Influence of an imposed vertical current on the droplet formation during a melting process

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Abstract

The droplet formation during the melting of an electrode under the action of strong vertical current is simulated with a multiphase-MHD approach. A VOF approach is used for the interface tracking, and a potential formulation is used for the electric and the magnetic field. The Lorentz force and the Joule heating is recalculated at each time step in function of the phase distribution. The first results provided by this model are presented. Two values of metal/slag surface tensions are explored. The effect of the presence of a horizontal magnetic field is also investigated.

Introduction

The Electro-Slag-Remelting (ESR) process is an advanced technology for the production of components of e.g. high quality steels. An alternating current (Figure 1) is passed from a conventionally melted and cast solid electrode through a layer of molten slag to the baseplate. Because of the electrical resistivity of the slag, Joule heating is generated and the slag transfers this energy to ingot and mould surfaces and to the melting electrode tip. The molten metal produced in the form of droplets passes through the slag and feeds a liquid pool from where directional solidification takes place. The slag and the ingot are contained in a water cooled copper mould. As also the baseplate is water cooled, a heat flow regime is imposed that gives controlled solidification, and this results in improved structure characteristics of ESR ingots.

This process involves two liquids, a liquid metal and a liquid slag. Each liquid is subject to a phase change due to melting 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).

Physically, the development of the heat and mass transfer at slag/droplet interface is important for the final ingot quality, composition and cleanliness. Visual observations of the droplet formation just under the electrode being melted is almost impossible. Due to the presence of high temperatures, opacity of the materials, and the presence of the mould it is not possible to directly observe the behaviour the slag/pool interface. Although usually assumed flat, a previous work [1] using a Volume of fluid (VOF) model has shown that the interface between a layer of slag and steel layer in a cylindrical cavity is highly coupled with the distribution of the electric current. A full scale simulation of the ESR process using a VOF model has shown that the shape of the pool interface is likely to be non flat. Depending on whether a “flat” or “free” interface is assumed, an appreciable difference was found in the prediction of the pool shape and thickness [1]. This difference was due to a different magnitude and distribution of the Joule heat generated.

Usually the effects of the droplets are essentially taken into account in the form of a momentum and energy source applied to slag and pool regions [2-4]. Nevertheless this approach needs an empirical or semi-empirical radial droplet distribution, and droplet temperature. The latest were selected according to the resulting pool shape. However, as the steel/slag density and viscosity ratio are neither very large nor very small, one can expect an important transfer of momentum between the droplets and the slag flow. And, as the electric conductivity of steel is known to be much higher than that of the slag, the distribution of the steel phase within the slag will be a critical parameter to predict the distribution of the electric current density which controls the Lorentz force magnitude. From these physical facts, one can expect in this nonlinear system a slight change in the distribution of the steel droplets in the slag which can result in totally different flow behavior.

For fundamental and technical reasons it is important to study how the droplets forms and behaves in the slag. The present work present the results given by a 3D Magnetohydrodynamic (MHD) model coupled with a VOF model for the phases (steel, slag) distribution. During the process the electrode can develop a flat or a parabolic surface, here it is assumed flat. The electric current distribution is dynamically calculated from the transient phase distribution. Then the electromagnetic forces and the Joule heating are recalculated at each time step.

Numerical Model

The calculation domain is a cylinder of 20 cm high and 5 cm radius. The electrode has a radius of 3.5 cm. The container is filled with a layer of liquid slag (17 cm high) and a quantity of liquid steel (3 cm high). The total number of volume elements is 3.4 Million cells.

Properties of steel and slag are assumed to be constant. The electrode supplies a total DC current of I_0=1000 Amperes.

The interface between the two phases is tracked with the 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.

In a two phase system the properties appearing in the momentum equation are determined by the presence of the component phase in each control volume. The local values of a physical property Θ (such as density, viscosity, electric conductivity) are interpolated by the following formula $\Theta = \Theta_1 f_1 + f_2 \Theta_2 + f_3 \Theta_3$, where the subscripts 1,2,3 indicate the corresponding phase. The value of the surface tension is chosen to be equal to 0.1 or 1N/m. Depending on the dynamic of the interfaces, the typical calculation time step lies in the range of 10^{-3}-10^{-5} second.

<u>*Fluid flow*</u> The motion of the slag and liquid steel is computed with the buoyant Navier-Stokes equations. The effect of the turbulence is estimated with a Smagorinsky LES model. The no-slip condition is applied at the lateral walls. The electrode and the bottom surface are modelled as velocity inlets.

