Selected Numerical Investigations on ESR Process

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Abstract

Electroslag remelting (ESR) and protective gas electroslag remelting (PESR) are standard processes for the production of high quality tool steels. A consortium consisting of an university department (LEOBEN), an independent software vendor (ESI Group), a plant producer (ALD), a research centre (CSM) and a steel producer (Böhler Edelstahl GmbH) was founded with the objective to generate a computational tool to model the PESR-process. To achieve this goal, three major tasks were identified and distributed amongst the partners of this project according to their skills and expertise. One task consists in performing experiments on laboratory and industrial scale ESR processes. The second task was to investigate the phenomena occurring in the process with a CFD tool. The aim of this task was to lighten some important physics such as the steel-slag interface and the steel droplet distribution in the slag phase. The third task consists in building up a software tool which is able to simulate the full process including electrodynamics, fluid flow, thermal and solidification phenomena. This task includes the development of the mathematical model and its implementation within the framework of ESI Group's CALCOSOFT-2D software. During the last three years, the collaboration between the involved partners produced a large amount of interesting results. In the present publication the outcome of the computational tasks 2 and 3 are summarized.

Keywords

Protective gas electroslag remelting process, numerical process simulation, CFD analysis, software development

Introduction

Protective gas electroslag remelting (PESR) is an advanced technology for the production of components made of high quality steels. It provides a route for the production of components with enhanced properties. Developing new steel grades with superior quality needs improved melting technology requiring a large number of trial ingots. As most of these trial ingots will not show the intended mechanical properties such process development is very costly. The approach of the project described in this publication is to use numerical simulation technique to overcome these high numbers of test trials. The optimum conditions of the protective gas electroslag remelting process should be established by implementing a physics-based computational model to predict the behavior and the required melting parameters of the process. In following this way, the final challenge will be the optimization of the ESR process, leading to improvements of the quality of the produced material as well as saving resources and avoiding undesirable waste of energy.

To accomplish this work program a consortium consisting of industrial and scientific members was founded. Three major tasks were identified and distributed among the partners, according to their different professional specialization and equipment. The first task concerns the collection of experimental data necessary for the validation of the numerical model. It contributes also with investigations and measurements on experimental and industrial ESR process scale. Details about this experimental task are presented in publication [1]. The more computational part of the project is represented by the second and third tasks.

The second task is to investigate with a CFD tool the hydrodynamics occurring in the process, in particular the flow of slag and melt and the melting process itself. An important unknown aspect is the interaction between the liquid steel and the liquid slag phase. This interaction occurs at the slag-liquid pool interface and around the steel droplets during their falling through the slag region. This task was investigated with the help of the most advanced numerical technique such as the VOF and Euler-Euler methods for multiphase flow. A magnetohydrodynamic module was written and coupled to the CFD software FLUENT, to compute the change of the electric current path according to the phase (steel-slag) distribution. Liquid steel being a much better conductor than the slag phase, the electric current will always select the path where it encounters the most often or rapidly the steel phase. The model was successfully applied to several phenomena occurring in the ESR process. Another aspect studied here concerns the actual magnitude of the electric insulation of the solidified slag thickness. A model coupling the electric and the heat flux though the layer is presented.

The challenge of the third task was to build up a new software tool which can be used for industrial numerical simulations of the whole ESR process including solidification. ESI Group's software, CALCOSOFT-2D, is a powerful industrial finite element tool which is able to simulate various continuous casting processes. It deals with microstructure formation, macrosegregation, heat transfer and fluid flow in solidification processes. Within the framework of this project a specialized new module for CALCOSOFT-2D has been developed which solves the electrodynamic problem of the ESR remelting process, coupled with fluid flow and heating in the slag and melt pool and solidification in the cast ingot.

To our knowledge, the new software tool is the first industrial software enabling the simulation of ESR processes, from macroscopic aspects such as magnetohydrodynamics, electromagnetic, convection and heating phenomena. The software development enhances the ESR industry's ability to understand the influence and interaction of complex process conditions with production issues such as quality and productivity requirements. The recent developments therefore contribute to the specific tools and methods needed to keep the ESR industry at the leading edge.

