{2 \cdot g} \tag{21}
\]

As we are using the VOF method, the mesh determined what droplet sizes can be resolved. Sadly, there is no experimental
information or correlation about the real droplet size in the simulated process. We assume that the droplet size of the detaching droplets will be above 5 mm, which seems reasonable compared with the mainly gravity-driven droplet-size formation of different fluids, and use a mesh size of $\approx 1.25$ mm in the slag/metal area. For the EMAG simulations, we must use a much coarser mesh (element size: $\approx 5$ mm), due to much higher demands for main memory for each finite element. The resulting meshes are shown in Figure 4. For the CFD mesh we get a mesh of about 1.2 million cells and for EMAG mesh we use about 90,000 cells.

2.4. Coupling between EMAG and CFD

For the coupling between the CFD and the EMAG software, the routine shown in Figure 5 is used. Due to the high computational demand of each simulation, the coupling between the simulations is done explicitly over time. Due to the closed source nature of both codes (limited accessibility), a file-based coupling approach is used, which means the simulation codes read/print out the exchanged properties to separate files. The CFD code calculates the thermal multiphase flow and prints out the interpolated (to the FEM mesh) phase distribution $\alpha$. These are then read by the FEM code, which then calculated a steady harmonic solution of the interpolated distribution. Lorentz forces $F_L$ and Joule heat $Q_J$ are written to files, which are then read, interpolated, and applied by the CFD code again.

Currently, the routine uses a custom nearest-neighbor approach, which uses a mapping table calculated at the beginning of the procedure, as the meshes are constant during the procedure. The routine is implemented using different so-called user-defined functions (UDF) for the CFD software (ANSYS Fluent) in accordance with custom scripts for the EMAG software (ANSYS Mechanical APDL); the source code can be found at the given link.\[33\]

2.5. Boundary Conditions

Geometry and boundary conditions were derived from (operating data) of an ESR trial facility at the Institute IME Process Metallurgically and Metal Recycling of the RWTH Aachen University. The melt rate and applied current boundary conditions, whose spatial position is shown in Figure 6, were determined from mean values for process data during the stationary phase of the process.

A rotation speed of 50 rpm was chosen, because it was the maximum achievable rotation speed by the time of the related experimental investigations. The inlet velocity for the 50 rpm case is slightly increased, due to the increase in melt rate under electrode rotation, as shown in Table 2. The mold region was initialized with a temperature of 25 °C and all other areas with 1500 °C; the velocities were set to zero in the fluid region and the turbulence properties were set to very low values for stability reason (practically zero).

2.6. Thermophysical Properties

The metal phase is steel 1.2334; the thermophysical properties were calculated with a CALPHAD software for the assumption of phase equilibrium (why the modeled properties below the liquidus temperature of 1474 °C should only be used with care for other applications), as shown in Figure 7.

For the slag (70% CaF, 30% Al$_2$O$_3$), we evaluated some literature data and decided to use the material data, as shown in Table 3.\[12,17,36\] The interface tension between liquid metal and slag will be assumed with 1.0 N m$^{-1}$.

As we wanted to model two cases, an insulating and a noninsulating slag skin, to investigate the differences between the two assumptions, we used an electrical resistivity of 5 Ω·m for the noninsulating and 500 Ω·m for the insulating slag skin.

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**Table 1. Geometrical data used for the simulations (see also Figure 6).**

| Property         | Value [mm] |
|------------------|------------|
| $d_{El}$         | 106.5      |
| $d_M$            | 153        |
| $\Delta d_{El}$  | 15         |
| $\Delta d_M$     | 1          |
| $h_{El}$         | 5          |
| $h_M$            | 150        |
| Slag bath height | 100        |
| Metal bath height| 50         |
| Height electrode | 15         |

**Figure 4.** Numerical meshes for: a) CFD and b) EMAG simulations.
Figure 5. Schematic of the coupling procedure between CFD (FVM) and EMAG (FEM) model.

Figure 6. Geometry (Table 1) and boundary conditions (Table 2): a) CFD and b) EMAG.
2.7. Evaluation of Dripping Behavior

To evaluate the dripping behavior, without having to manually evaluate all simulation data, we developed a routine called continuous phase area detection (CAPD). CAPD is implemented in C via the so-called UDF within the CFD software and it can be found at the given link.[37] Every time iteration, the code scans through each cell and searches for over cell edges connected cells containing a certain minimal volume fraction of a target phase. The computational overhead is negligible. The connected cells are then filtered and grouped into a so-called droplet continuous phase area (DCPA). The DCPIAs are then characterized by timestamp, center of mass, mass, volume, and minimum, maximum, and average volume fractions.