<u>*Electromagnetics.*</u> The potential equation is computed from the equation of the conservation of the electric current:

$$\nabla \cdot \vec{j} = \vec{\nabla}(-\sigma \vec{\nabla} V) = 0 ,$$

where *V* is the electric potential. A flux condition is applied at the bottom surface, while a constant electric potential is applied at the electrode. No current is allowed to enter the later wall. The magnetic field is then extracted by solving the magnetic potential equations. The computed electromagnetic field is dynamically adjusted from the space distribution of the electric conductivity, which is in turn function of the predicted phase distribution. The Lorentz force acting on both slag and steel is defined by:

$$\vec{F}_L = \mu_0 \frac{1}{2} \vec{j} \times \vec{B}$$

The electric resistance can be calculated at each time from the total joule heating generated in the domain:

$$Res(t) = \frac{1}{I_0^2} \int_e \frac{j^2(\vec{x},t)}{\sigma(\vec{x},t)} d\vec{x}^3$$

The deviation from the average resistance is defined by:

$$\delta Res(t) = Res(t) - \frac{1}{2T} \int_{-T}^{T} Res(t) dt ,$$

where *T* is an averaging time large enough to include several droplet departures.

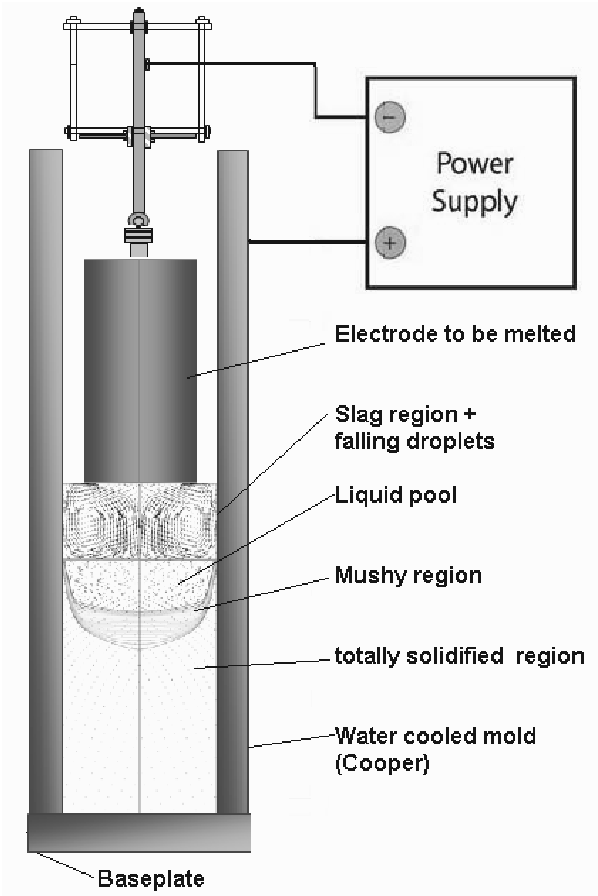

Figure 1: Schematic view of the ESR system.

Results and Discussion

a) Surface tension of 1N/m

Figure 2 shows the evolution of the resistance around its main value during the numerical melting experiment. The curve shows several strong variations. The resistance decreases with the decrease of the distance between the accumulated liquid metal under the electrode and the slag/pool interface. The minimum value of the resistance is reached at the departure of the first droplet (~1-2 cm). Then a slight increase occurs before a second minimum is reached corresponding to the detachments of a second large droplet. Then some secondary droplets are released, that have smaller electric signature. The droplet departures occur at a frequency of about 0.5 Hz.

When the horizontal magnetic field is applied in the y direction, an additional Lorentz force acts on the liquid metal and push it in the x direction (Figure 3). In fact the droplet is not released from the centre of the electrode but at mid distance from the electrode periphery. In the present case the droplets collided on the lateral wall. The presence of the magnetic field increases the droplet departure frequency to almost 1 Hz. Since the melting rate is not modified, the droplet size at departure is released at shorter distance from the electrode leading to smaller minimum pick in the electric resistance signal (Figure 2).

The melting rate is carefully controlled during the ESR process. The control is achieved mainly by adapting the amount of current imposed through the electrode. If during the melting the imposed vertical current is suddenly increased by a factor of 30 % (to 1300 Amps), the Lorenz force is locally increased by a factor of 70 %. The liquid metal faucet can be subject of a strong magnetic pinch effect. In the present case the liquid metal faucet does not survive and explode into multiple mini droplets (Figure 4).