CFD analysis

The Electro-Slag-Remelting (ESR) is a process which involves two liquids, liquid steel and liquid slag. And each liquid is subject to a phase change due to melting or freezing. The steel phase is first solid, then it is melted when the electrode is in contact with hot slag. The steel is melting in the form of small droplets which then fall down through the slag to the liquid pool, where the steel is finally re-solidified by the mould cooling. The liquid slag becomes also solid at the vicinity of the cooling mould, this is called the solidified slag layer or slag skin. From a fluid dynamic point of view, the ESR process is then clearly a multiphase process, with a free interface (liquid steel/liquid slag), and with a mixed area (slag and falling steel droplets). Nevertheless, we are not aware about any work using a multiphase approach to simulate the ESR process in the literature. Often the slag media and the liquid pool are studied independently [2-3]. Some recent simulations couple both media through a fixed flat interface [4-5].

Our approach consists in applying modern CFD techniques to predict realistic phase distributions in this complicated process. But the presence of the vertical electric current brings an additional difficulty to the problem. The difficulty comes from the fact that the electric current distribution is highly coupled to the phase (steel/slag) distribution. Liquid steel being a much better conductor than the slag phase, the electric current will always select the path where it encounters the most often or rapidly the steel phase. The phase distribution is in turn influenced by the electric current distribution through the induced Lorentz force. In the present investigation, two kind of multiphase models were used. The first is the VOF model dedicated to problems where the two phases are separated by an interface to be tracked, it has been applied to studies on the steel-slag interface. The second is the Euler-Euler model dedicated to interpenetrating phases which was applied to study the interaction between the slag flow and the falling steel droplets. In the following, some typical results of these two numerical models are presented.

a) The electric current distribution. The presence of two phases in our domain makes the local value of the electrical conductivity vary in time and space. The distribution of the electric current coming from the top electrode is controlled by the distribution of the phase fraction, 1 if the cell is full of steel, 0 if it is full of slag. When the VOF method is used, the phase fraction varies suddenly from 0 to 1 over a distance corresponding to one grid size. This leads to the presence of extremely strong electric conductivity gradients at the interface. A special treatment is applied at the interface to avoid numerical problems. The ability of the model to predict the change in direction of a current across a steel/slag interface is illustrated in figure 1. This special treatment allows to study the exact shape of the slag/pool interface.

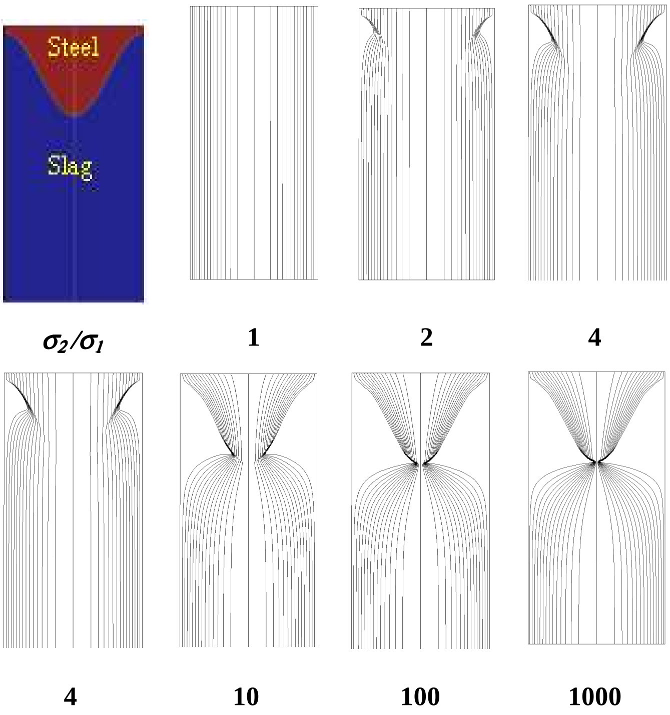
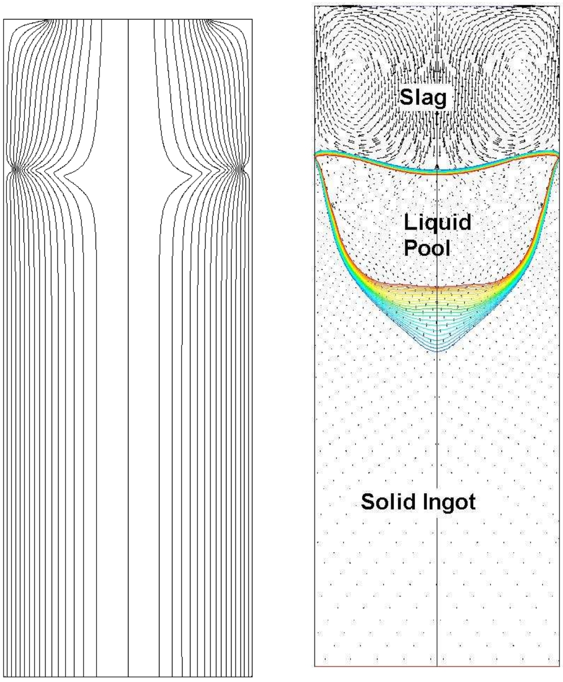