3. Results

We simulated a nonrotating (0 rpm) and a rotating electrode case (50 rpm) between 0 and 10 s, both for the assumption of an insulating and a conductive slag skin. As the simulation duration is very short, the results may still be influenced by the initial conditions, what we accepted due to the long computing times. A time step of 0.001 s was used for CFD simulations. The simulations were each run on 32 core machines and ran between 3 and 4 weeks. As shown in Table 4, there is no significant difference between the droplet detachment times of the first droplets, as a first indicator for the average metal film size, due to the slag skin conduction assumption. The average values, which are shown in the following sections, were averaged between the time after the first droplet detachment and 10 s.

| Name | Description | Value |
|------|-------------|-------|
| \( \nu_{in} = 0 \text{rpm} \) | Normal inlet velocity of liquid metal | \( 3.47 \times 10^{-4} \text{ m s}^{-1} \) |
| \( \nu_{in} = 50 \text{ rpm} \) | Inlet temperature | 1494 °C |
| \( T_{in} \) | Backflow temperature | 1494 °C |
| \( T_{in} \) | Cooling water temperature | 20 °C |
| \( T_{in} \) | Temperature of surrounding argon | 50 °C |
| \( \alpha_{w} \) | Heat transfer coefficient between water and mold | 10 000 \( \text{W m}^{-2} \text{K}^{-1} \) |
| \( \alpha_{s} \) | Heat transfer coefficient of free slag surface | 300 \( \text{W m}^{-2} \text{K}^{-1} \) |
| \( \varepsilon_{s} \) | Emissivity of free slag surface | 0.6 |
| \( I_{El} \) | Applied current | 3200 A |

Table 2. Boundary conditions.

| Name | Description | Value |
|------|-------------|-------|
| \( \rho \) | Density | \( 7.8 \text{ g cm}^{-3} \) |
| \( \rho_{d} \) | Electrical resistivity | \( 1.15 \text{ cm} \) |
| \( \varepsilon_{p} \) | Electric permittivity | \( 2.4 \text{ V s cm}^{-1} \) |
| \( \lambda \) | Thermal conductivity | \( 1.9 \text{ W m}^{-1} \text{K}^{-1} \) |
| \( \mu \) | Viscosity | \( 8.2 \text{ mm Pa s} \) |

Figure 7. Thermophysical properties of 1.2334 calculated with JMatPro (equilibrium based).

Table 3. Material data for slag as used in the simulations.

| \( \rho \) | \( \rho_{d} \) | \( \varepsilon_{p} \) | \( \lambda \) | \( \mu \) |
| [kg m\(^{-3}\)] | [\Omega cm] | [\text C\(^{-1}\)] | [W m\(^{-1}\) K\(^{-1}\)] | [Pa s] |
| \( T \) = \(-0.215 \cdot T + 2990 \) for \( T \) in °C | 0.42 | 1650 | 50 | 0.025 |

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3.1. Electromagnetic Properties

Due to the coupling principle and the different meshes between CFD and FEM (EMAG) simulation, there are certain coupling errors between both simulations, especially considering the coupling of small- or low-phase-fraction cell areas. In Figure 8, the difference in the coupled electromagnetic properties for the assumption a) conductive or b) insulating slag skin is shown for an electrode rotation of 50 rpm.

In the metal/slag area, both properties have slightly higher values; also, the difference is slightly higher with increasing distance from the electrode. This means that the influence of these assumptions especially to the droplet formation should be relatively low. However, this may change for larger simulated times, as the influence of initial conditions may become weaker and the differences, for example, in Joule heating, may become more significant.

3.2. Temperature Field

As can be expected, the simulated average temperatures in case of an insulating slag skin are slightly higher than those for the not-insulating slag skin, as shown in Figure 9. If we compare the temperatures at the last simulated time stamp (10 s) between 0 rpm and 50 rpm electrode rotation, it can be seen that in case of electrode rotation, the mean temperature is somewhat lower and more homogenous than for a static electrode. This makes sense, due to the higher velocities in the slag area and therefore increased heat transfer between the electrode and slag or walls (slag skin) and slag. As there is no solidification modeling right now, we expect a larger model error for the temperature field in the lower third of the figure.

3.3. Flow Field

Even if there are minor differences in the velocity fields regarding the assumption of the slag skin conductivity, the difference caused by electrode rotation is way more pronounced. Figure 10 shows the velocity field for case a) SC and b) rotating conductive (RC). In comparison it can be concluded that the electrode rotation leads to circular flow around the rotation axis in the slag phase, which leads to an uprising flow field in the center, which is much less influenced by the position of the falling droplet paths.

3.4. Droplets

Using the described CPAD routine, we get additional information from the simulation data. Figure 11 shows the droplet frequency (a), the mean distance of the droplets from the rotation axis (b), the residence time and trajectory length after detachment (c), and the calculated mean thickness of the liquid metal film beneath the electrode (d).

