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Shape and stability of the slag/melt interface in a small dc ESR process

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Abstract

The electro-slag remelting (ESR) process has been used effectively to produce large ingots of high quality based on the controlled solidification that can be achieved. Despite numerous simulations, it is still challenging to predict important operating details of the process, such as the effect of the electrode immersion and, more importantly, the results of instabilities in the melting system (electrode, slag, pool). In order to have a better understanding of the process, the present work aims to verify the validity of two assumptions which were widely used in previous simulations. First is the flatness of the slag/steel interface, and second concerns the verticality and the stationarity of the density of the electric current over the entire domain. In the present paper, a mathematical model of the magneto-hydrodynamic (MHD) phenomena occurring during ESR, modelling more rigorously the closure of the electric current at the mould is presented. At the present stage, the model does not include any buoyancy or solidification effects. The multiphase aspect of the problem is solved by using a VOF model, the domain is divided in two sub-domains (steel and slag) separated by a free interface. The effect of the imposed dc current and the mould diameter on the initial interface was investigated. We show that except if the mould is insulating, the interface is never flat. In some cases the interface even becomes unstable leading to an electric shortcut.

Keywords: Steel; Slag; Free interface; DC electric current; MHD; Thin wall boundary condition; Turbulence; Stability; VOF, CFD

1. Introduction

Electro-slag remelting (ESR) is an advanced technology for production of components of e.g. high quality steels. An alternating (ac) or direct current (dc) is passed from a conventionally melted and cast solid electrode through a layer of molten slag to the baseplate (Fig. 1a). Because of the electrical resistivity of the slag, Joule heating is generated and the slag transfers this energy to both ingot and mould surfaces and to the melting electrode tip. The molten metal produced in the form of droplets or a continuous stream passes through the slag and feeds a liquid pool which then solidifies directionally. 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 characteristic of ESR ingots. The present investigation aims to create a numerical model that can predict all these features with a minimum of assumptions. In terms of modelling, the ESR process is a multiphase magnetohydrodynamic (MHD) system with heat and mass transfer. Early simulations [1–5] can be found in literature, but due to the complexity of the system and due to the computational restrictions, several assumptions and simplifications were necessary. Although the ESR processes usually utilize ac fields, dc fields were also used for scientific investigations [6–9]. Here, we have chosen to simulate the case of a small dc ESR system using a relatively high current density. This dc model constitutes the first step toward building a multiphase model with free interface coupled with MHD forces created by an ac current. The present work aims to verify two generally admitted assumptions, first that the slag/liquid steel interface is often assumed to be flat, and second that the density of the electric current is constant in time and vertical over the entire domain. At the present stage does not include the heat generation, and so the buoyancy and solidification effects. The prediction of a realistic shape of the steel/slag interface and a realistic electric current distribution can better the estimation of the Joule heating.

2. The numerical model

The calculation domain is presented in Fig. 1b. An electrode of radius $R_1 = 75$ mm is put in contact with a cylindrical container of radius R_2 and height $h = R_1$ filled with a layer of liquid steel

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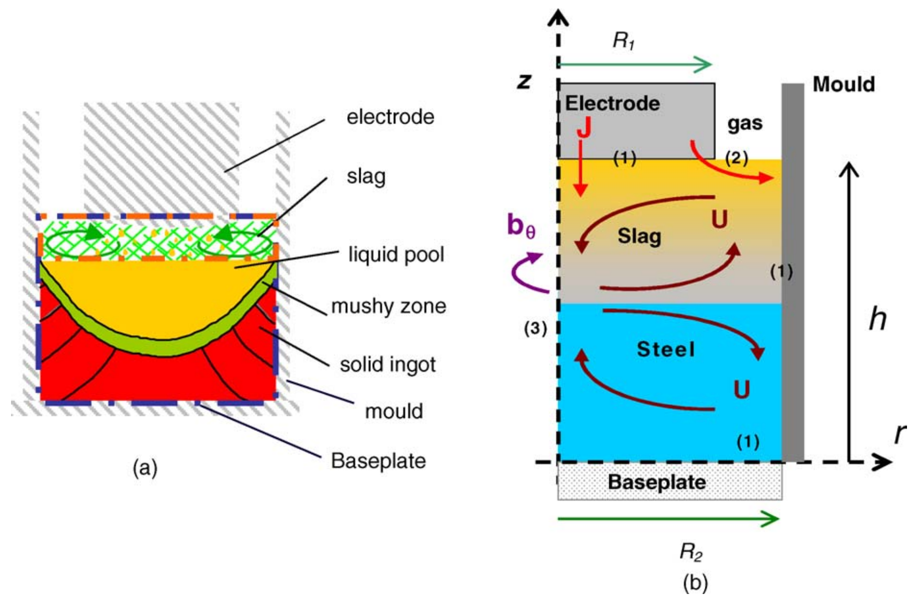