Figure 1: Electric current distribution in response to the steel/slag electric conductivity ratio.

b) **The slag-pool interface.** The VOF model was applied to an experimental ESR process scale to check if the slag-pool interface is flat or not. The flow, the temperature and solidification field were computed. The electric current distribution was coupled to the shape change of the steel-slag interface. Initially flat, the interface was curved by the strong slag flow, which then leads to a modification of the electric current path. The results are summarized in Figure 2, where it can be observed that the interface at its equilibrium state is not flat. The solidification characteristics of the ingots were found to be very different from the ones obtained with the assumption of flat slag-pool interface. Details on calculations and results can be found in [6].

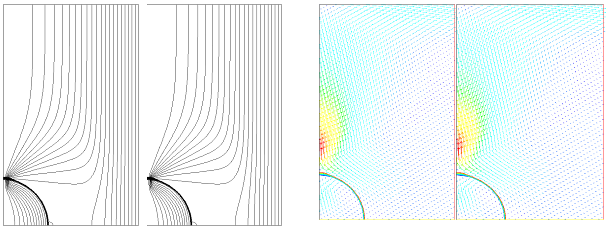


Electric current paths **Resulting slag/pool interface and pool shape**

Figure 2: Results for ESR process when the slag/pool interface is left free to move

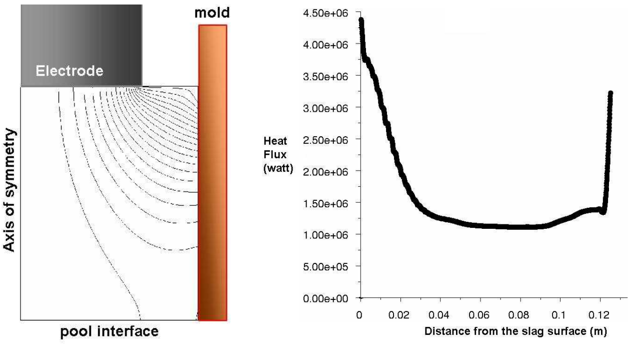
c) **Droplets-slag interaction.** The slag region has been studied with the help of the Euler-Euler multiphase model. The primary phase, the slag is totally coupled with the steel droplets phase through specific drag laws. The interaction between the two phases is done through the modification of the electric current paths due to the presence of the steel droplets. An important outcome of this model is the radial distribution of the droplets when they enter the liquid pool. This distribution is exported to CALCOSOFT-2D to model the momentum and the heat flux entering the liquid pool (see next section about ESR process simulation software). The results of this model are presented in another parallel paper [7].

d) **Microscale study.** The VOF model was also applied at the scale of a spherical steel droplet of diameter *d*. It was shown that an isolated steel droplet surrounded by a slag media, deviates the current over a domain corresponding to a cylinder with a diameter 2*d* and height 2*d*. The density of current is much higher in the droplet than in the surrounding slag. The presence of the droplet creates an additional Joule heating region (resistance) at the extremities where the current enters and leaves the droplet. It is surprising, that even with a small current density (30 Amps over a droplet of 1 cm diameter) the flow resulting from the deviation reaches already a magnitude similar to that found in simulation of the macroscale flow in the slag region(~0.1 m/s). This probably means that the steel droplets have an important interaction with the surrounding slag turbulence.



Electric current **Flow velocity (max 0.1m/s)**

Figure 3: Electric current paths and velocity fields around a 1 cm diameter droplet submitted.