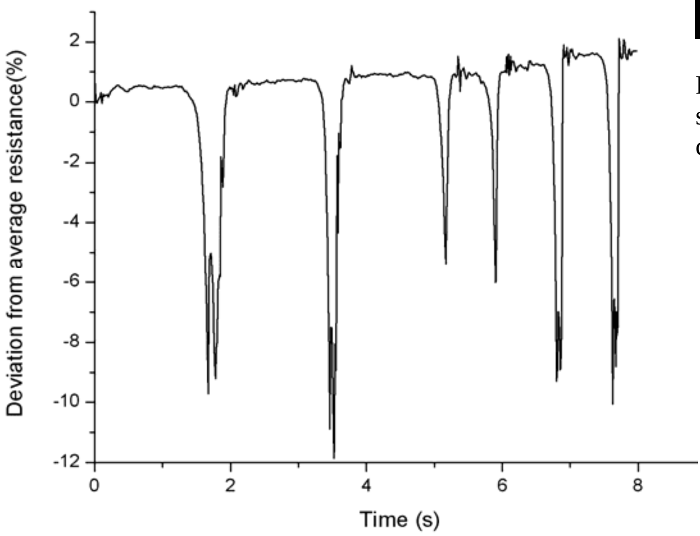

Figure 2: Fluctuation of the resistance during droplet departure without (t<4.5 s) and with horizontal magnetic field (t > 4.5 s).

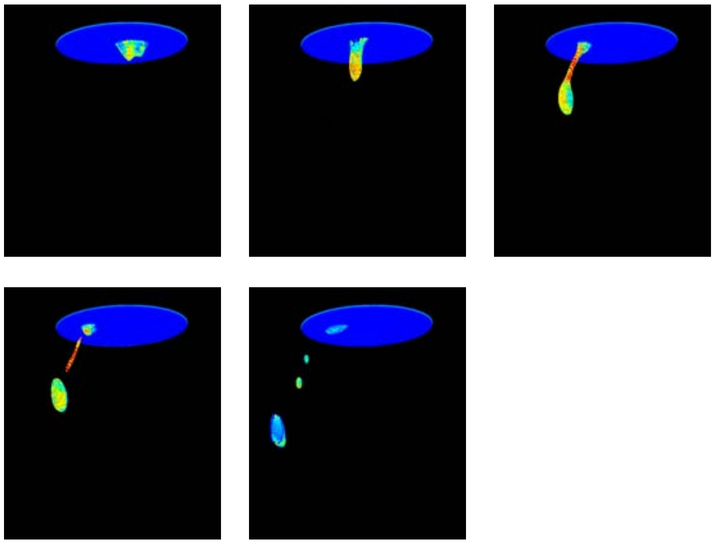

Figure 3: Droplet formation with an axial magnetic field coloured with electric current density magnitude [10^4 -10^9Amp/m^2]

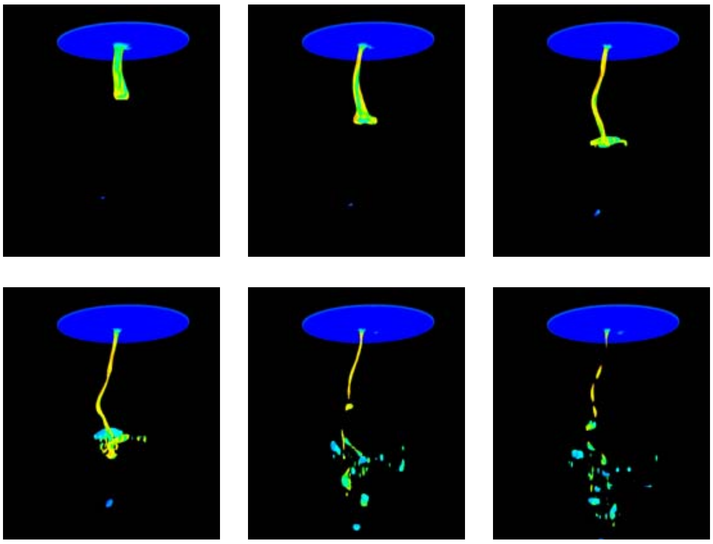

Figure 4: Splash of liquid metal when the imposed current is suddenly increased by 30 %. Interface coloured with electric current density magnitude [10^4 -10^9 Amp/m^2].

b) Small surface tension of 0.1N/m

Properties of slags are known to vary strongly with proportion of chemical components. From one slag to another, the viscosity or the surface tension can differ by large factors. In addition, strong variations with temperature exist as well.