Fig. 1. (a) Schematic representation of an ESR system. (b) Geometry of calculation domain and flow boundary conditions. At the walls: $\vec{u}=0$ (1). At the slag/gas interface: $\partial\vec{u}/\partial z=0$ (2). At the axis of symmetry $u_r=0$ and $(\partial u_z/\partial_r)=0$ (3).

and a layer of liquid slag. The properties of both steel and slag as the density (ρ), dynamical viscosity (μ), and electrical conductivity ($(_\mathrm{f}$) are assumed to be constant. The magnetic permeability ($(_0$) is the same everywhere and equal to the vacuum magnetic permeability. The lateral wall, i.e. the mould has a thickness (e_w) and an electrical conductivity ($(_\mathrm{w}$). The electrode supplies a total dc current of 2500 A. As the calculation domain involves a free interface, a numerical technique is required to capture its evolution. The volume of fluid (VOF) method presents in 'fluent' is used since it is a robust, powerful, extensively applied technique. The surface tension is supposed to play a role on much smaller scales than the dimensions of the present geometry. The density ρ, the viscosity μ and the electrical conductivity σ at any cell vary according to the respective fraction of the steel, F, and slag, $1-F$, existing in the cell. For example, the electric conductivity is estimated as $\sigma=\sigma_1+F(\sigma_2-\sigma_1)$, where σ_1 and σ_2, respectively, the electric conductivity of liquid slag and steel. Since the liquid steel is about 10^4 more conducting than the liquid slag, we expect an influence of the slag/liquid pool interface on the electric current distribution. In addition, the liquid steel and slag have very different heat properties, a non-flat steel/slag interface will therefore have a significant influence on the solidification process.

The problem is expressed in cylindrical coordinates (r, $($, z) under the hypothesis of axial symmetry ($\partial/\partial(=0$). The MHD effect leads to an additional force (Lorentz force) in the momentum equation. In the present model, the MHD Lorentz force (F_r, $F_\theta=0$, F_z) caused by the interaction of imposed electric current and the induced magnetic field, is derived from the Ampere's law by solving the induced magnetic field. The problem considered here is governed by the classical Navier–Stokes equation:

$$\frac{\partial\rho\vec{u}}{\partial t}+\nabla(\rho\vec{u}\cdot\vec{u})=-\nabla p+\rho+\nabla(\mu_\mathrm{T}(\nabla\vec{u}+\nabla\vec{u}^\mathrm{T}))+\vec{j}\otimes\vec{b}, \quad (1)$$

where $\vec{u}=(u_r,u_\theta=0,u_z)$ is the velocity of the flow, p the pressure, $\vec{b}$ the induced magnetic field, and $\vec{j}=\vec{\nabla}\times\vec{b}/\mu_0$ the electric current density. The turbulent viscosity μ_T is computed with the help of a $k-\varepsilon$ model. The velocity respects the boundary conditions described in Fig. 1b.

