SPATIO-TEMPORAL VARIATION OF THE ELECTROMAGNETIC FIELD IN THE ELECTROSLAG REMELTING PROCESS

A. Kharicha, A. Ludwig, M. Wu
Christian Doppler Laboratory for Advanced Process Simulation of Solidification and Melting, University of Leoben, 8700 Leoben, Austria
Franz-Joseph Strasse 18. 8700 Leoben, AUSTRIA,
abdellah.kharicha@uni-leoben.at

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Abstract

In the present paper, the droplet formation during in an Industrial scale ESR process is simulated with an advanced 3D multiphase-Magneto-hydrodynamic numerical model. The momentum, energy and electromagnetic fields are fully coupled. The computational domain includes a layer of slag and a layer of liquid steel. It is shown that a complex interaction between the electromagnetic field and the phase distribution occurs. This interaction generates turbulent 3D behaviours of the flow and the slag/metal interfaces.

Introduction

The Electro-Slag-Remelting (ESR) process is an advanced technology for the production of components of e.g. high quality steels [1-12]. An alternating or direct current (5000-50000 Amps) is passed from a conventionally melted and cast solid electrode through a layer of molten slag to the baseplate. In the near future, the steel industry will have to produce much larger ingots for larger parts with improved cleanliness levels and at very low segregation limits. Large number of publications can be found in the field of simulation of the ESR process, but almost all are performed in 2D. Unfortunately simple models using rough 2D approximations cannot be used in large geometries where 3D effects are believed to be dominant. This process involves two liquids, a liquid metal and a liquid slag. Each liquid is subject to a phase change due to melting and/or solidification. From a fluid dynamic point of view, the ESR process is clearly a multiphase process, with free interfaces (slag/pool, gas/slag), and with a mixed area (slag and falling steel droplets) [7-12]. Electric current densities are much larger than those observed in Aluminium reduction cells, assuming flat slag/metal interfaces the current density is of about 10^4 to 10^5. With those current densities, the Lorentz force is able to dominate the momentum of the system, especially if the position of the slag/metal interfaces is space and time dependant. To explore those effects a 3D MHD model has recently been built. It was already successfully applied to the melting of small electrodes [12]. This model is now used to explore the droplet formation during the melting of an industrial scale electrode.

Numerical Model

The fluid calculation domain is a cylinder divided into 13.8 million volume elements (Figure 1). The electrode has a radius of 21 cm. The containe r(30 cm radius) is initially filled with the quantity of liquid slag (10 cm high) and liquid steel (10 cm high). The interface between the air and the slag, known as the exposed slag surface, is modelled with a slipping fixed wall. The electromagnetic field is solved on a cylindrical domain which is 30 cm high and 75 cm radius. It includes the fluid domain, the solid electrode (10 cm high), and a large surrounding void region (Figure 1). Inside the fluid region the electromagnetic field is resolved on the same mesh than the momentum field. Outside the fluid region much less variations of the electromagnetic field is expected, thus only 238 000 volume elements are used to mesh this outer domain. The electrode supplies a total DC current of $I_0 = 13\ 000$ Amperes.

The interface between the two phases is tracked with a geometric reconstruction VOF technique. A single set of momentum equations is shared by the fluids, and the volume fraction of each of the fluids in each computational cell is tracked throughout the domain. According to the local value of the volume fraction f, appropriate properties and variables are assigned to each control volume within the domain. The electromagnetic field is solved by using the electric field ϕ and the magnetic potential vector $\vec{A}$. In the liquid the computed electromagnetic field, and the resulting Lorentz force and Joule heating, are fully coupled to spatial distribution of the electric conductivity. It is then possible that the metal distribution in the fluid domain generates a non axisymmetric electric current flow. The time step is controlled by turbulence and the dynamic of the metal/slag interface through a chosen maximum courant number of 0.1. The calculations, which for the present analysis lasted about 60 days, were performed with a supercomputer Intel Nehalem Cluster 2,93 GHz with 16 Cores.