Electric current **Heat flux at the mold**

Figure 4: Exact current distribution in a ESR region and heat flux at the mould..

e) **Importance of the mould current.** It is generally assumed [1-6] that due to its very low electric conductivity, the solidified slag layer insulates perfectly the slag from the cooper mould Depending on the chemical composition of the slag, the ratio between liquid and solid slag-skin electric conductivity is of order *10-100* This ratio depends strongly on the actual temperature of the slag-skin layer. Nevertheless, the thickness of the solidified slag being small (e_S *~0.1-5mm*), the radial resistance of this layer ($\sim e_S / \sigma_S$) is still smaller or of the same order than the vertical resistance of liquid slag ($\sim H/ \sigma_l$). In addition, if we consider that the mould material is generally a metal, and the fact that the electric current chooses the less resistive way, one can think that an important part of electric intensity can circulate through the lateral wall to reach the base plate.

In order to model correctly the part of the current that might circulate through the walls, it is necessary to measure experimentally the electric conductivity of the slag from solid temperatures (~500 K) up to liquid temperatures (~1800 K). In the present model the solidified slag layer is fully resolved with a grid providing about 10 to 50 nodes within the layer. A constant heat transfer coefficient of about 3500 W/m2 is used at the mould. It was found that in some geometrical configuration up to 90 % of the total current crosses the solidified slag layer. Due to the occurrence of high Joule heating, the mould current together with the heat flux at the mould control the thickness of the slag layer. The presence of heat flux pike at the top slag surface can also be explained by the presence of the mould current

(Figure 4). Details about this model will be soon published in a journal paper.

ESR Process Simulation Software

Nowadays metallurgical industries search for integrative physics-based numerical software tools covering all aspects of manufacturing processes with the objective of better understanding and controlling the processes, further cost reduction and production quality assurance. In a previous project [8][9], a model to simulate the Vacuum Arc Remelting (VAR) process had been developed and implemented into CALCOSOFT-2D, a commercial software package of ESI Group for modelling on continuous casting processes. Based on these experiences involving direct electrical currents in metallurgical processes, the scope of CALCOSOFT-2D was extended to cover also the ESR production process, taking alternating currents into account [10][11].

The simulation approach includes the current input, thermal and fluid flow in the slag and the pool due to buoyancy and Lorentz forces, Ohm's heating, solid transport of the ingot due to the melt rate of the electrode and an implicit description of the passage of metal droplets (velocity, temperature) through the liquid slag layer determined by the Euler-Euler model of the second task.

a) General model description. A macroscopic physical model for the simulation of the ESR process has been derived and implemented as a new specific module into CALCOSOFT-2D. The physical model is based on magnetohydrodynamic (MHD) equations and proper assumptions. The mathematical solver uses a standard Finite Element Method to find the solution of the coupling of quasi steady-state Maxwell's equations with the conservation equations of mass, momentum and enthalpy on a level which enables a macroscopic process description. Outcomes are results such as electrical field and current density in the slag, melt pool and cast ingot, magnetic induction, Lorentz forces and associated liquid convection in the slag and in the melt pool, Ohm's heat dissipation and associated heating in the slag and in the ingot. The modelling is done on 2-dimensional axis-symmetrical geometrical domains consisting of quadrilateral or triangular finite elements in the presence of alternating currents passing through the electrode, slag, ingot and mould.

During ESR, the consumable electrode is dipped into a pool of slag in a water-cooled mould. An electric current passes through the slag, between the electrode and the ingot being formed, and superheats the slag so that drops of metal are melted from the electrode. They travel through the slag to the bottom of the water-cooled mould where they solidify. The interface between the slag and the pool is the location of mass transfer due to the passage of the droplets, created by the melt of the electrode, from the slag to the metal liquid pool. In the numerical approach implemented here, this interface is assumed to be fixed and horizontal. The modeling of the mass transfer from the electrode to the pool was realized by prescribing a Gaussian shaped profile of velocity, depending on the droplet distribution on the interface between the slag and the pool, taken from outcomes of task 2 described above. This velocity profile is directly applied on the top surface of the pool.

b) Slag-pool interface model. As the molten metal is assumed to be incompressible, an outlet linked to the melt rate and equal to the solid transport velocity is prescribed on the bottom section of the ingot, see Figure 5. On the other hand, to avoid mixing of the slag and pool fluids, no inlet and no outlet have to be defined for the slag domain. Thus, in the numerical model, the vertical components of the velocity vector have to be discontinuous across the interface between the slag and the pool. Actually, on the side of the slag, the vertical component is fixed to zero, because fluids are assumed to be immiscible, while the velocity profile modeling the mass transfer from the electrode to the pool has to be defined on the pool side, see Figure 6.