We can show that only the tangential component of the induced magnetic field b_θ is relevant to the description of the problem. The Lorentz force acts then only in the r and z directions, thus only the radial and the axial components of the Navier–Stokes equation are solved. The tangential component of the induced magnetic field can be deduced from the linearized induction equation written to the first order as:

$$\frac{1}{\mu_0\sigma}\left(\Delta b_\theta-\frac{b_\theta}{r^2}\right)=0 \quad (2)$$

It is known that the shape of the melting electrode depends strongly on both the imposed current and the descend velocity of the electrode [6]. Here, we study the case corresponding to a relatively small descend velocity, so that the electrode keeps a flat shape. With this assumption the density of the dc electric current at the cathode is uniform. According to the Ampere's law, the boundary condition at the cathode is:

$$b_\theta=\frac{\mu_0 I_0 r}{(2\pi R_1^2)}. \quad (3)$$

We assume the bottom wall (baseplate) to be perfectly conducting, i.e. $j_r=0$, so according to $\vec{j}=\vec{\nabla}\times\vec{b}/\mu_0$ the magnetic field should verify $\partial b_\theta/\partial z=0$.

It is generally assumed [1–5] that even near the mould the electric current density is vertical, so that the mould behaves as it is insulating. This hypothesis is based on the fact that a solidified slag layer is usually present at the mould. Depending on the chemical composition of the slag, the ratio between liquid and solid slag-skin electric conductivity is believed to be of order 10–100 [7,8]. This ratio depends strongly on the actual temperature of the slag-skin layer. Nevertheless, the thickness of the solidified slag being small ($e_s \sim 0.1$–5 mm), the radial resistance of this layer ($\sim e_s/\sigma_s$) is still smaller or of same order than the vertical resistance of liquid slag ($\sim H/\sigma_T$). 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 baseplate. In the present study, the temperature distribution is not predicted, we consider only the case of an isothermal and liquid domain in perfect electric contact with the mould. So, here the closure of the electric current depends strongly on the mould electrical properties (thickness and conductivity). Consequently, the Lorentz force, the Joule heating and the velocity distribution are governed by these parameters. In order to model the part of the current that can circulates through the walls, we use a "thin wall" boundary condition which avoids having to solve the induction equation (Eq. (2)) in the solid media, by assuming that the electric potential does not vary across the wall. It is justified by the fact that the variation of the electric potential across the thickness of the wall is much smaller than the variation across the fluid, which is true only for $e_w/R < 0.3$. The "thin wall" boundary condition is modelling technique that has been recently extended to axis-symmetrical MHD problems with successful results [10]. Using this assumption, it can be shown that the boundary condition at the mould is:

$$\frac{\partial b_\theta}{\partial r} = \left(\frac{\mu_0 I_0}{2\pi R_2} - \left(1 - \frac{k}{R_2^2} \right) b_\theta \right) \frac{R_2}{k}. \tag{4}$$

The significant parameter is the conductance ratio $k = (_{\mathrm{w}} e_{\mathrm{w}}/(R_1$, where σ_w and σ are the conductivity of the wall and the fluid, respectively, and e_w is the wall depth. Depending on the volume of fluid fraction of steel and slag in a cell adjacent to the mould, the value of σ varies by a factor of 10^4. So, depending on which phase is in contact with the mould, the conductance ratio can also vary by a factor of 10^4. In what follows, k will indicate the conductance ratio between the steel phase and the mould, the corresponding conductance ratio for the slag phase is $k_2 = 10^4 k$.

The model presented in this paper intends to predict the flow velocity, the interface evolution, and the electric current distribution, but at the present stage it does not include the prediction of the temperature, the buoyancy effects, and the phase change.

3. Results

Two mould diameters were studied, a first case with $R_2 = 1.3R_1$ (= 97.5 mm) corresponding to an industrial size, and a second case with $R_2 = R_1$. For both cases, three values of the mould conductance ratio were investigated, an insulating mould ($k = 0$), a perfectly conducting mould ($k = +\infty$), and an intermediary case with $k = 0.1$. All the results have shown that the flow is organised into two main vortices, one in the slag and one in the steel layer (Fig. 2). The Lorentz force has almost the same magnitude in the steel and slag layer, but since the slag density is smaller, the magnitude of the flow velocity is much higher in the slag layer. In the following only the detailed results for the phase and the electric current distributions are presented for each case. Then an attempt of explanation will be given.