Results and Discussion

Figure 2 represents the evolution of the electric current density during the formation and the departure of several droplets. To minimize the electric resistance, the electric current chooses in priority to travel through the liquid metal. The formation of a droplet starts by the thickening of the liquid film (5-7 mm) in a form of a bag. In figure 2 a we can observe almost 20 positions from where the droplets can possibly depart. When the thickness of the liquid film bag exceeds 13 mm an elongated faucet forms. The electric current density increases strongly during the faucet formation. But when the departure of the first droplet occurs a slag gap forms between the drop and the remaining faucet, the current density decreases. The electric current density decreases also to lower values during the departure of smaller droplets (satellite droplets). During the fall, the large droplets flatten and develop a lentil or a crescent shape (Figure 2e). The depressions (with low electric current density) created by the impacts on the slag/pool interface can easily be observed in figure 2 c-f). Around the droplet being formed, the electric current density reaches values (10^7 A/m^2) much larger than those normally observed in the periphery of the electrode (10^5 A/m^2).

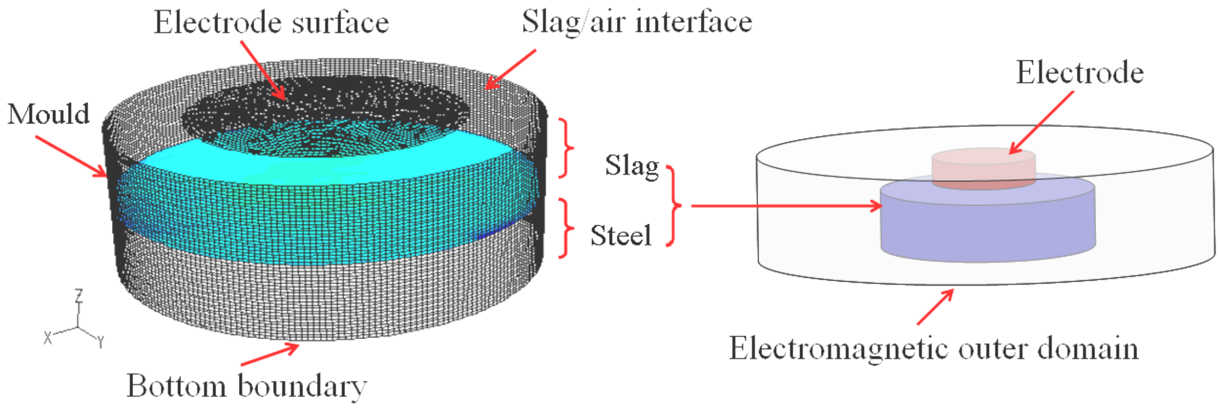
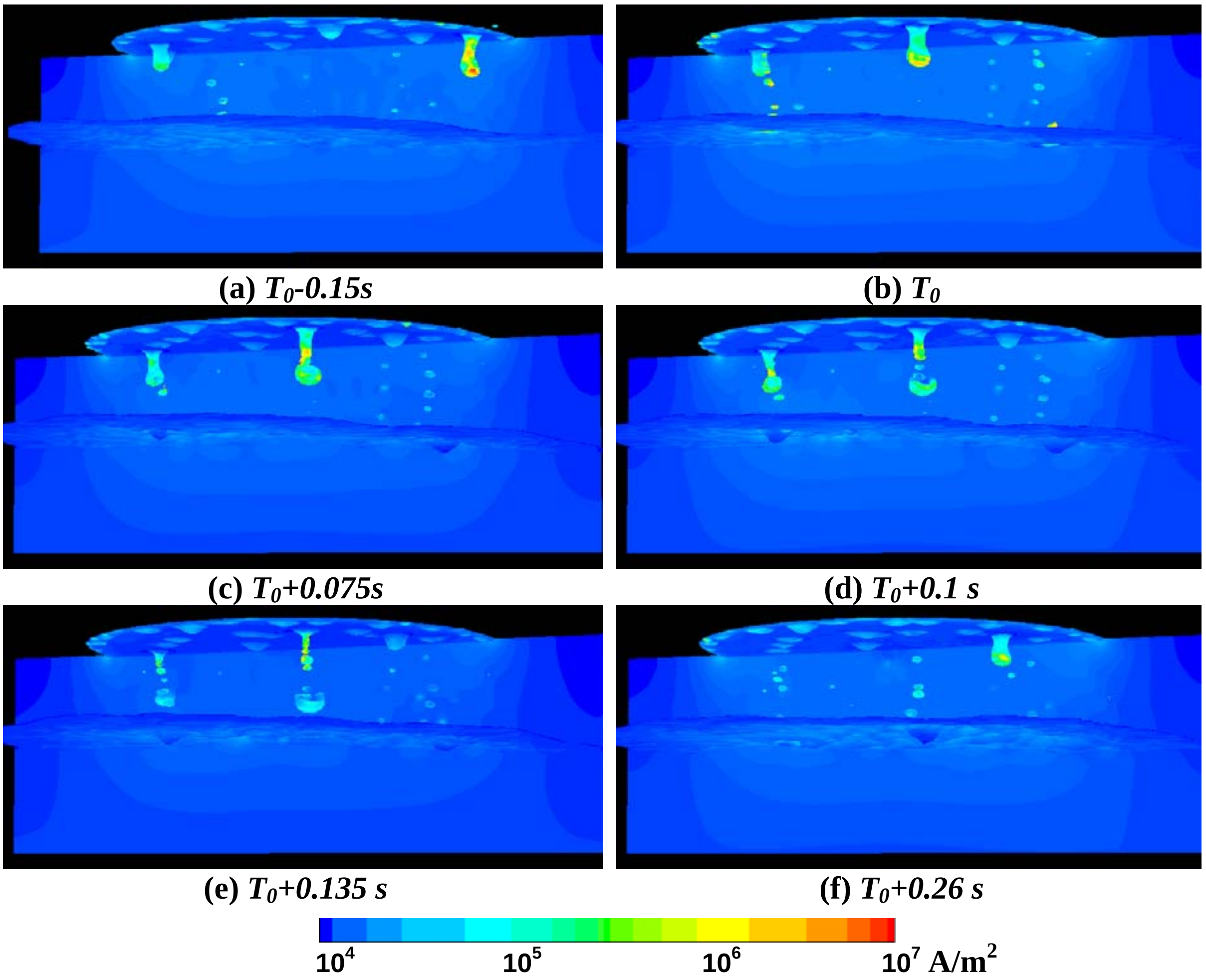