As we used a higher melt rate for the rotational electrode cases (R), a downscaled droplet frequency is also given in Figure 11a. Comparing these values, an electrode rotation of 50 rpm does not influence droplet frequency significantly. Otherwise, droplet distance from the rotation axis rises (b), which seems plausible, and both the length of trajectory and the residency time lower. The latter seem counter intuitive, but if we look at the different local film thicknesses, Figure 12, and the mean film thicknesses, Figure 11d, we see that there is a potentially larger reservoir volume during droplet detachment in the rotating case. This will lead to a slightly later detachment of individual droplets. Furthermore, the centrifugal acceleration does not have a dominant influence on the droplet trajectory for the later detaching droplet, which is still dominated by gravity. Therefore, the lower evaluated residence times and trajectory lengths, given in Figure 11d, probably will not have any real negative influences on the processes itself. They are more relict due to the evaluation (CPAD) procedure itself. Therefore, as comparison, the (scaled) droplet frequencies are better indicators for potential enhancements regarding the droplet characteristics.

To conclude, for the simulated cases, there is no significant difference in droplet size, residence time, or length of the droplet.

| Case | Conductive slag skin [rpm] | Time of first droplet detachment [s] |
|------|----------------------------|------------------------------------|
| SI   | x 0                        | 3.40-3.42                          |
| SC   | x 0                        | 3.40-3.42                          |
| RI   | x 50                       | 6.28-6.30                          |
| RC   | x 50                       | 6.28-6.30                          |

Figure 8. Averages values for Joule heating (left) and Lorentz force (right) for a) RI and b) RC.
trajectory, but a significant increase in average film thickness and a larger radial distance of the droplets from the rotation axis.

4. Discussion

Comparing the results of the changed flow field and temperature field against other research publications, especially those of Huang et al., which use a very similar geometry setup, the general observations regarding rotational-induced changes to flow field and temperature distribution tend to agree.\cite{23,24} Huang et al. do not show quantitative analysis about the film thickness, but from the qualitative figures for different cases, the “ring formation” near the edge of the electrode for rotation speeds around and above 40 rpm also can be observed. Furthermore, adopting the here called CPAD routine for further simulation evaluations seems to be useful, as these data may indicate behavior that one might otherwise not notice within the large amounts of transient CFD data.

A major issue with the coupled simulation (FEM–FVM) approach used in this work (besides the limit resolution of the FEM mesh) is its poor performance compared with other approaches. Here, the roughly estimated performance disadvantage factor per timestep is between 100 and 200.\cite{22,24} Even if the
use of a simplified MHD modeling approach, for example, using the ANSYS Fluent MHD module, does not allow the consideration of temperature-dependent conductivities, eddy, or displacement currents (remark: to the best of our knowledge, there are no comprehensive publications on how relevant these influences can be within the wide range of different ESR processes), using simplified MHD approaches for the modeling of the rotating-electrode ESR processes, as done by mentioned publications, obviously offers a very significant performance advantage, with comparable results in the tendency. Regarding the case of a rotating electrode simulation, this is especially caused by the fact that a 3D resolution is necessary. This is additionally enhanced by the fact that the required time step size for the multiphase flow simulation, due to stability reasons, must be in the same order of magnitude as it is necessary for the resolution of the grid frequency (50–60 Hz) of the alternating current.

This is especially relevant as simulating larger process times (600–1800 s) are usually used to make more viable predictions to find ingot quality. Though it would be possible to adopt a zonal-separated approach, for example, that described by Gieselsmann et al., which would allow the use of a coupled FEM–FVM model for complete process modeling in reasonable times, such a solution does not seem optimal under the mentioned aspects. This is especially the case under the aspect that also industrial-sized plant geometries should be investigated, to further evaluate the application of a rotating electrode.

In the long term, the development of generally more capable and flexible FVM-based electromagnetic solver approaches, for example, by Beckstein et al., could add more flexibility to future ESR simulations and furthermore unify the foundation of many ESR simulation approaches.
5. Conclusion

From our simulations, we conclude that electrode rotation can influence both droplet characteristics and mean film thicknesses below the electrode. However, possible positive changes of those parameters are not reached within the simulated geometry and a rotation rate of 50 rpm. This seems to be caused by the fact that the weak centrifugal forces seem to promote the formation of a liquid metal ring below the electrode; as this type of film provides a larger reservoir for the droplet during droplet detachment, and the changes here are not only positive. Positive effects to film thickness or droplet characteristics should be expected when rotational acceleration forces clearly dominate over gravity forces, which for our geometry will be the case somewhere above 180 rpm. As higher rotation speeds could also lead to conceivably negative influences, this must be evaluated in future simulations.

In the described simulations, the differences between the flow and temperature field, between the static and rotational electrode case, are more significant. Both in practice may lead to positive aspects such as higher melt rate (respectively, lower power consumption) or a shallower metal pool. However, it is to be expected that both aspects are also highly geometry deepened as the changes to heat transfer from the changed flow field will both influence the heat transfer between electrode and slag and slag and mold. A positive effect of rotation on the diffusion layer between the metal and slag is possible, but it is difficult to quantify from these simulations.

At least, as the flow field is less influenced by single-droplet detachment, an electrode rotation may be used, to enhance the stability of the process control, as the flow field probably will be more independent of other process parameters.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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