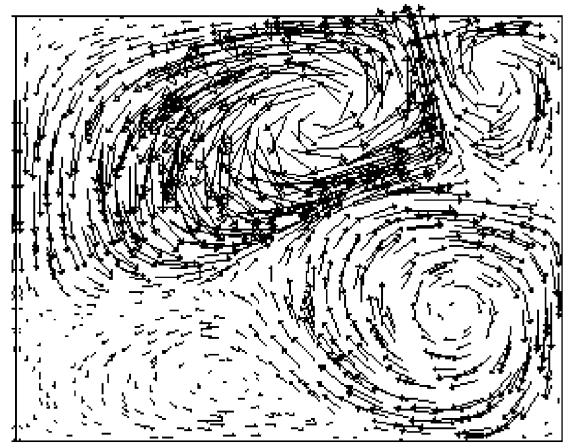

Fig. 2. The velocity field at the equilibrium state in the r–z plane for $k = 0$ and $R_2/R_1 = 1.3$.

3.1. Case where $R_2 = 1.3R_1$

Here, there is a large gap between the electrode and the mould. This gap is the slag-free surface in contact with an electrically non-conducting gas, i.e. the electric current lines are then tangential to this surface. If the mould is electrically insulating the distribution of the electric current is almost vertical, except at the upper slag/gas interface where the current is horizontal (Fig. 3). The initially flat interface oscillates until it reaches a stable profile, convex in the centre and nearly flat at its highest level near the lateral wall. The flow system reaches then a steady state. For a perfectly conducting mould the result is similar than for the insulating case, but the shape of the interface is not flat at the lateral wall (Fig. 4). We can notice that almost one-third of the current released from the electrode penetrates the mould. The case of $k = 0.1$ was found to be very different from previous cases (Fig. 5). In the final state, the liquid steel recover the total surface of the mould, and the interface reaches the gas level. The part of the electric current closing through the mould is less important than for the perfectly conducting wall.

3.2. A theoretical case with $R_2 = R_1$

In here there is no gap between the mould and the electrode, but with theoretically no electrical contact between the two elements. If the mould is insulating, the electric currents were found to be strictly vertical over the entire domain (Fig. 6). The oscillations of the initially flat interface decreased in amplitude leading to a flat interface. If the lateral wall is partially ($k = 0.1$) or perfectly conducting the interface is unstable. At the vicinity of the mould, the level of the liquid steel increases until it reaches the electrode (Fig. 7). This creates an electrical shortcut that invalidates our hypothesis of uniformly distributed electric current at the electrode. Physically all the current should penetrate the domain at the shortcut location. The boundary