Figure 1: Calculation domain



(a) T_0*-0.15s**(b)** T_0

(c) T_0*+0.075s* **(d)** T_0*+0.1 s*

(e) T_0*+0.135 s* **(f)** T_0*+0.26 s*

Figure 2: Electric current density

The movement of the liquid-pool interface is clearly observable in figures 2. The maximum measured elevation of the interface is of about 3 cm. Its movements has a strong non axis-symmetric behaviour, resulting from a combined action of the droplets impact, but also from MHD actions similar to those observed in aluminium reduction cells[13-15].

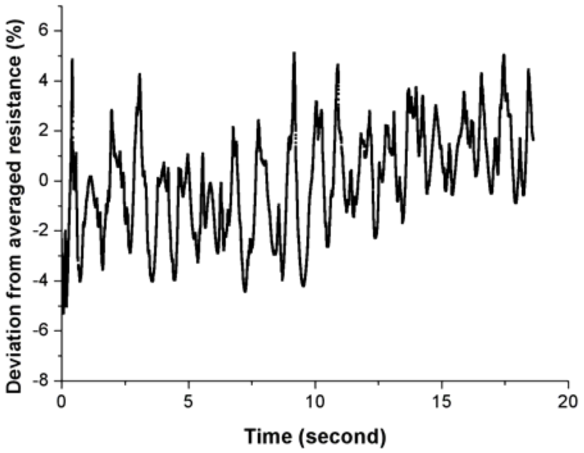


Figure 3: Fluctuation of the electric resistance during melting.