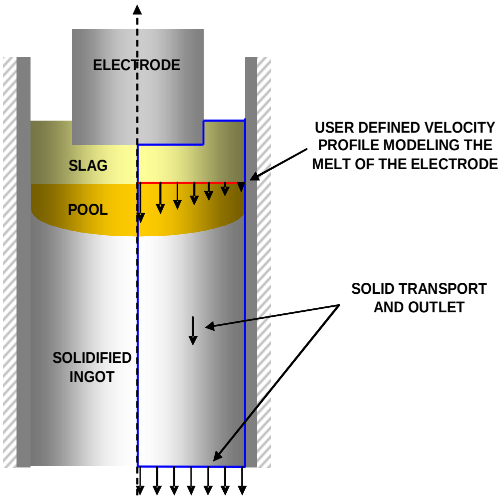


Figure 5: Fluid Flow situation for the ESR model

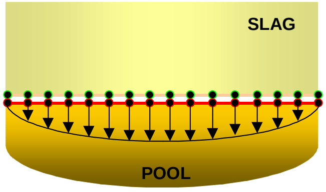


Figure 6: Slag-pool interface velocity and double nodes.

The prescription of the vertical velocity components described above, requires the doubling of nodes at the interface, which consequently removes completely the interaction by momentum transfer between the two fluids. This creates a situation corresponding to a slip condition between the two fluids. However, we build up a new numerical technique enabling also the treatment of no-slip conditions between the two immiscible fluids. For no-slip conditions the radial components of the velocity on each side of the interface have to be linked, i.e. they have to be continuous across the interface. For this purpose, the implemented double nodes can be removed for the radial components, while they are still kept for the vertical components. This particular boundary condition for the slag-pool interface, avoids any prescription (to zero) of the radial velocity components as it was done by previous modeling in the past. Two test examples, a simple natural convection flow and a ‘Couette’ flow with assumed fixed contact surfaces, were used to demonstrate that the flow behavior at the slag-pool interface is well treated by our numerical technique.

c) Boundary conditions. Besides the implementation of the implicit macroscopic modeling of the droplets and the associating interface condition described above, we focused on the boundary conditions dedicated respectively to the three sets of equations, describing heat transfer, fluid flow and the electromagnetic problem of the ESR process. This important ongoing discussion of boundary conditions should be taken as a evolving basis for upcoming simulations of the ESR process.

Figure 7 illustrates the geometrical domains, the boundaries and interfaces of the ESR model which are used to apply initial or boundary conditions to fit precisely the physics of the metallurgical process. To give examples, the thermal conditions model the heat transfer by convection and radiation between the electrode and the protective surrounding gas, the heat exchange across the interface between the electrode and the slag, the heat exchange between the slag or ingot and the mould through an interface defined by heat-link elements. An air gap due to shrinkage of the solidified ingot and solidified slag layer creation are taken into account, leading to altered boundary conditions between the slag and the mould or ingot and the mould, respectively. On the free surface of the slag, the boundary condition models heat transfer by convection and radiation. At the tip of the electrode, where the melt of the electrode takes place, the temperature rises near the melting point of the metal. In practice, a temperature slightly above the liquidus line may be imposed. At the interface between the two fluids slag and pool, the temperature can be assumed almost continuous. Thus, a huge heat transfer coefficient and heat-link elements are used. The heat extraction from the bottom of the ingot and from the mould by the water cooled jacket, as well as the heat exchange by convection and radiation of the mould with the air or protective gas is prescribed on the associated boundaries. Additionally, the heat loss of the slag while cleaning the droplets as well as the heat transfer from the droplets to the liquid metal pool are modeled by applying adequate heat sink and heat source functions imposed on the slag and ingot domains, respectively.

During the start up phase of the ESR process, the immersion depth of the electrode tip and the electric power of the furnace are controlled in order to obtain a constant melt rate. The electric power, the current and the resistance of the whole system are computed by the control system. The current intensity is given as input data. A thin layer of solidified slag is spread out along the walls of the mould, isolating the slag and the ingot from the mould. The alternating current passes through the electrode, the slag and the ingot to the basement and then returns to the electric system through the mould. However, sometimes during short time intervals, a contact between the slag or top of the liquid pool and the wall of the mould can be detected, modifying the flow of the current through the ingot.