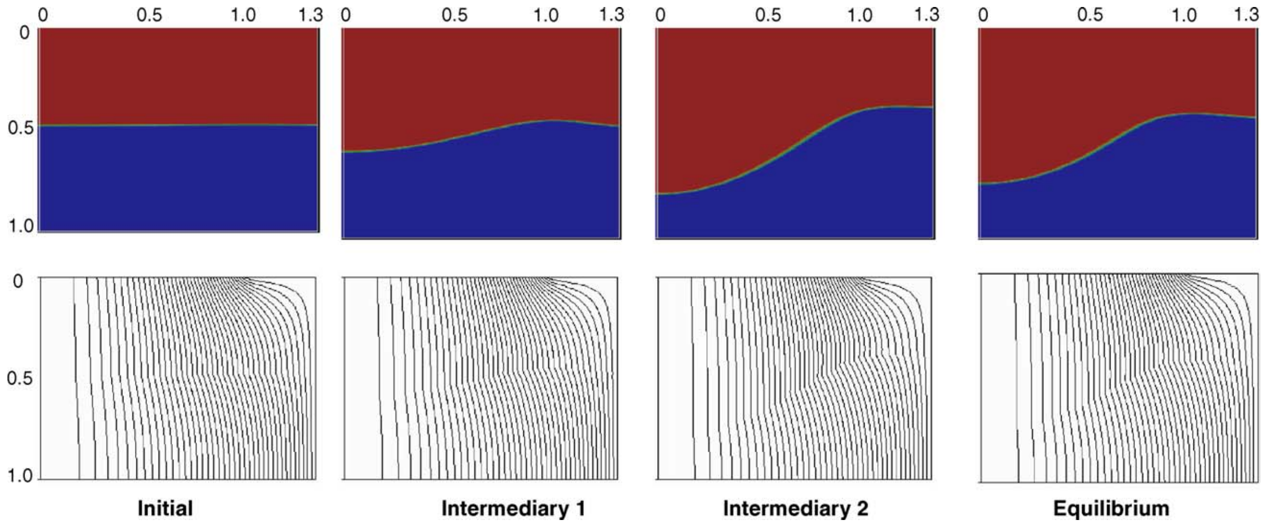

Fig. 3. Evolution of the phase (upper) and the electric current (bottom) distributions in the *r*–*z* plane for an insulating mould ($k = 0$) with $R_2/R_1 = 1.3$ and $H/R_1 = 1$.

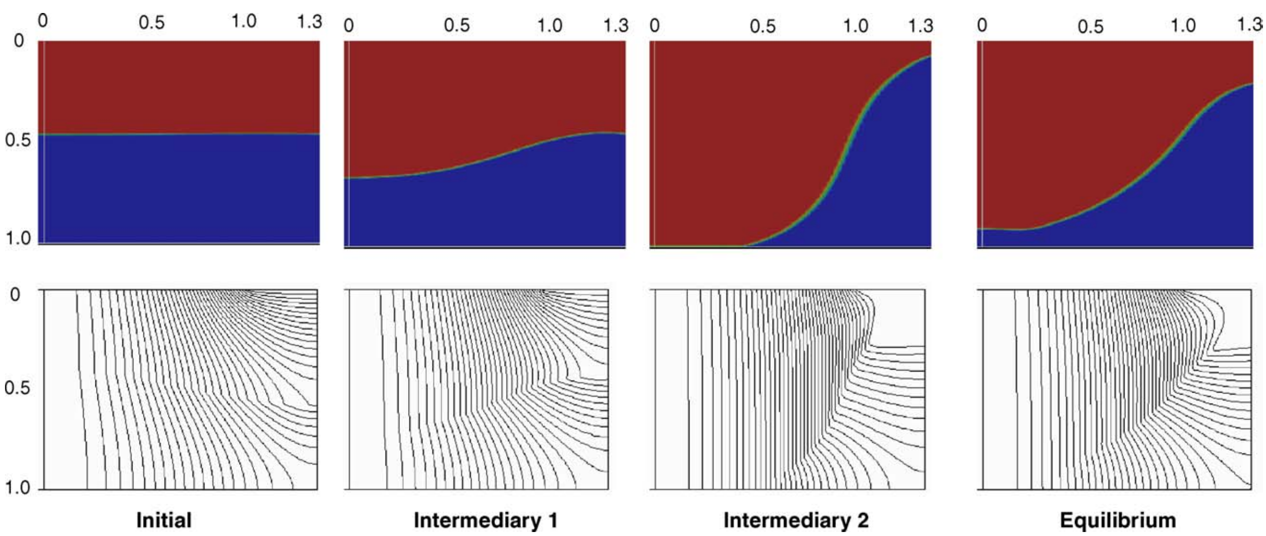

Fig. 4. Evolution of the phase (upper) and the electric current (bottom) distributions in the *r*–*z* plane for a perfectly conducting mould ($k = +\infty$) with $R_2/R_1 = 1.3$ and $H/R_1 = 1$.