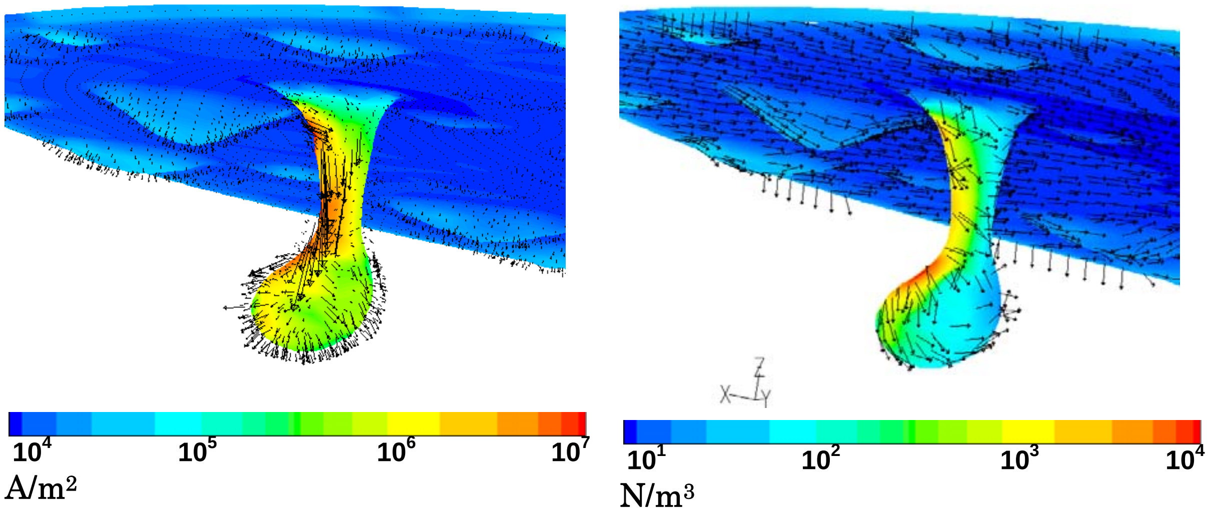


Figure 4: Electric current (a) and Lorentz force vectors (b) at the surface of a liquid metal faucet just under the electrode being melted.

(a)

(b)

Figure 5: Magnetic field iso-lines over the surface of the electrode. The magnetic field vectors are oriented along the lines: a) without melting b) with melting

Spacio-Temporal Variation of the Electromagnetic Field

The main power generated (computed) during the processes fluctuates around 650 kW. Since the imposed current is here fixed, those fluctuations are related to a time variation of the electric resistance of the system. The electric resistance fluctuates around its mean value depending on the metal distribution in the calculation domain (figure 3). The fluctuations can reach 5% at some points, but in average it is lower than 2%. The lowest resistance picks correspond to situations where long faucets are present, and the highest correspond to situations with a minimum of droplets between the electrode and the interface. The movement of the interface can also affect the resistance path by decreasing at some position the distance between the electrode and the liquid pool. It can be noticed that the maximum and the minimum picks follow a tendency, they can be enveloped or modulated by waves of smaller frequency. The minimum picks correlate with the existence of one or more low resistance metallic path. If a faucet is created just at position corresponding to a high level pool interface, the resistance will drop to a very low level. The maximum picks can be related to a time where almost no droplets are present, the maximum level reached must correlate also with the pool interface shape. It is certain that the movement of the interface acts as a modulator on the amplitude of the fast fluctuations generated by the droplets fall. It must be reminded that in the present simulation the slag/air interface is assumed flat and non moving. In industrial practice the resistance fluctuations would include the contribution of the slag/air interface movement. Thus the computed resistance swing (2 to 5 %) given here represents the minimum reachable swing. The value of the resistance is an indicator for the state at which the process is at a certain time. The resistance swing is then somehow a measure of the turbulence present in the process. The turbulence includes the flow but also the electromagnetic field. In figure 4, it can be seen how a liquid metal faucet perturbs the electric current field. Depending on the position of the faucet, the resulting Lorentz force reaches values that are one to two orders of magnitude larger than what is calculated from simple 2D models. It can be noticed that the Lorentz force is not simply radialy oriented. This is due mainly to the change in direction of the electric current when it crosses a curved interface. A second reason lies on the fact that the strong electric current within the faucet generates an additional magnetic field vortex centred on the faucet. This is why the iso-magnetic line at the surface of the electrode shows strong disturbance in several positions (Figure 5a-b). The small disturbances are due to the liquid metal bags, while the strongest disturbances are due to the presence of faucets or to the departure of droplets. Locally this additional magnetic field was found to be much larger in intensity than the magnetic field that would generates a uniform electric current over the electrode surface (Figure 5a).

Conclusions

In the present work a 3D VOF model was coupled with a Magneto-hydrodynamic model to simulate the droplet formation during melting of electrode. The model can predict the electric and magnetic field distribution in function of the metallic distribution in the low electric conductivity slag. The model was applied to the melting of an industrial scale electrode assuming a constant melting rate and a constant imposed DC electric current intensity. Although computationally extremely expensive, three dimensional MHD simulations are rather necessary if fundamental knowledge of the process is desired. The results can then be used to further develop or to tune the actual 2D models in order to give simultaneously fast and good results.

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