The boundary conditions for the electromagnetic problem involves functions depending on the input current and distance to the symmetry axis, which are derived with the help of Ampere’s theorem and a coaxial wire model, prescribing the magnetic induction on the interfaces electrode-protective gas, slag-mould, ingot-air gap, air gap-mould, the free surface of the slag and the outside of the mould. On the cut sections of the ingot, the electrode and the mould so called natural conditions prescribing an induction flux of zero are applied. On the interfaces between the two domains electrode-slag or slag-pool, the continuity of the magnetic induction and the continuity of the normal component of the electric field are used to define the boundary conditions. While the nodes are doubled on this interface for the heat flow, the double nodes are removed for the magnetic induction problem. On this kind of boundary, the user of the software has nothing to prescribe.

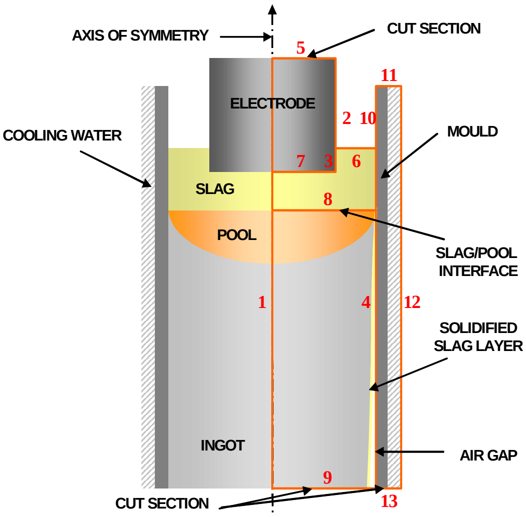


Figure 7: Main boundary conditions for ESR process.

d) ESR process simulations. Numerical experiments demonstrating the full coupling of the updated electromagnetic solver with the heat and fluid flow solvers of CALCOSOFT were performed. The samples included a comparison of VAR process simulation results as well as examples with ESR process geometry. The influence of the electrode immersion into the slag on the fluid flow motion pattern and temperature distribution inside the slag and pool as well as modifications of the electric current flow from the slag and ingot to the mould were examined. The studies showed that the new PESR module in combination with appropriate boundary conditions is able to produce reasonable simulation results describing the process.

Moreover, we made numerical simulations on the PESR process using a complete geometry, i.e. surrounding the slag and ingot with a water-cooled copper mould, rather than using an implicit mould only. The latter computations were performed in close cooperation between ESI Group SA and Böhler Edelstahl GmbH, utilizing the project partner’s practical technological expertise in the field of modern steel making processes.

The physical and chemical data of the slag, the electrode and copper mould are derived from ESR furnace installations and other process equipment in their Austrian production plants.

An electrical alternating current of 9000 Amperes and a frequency of 50 Hertz is passing through the whole system. An air gap and a slag skin of variable estimated size surrounding the ingot and the slag pool are taken into account to define the boundary conditions for the magnetic induction on the ingot and slag side of the interfaces ingot-mould and slag-mould, respectively. Macroscopic stationary simulation results are presented in Figure 8 and Figure 9.