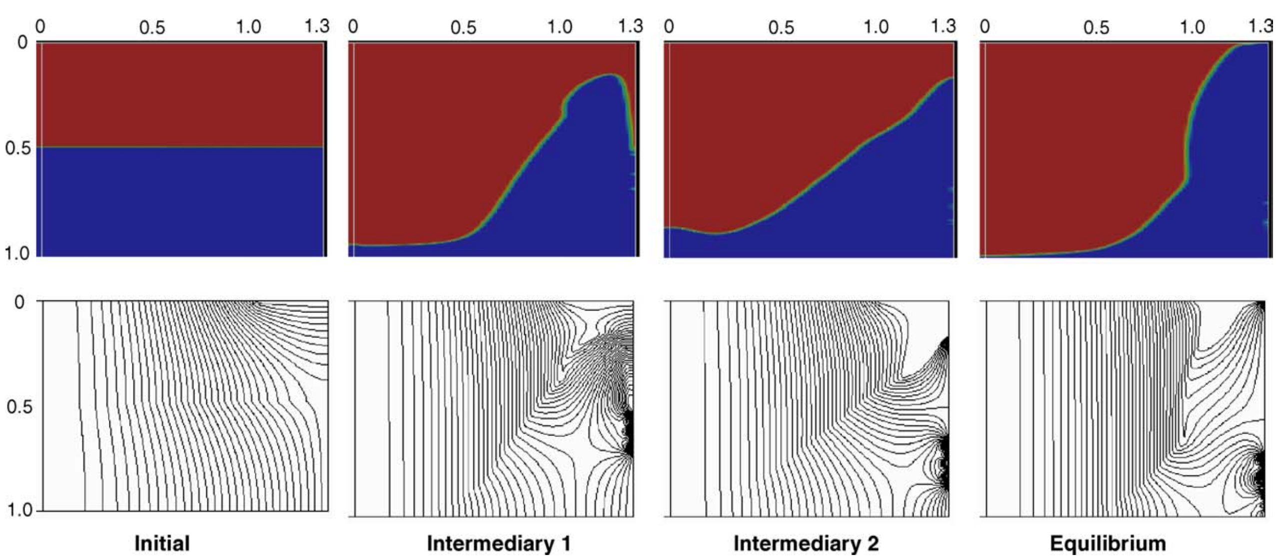

Fig. 5. Evolution of the phase (upper) and the electric current (bottom) distributions in the *r*–*z* plane for a conducting mould with $k = 0.1$, $R_2/R_1 = 1.3$ and $H/R_1 = 1$.

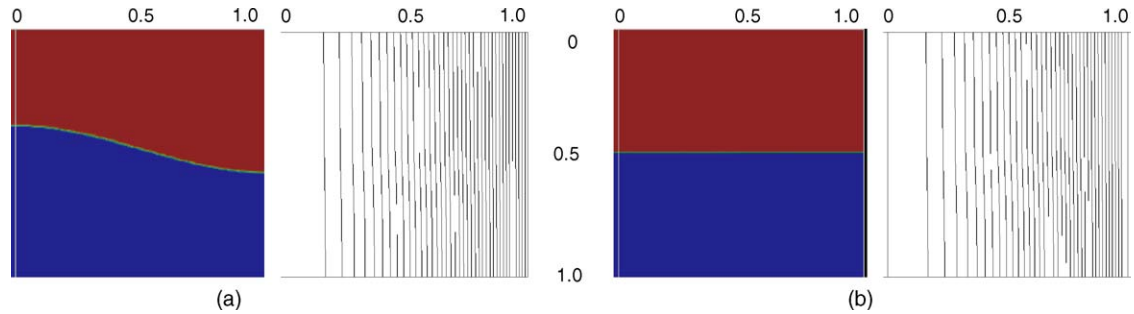

Fig. 6. The initial (a) and final (b) phase and electric current distributions for the case of and $k = 0$, $R_2/R_1 = 1$ and $H/R_1 = 1$.