The same simulation than in the previous case is performed with a small surface tension of 0.1 N/m. In this case it can be observed that the computed resistance (Figure 5) doesnt shows the same behaviour than for large surface tension (Figure 2). The electric resistance is continuously fluctuating but doesn’t exceed 4% of the main value. It can be seen that these variations are due to an almost continuous release of small droplets (Figure 6). Here two to three faucets form and cut into droplets of about 0.5-4 mm diameter. Smaller droplets fall at smaller speed than large droplets, new droplets depart before even the impact of previous droplets on the slag/pool surface. This quasi continuous presence of droplets in the slag height doesn’t allow the electric current distribution to find a steady state, i.e. the resistance cannot reach a constant value in time. Nevertheless, the picks corresponding to the lowest value of resistance can still be attributed to some relatively large droplets departure (larger than 2 mm).

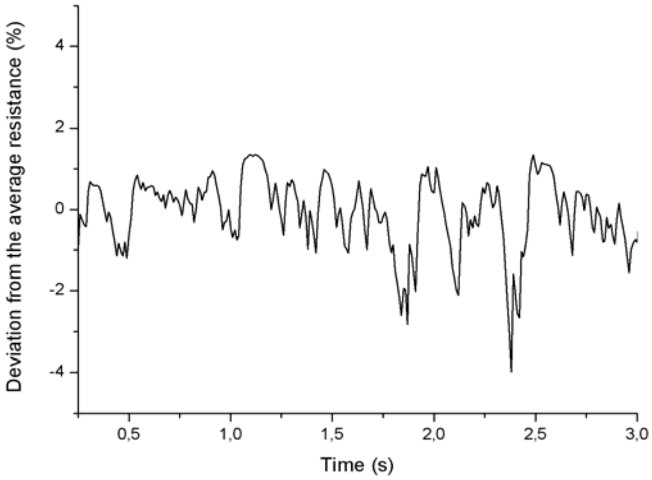

Figure 5: Fluctuation of the resistance during melting assuming a surface tension of 0.1N/m.

Since the liquid metal is not concentrated in an unique faucet, the electric current can choose several “metallic path” for travelling downward. Thus the faucets experience smaller magnitude of electric current density (max 7e8 Amp/m^2) than in the previous case (max 10^{10} Amp/m^2). This means that the Lorentz force is decreased by a factor of 10. Then the effective ratio between the Electromagnetic force over the surface tension force is not different from the case where the surface tension was set to 1N/m. The droplet formation is then controlled by a similar mechanism than in previous case.

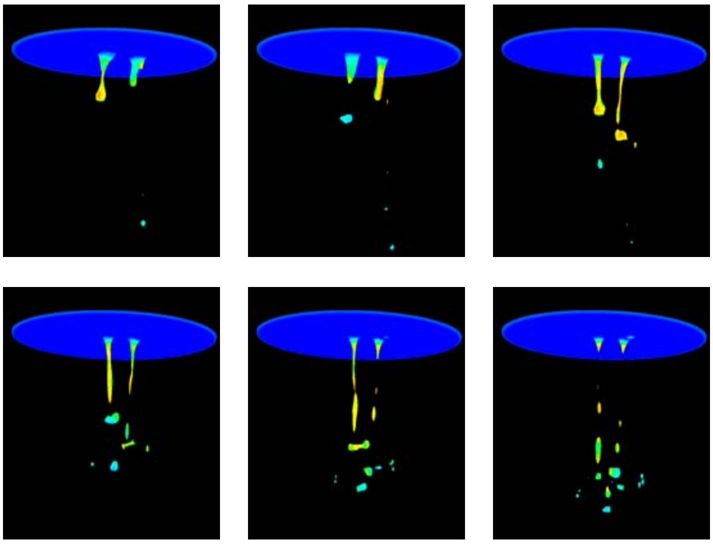

Figure 6: Droplet formation with small surface tension. Interface coloured with electric current density magnitude [10^3-10^8 Amp/m^2]

Conclusions

A 3D VOF model was coupled with a Magnetohydrodynamic model to simulate the droplet formation during melting of a metallic electrode. The model can predict the exact electric and magnetic field distribution in function of the metallic distribution in a low conductivity slag. The model was applied to the melting of small electrode assuming a small and a large value of the melt/slag surface tension. It was shown that with large surface tension only one faucet forms and larger droplets are released. The fluctuation of the resistance can easily be interpreted as lower picks shown up during the release of each primary or secondary droplet.

For small surface tension, two to three faucets appear from which smaller droplets depart. In this case the space between the electrode and the liquid pool surface is filled with many small droplets. The continuous release of droplets generates constant electric resistance fluctuations. In this configuration it is not possible to clearly link the resistance signal with a phase distribution in the cavity.

Some additional effort must be given to configurations with larger number of faucets. This corresponds to melting in larger systems or to melting under smaller surface tension.

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