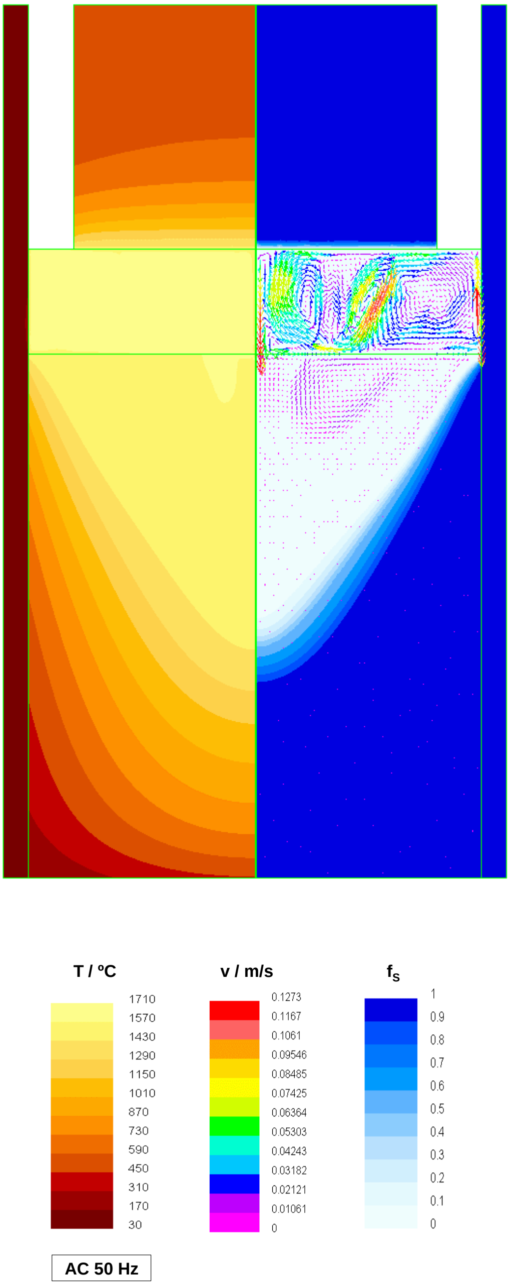


Figure 8: PESR process simulation with CALCOSOFT: temperature, velocity profile and solid fraction (in cooperation ESI Group and Böhler Edelstahl GmbH)

On the left side of Figure 8 the temperature distribution is shown, whereas on the right side the fraction solid and the liquid convection in the slag and in the melt pool are visible. The liquid convection patterns are determined by the competition between the electromagnetic Lorentz forces and bouyancy driven fluid flow.

Figure 9 shows the electrical current flow isoline mapping with associated skin effect (left side) and the Ohm’s heat dissipation with the associated heating mainly concentrated inside the upper slag domain.

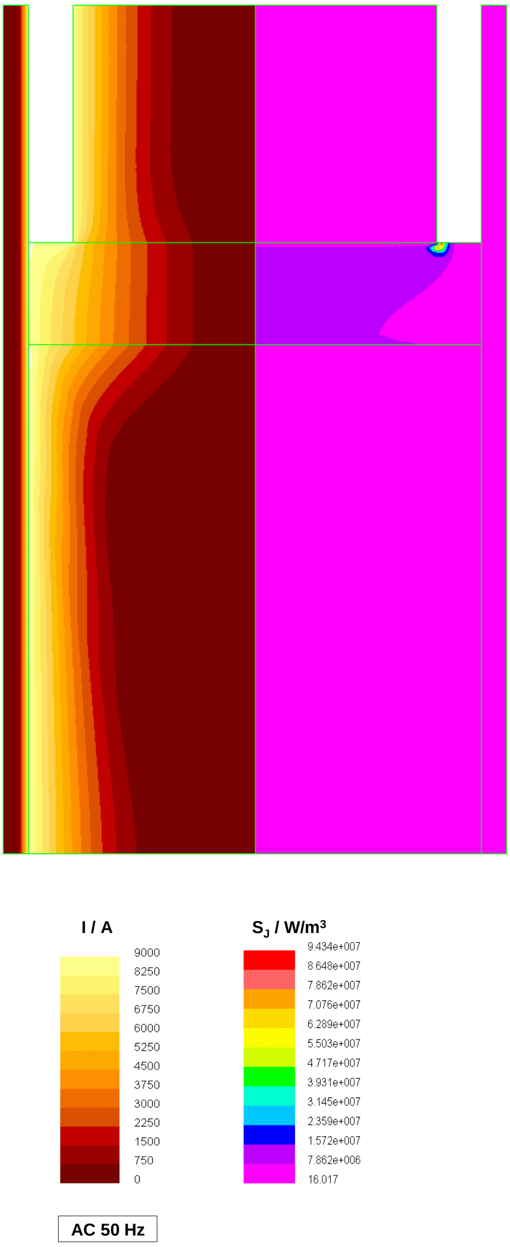


Figure 9: PESR process simulation with CALCOSOFT: electric current flow and Ohm’s heating (in cooperation ESI Group and Böhler Edelstahl GmbH)

Conclusion

The use of advanced CFD techniques has revealed the occurrence of so far unknown physical phenomena during ESR processes. These phenomena are all related to the sensibility of the electric current distribution with the presence of droplets and the possibility of a non flat slag-pool interface. It is also shown that the use of electric insulating boundary conditions at the mould is questionable.

At the same time, a physics-based ESR simulation tool was developed and implemented into CALCOSOFT-2D, a commercially available software package of ESI Group dedicated to continuous casting process simulation. Together with an extensive suite of specific and advanced modules for pre- and postprocessing, CALCOSOFT-2D can now be tailored to fit various particular needs in the field of macroscopic ESR process analysis, providing in-depth understanding of the influence of interacting process conditions and parameters to decrease the industrial process development costs and cycle time, validate a new process design or to find an optimum process window.

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