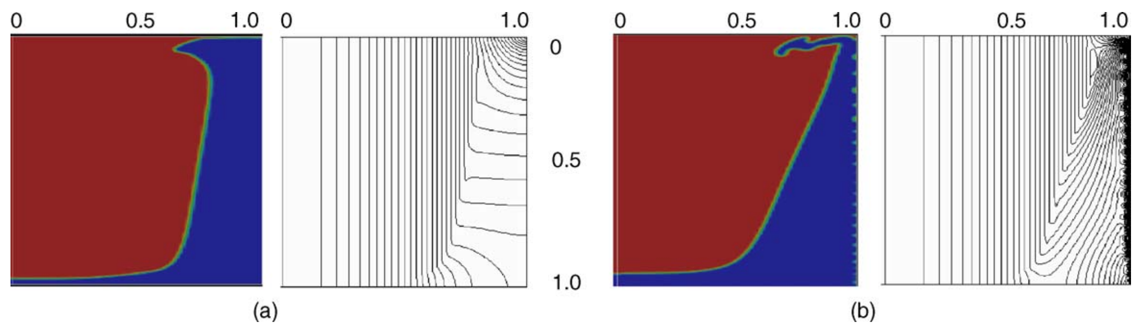

Fig. 7. The phase and electric current distributions just at the moment when the interface reaches the electrode leading to an electrical shortcut, $k = +\infty$ (a) and $k = 0.1$ (b) ($R_2/R_1 = 1$ and $H/R_1 = 1$).

condition (Eq. (3)) is then no more valid, and the computation is stopped.

4. Comments and discussions

All previous (known) simulations assume a fixed flat slag/steel interface. Our investigation has shown that this interface is flat only for $R_2 = R_1$ and $k = 0$. For all other cases the interface is far to be flat. The explanation is given by the fact that the dynamic of the interface is controlled by the equilibrium between the gravity, the shear stress and the Lorentz force. The gravity force tends to put the heavy steel under the liquid slag. And due to relative difference of steel and slag motion, and to the relative value of the dynamical viscosity, the interface is submitted to a shear stress force. But the most original part the explanation can be found in the discrete change of the Lorentz force through the slag/steel interface. Due to the low electrical conductivity of the bath and the high electrical conductivity of the molten metal, there is a jump of the electrical field at the metal/slag interface. In the centre, whereas the currents in the slag are mainly vertically directed, additional horizontal currents appear in the metal layer (Figs. 3–7). This gives rise to a discontinuous force at the metal/slag interface. When the interface is crossed, the vertical Lorentz force changes by:

$$\Delta F_z = (j_r(\text{slag}) - j_r(\text{steel}))b_\theta \propto (\sigma_1 - \sigma_2)\frac{I_0^2}{R_2^2} \quad (5)$$

This difference of Lorentz force pushes the interface downward in the centre. In fact as soon as the electric current has a horizontal component, the interface is no more flat. This effect is present in the insulating case (Fig. 3), but is stronger if the lateral wall is conducting. The magnitude of the electric current density decreases with mould radius ($I_0/\pi R_2^2$). So, the magnitude of the Lorentz force is then smaller for $R_2 = 1.3R_1$ than for $R_2 = R_1$. This is at the origin of the stability of the interface for the larger domain.

Some bubbles of slag remain clustered at the mould during the elevation of the liquid steel (Figs. 5 and 7b), perturbing the electric current distribution (see the electric vortexes at the mould). Although the slag density is smaller than the melt density, these droplets are moving down (Fig. 5), probably pushed by the downward directed steel flow at the mould.

5. Summary and outlook

The studied examples demonstrate that a special care should be given to the electric properties of the mould wall. The closure of the electric current occurring either through the fluid or through the mould modifies considerably the distribution of the Lorentz force, and so the hydrodynamic. In the present condition, the interface between the slag and steel phase was found to be flat only if the electrode has the same diameter than the mould, and if the electric current density is strictly vertical. This situation is unlikely to appear in an industrial process since the electric current density will have a horizontal component, due to the difference between the mould and electrode radius, and to the fact that the metallic mould is always much more conducting than the slag phase. In some cases, we have shown that the liquid steel can possibly reaches the upper electrode, leading to an electrical shortcut. These conclusions are valid only for systems mainly driven by electromagnetic forces created by a dc field.

In the case of an ac field, the presence of the skin effect will modify sensitively the electric current distribution, leading thus to different shapes of the slag/melt interface.

The model destined to compute the dynamic distribution of the electric current is now built. The next of this study is to model for dc and ac currents, the temperature distribution and the associated solidification, and its consequence on the variation of the slag electric conductivity at the vicinity of the cooling mould. In the future, this numerical model is destined to predict the electrode shape and the solidification front in both steady and transient states of the ESR process.

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