DROPLET FORMATION IN SMALL ELECTROSLAG REMELTING PROCESSES

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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 effects of the control system, as well as the presence of a horizontal magnetic field are also investigated.

Introduction

In the ESR process, the development of the heat and mass transfer at slag/droplet interface is important for the final ingot quality, composition and cleanliness. The heat transfer from the slag to the liquid pool is largely dominated by the droplets [1-13].

Transparent experimental models were built by J.Campbell [1] and Makroupoulos [2] in which single droplet departures during melting was observed. The slag used was a transparent eutectic LiCl-KCl alloy which was used to re-melt electrodes made of metals with low melting temperatures (Pb, Cu, Zn, Al). During the melting the voltage across the slag layer was monitored across with an oscilloscope. Figure 1 represents the typical oscilloscope trace of the voltage during the formation and detachment of aluminium droplets.

This typical change in electric parameters (voltage or resistance) can then be used to detect the occurrence of a droplet departure in conventional non transparent slag. Combining the resulting dripping frequency with the melting rate it was possible, for small electrodes, to estimate the typical droplet mass [3,4].

Systematic experiments using non transparent slag were performed by Korousic[4] in order to correlate the dripping frequency with process parameters. With the same power input and up to slag height of about 300 mm, the frequency of droplet departure was found to increase with the slag height. Almost no change was observed for slag height higher than 300 mm.

Amongst the other parameters that can exert an influence the droplet size are the shape of the electrode tip [1, 4, 6], the slag temperature, the slag compositions, the electric current frequency [1].

Other experiments have also shown that when a magnetic field is applied, deviation of the metallic droplet towards the mould or atomisation in much smaller droplets is observed [2, 6].

In industrial process condition, visual observation of the droplet formation just under the electrode being melted is very difficult. This is why no known experiments are reported for industrials scales ESR. Effects of droplets flow on the process were studied with computational tools [8]. Usually the influence of the droplets is essentially taken into account in the form of a momentum and energy source applied to slag and pool regions [8-13].

Thus, 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. The aim of the present work is to simulate the droplet formation for one specific meltrate. The investigation includes the exploration of the effect of a sudden rise of the imposed electric current intensity, as well as of the presence of a transverse magnetic field.

Numerical Model

The geometries and the process parameters reported in literature are various [1-7]. The present analysis chooses a calculation domain that is a cylinder (mould) 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. The melt rate is set to 34 Kg/hour. 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 such as density, viscosity or electric conductivity are linearly interpolated according to the local volume fractions of the slag and liquid metal. 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.

Heat and Fluid Flow

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 walls. The electrode and the bottom surface are modelled as velocity inlets. The energy equation is also solved in order to estimate buoyancy effect generated by the temperature field in the slag.

Electromagnetics

The well known *φ*-***A*** model is used to solve the electromagnetic field. It consists in simultaneously solving the electric potential potential *φ*, and the magnetic potential vector ***A*** equations. 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 mould wall. 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:

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

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

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

The deviation from the average resistance is defined by:

$$\delta Res(t) = (Res(t) - \frac{1}{2T} \int_{-T}^{T} Res(t)dt) / (\frac{1}{2T} \int_{-T}^{T} Res(t)dt) \tag{3}$$

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

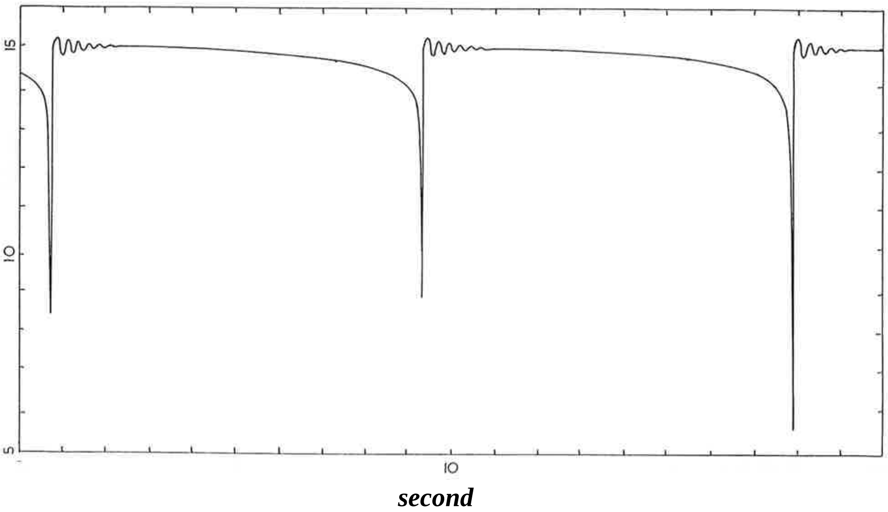

Figure 1: Oscilloscope trace of the voltage (Volt) during the formation and detachments of three aluminium droplets [Cambpel 1970)].

Results and Discussion

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 very similar than that measured by Campbel [1] (Figure 1). 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 typical droplet diameters are of about 10 mm for the larger ones, satellite droplets are of about 1-3 mm. The droplet departures occur at a frequency of about 0.7 Hz.

Surface Tension of 1N/m with an Imposed Magnetic Field

When a horizontal magnetic field of 0.1 Tesla is applied in the horizontal y direction, an additional Lorentz force acts on the liquid (metal and slag) and push it in the direction perpendicular to both electric and magnetic field (Figure 3). The presence of an imposed horizontal magnetic field much stronger than the one induced by the vertical current, changes the flow patterns. As a consequence of this flow, 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. This deflection was experimentally observed by Makropoulos [2]. The presence of the magnetic field increases the droplet departure frequency to almost 1.3 Hz. Since the melting rate is not modified, the droplet size at departure is released at shorter distance from the electrode leading to smaller droplet, and smaller minimum pick in the electric resistance signal (Figure 2). In a real system this increase in dripping frequency was clearly observed in experiment [4]. Although the power input was the same, an increase of the melting rate of about 20 % was also noticed. Perhaps this is the results of the strong stirring induced by the imposed magnetic field.

Influence of the Control System

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. Complex control algorithms are used in industry, during a process the imposed current is changed seconds after seconds on a discrete and non smooth manner. If during the process the imposed vertical current is suddenly increased by a factor of 30 % (from 1000 Amps to 1300 Amps), the Lorentz force is suddenly increased by a factor of 70 %. If at this time a liquid metal faucet is being formed, a strong magnetic pinch effect can modify its evolution. In the present case this sudden increase in electric current density was applied at the very beginning of the faucet formation. The liquid metal faucet elongates and finally explodes in multiple mini droplets (Figure 4).

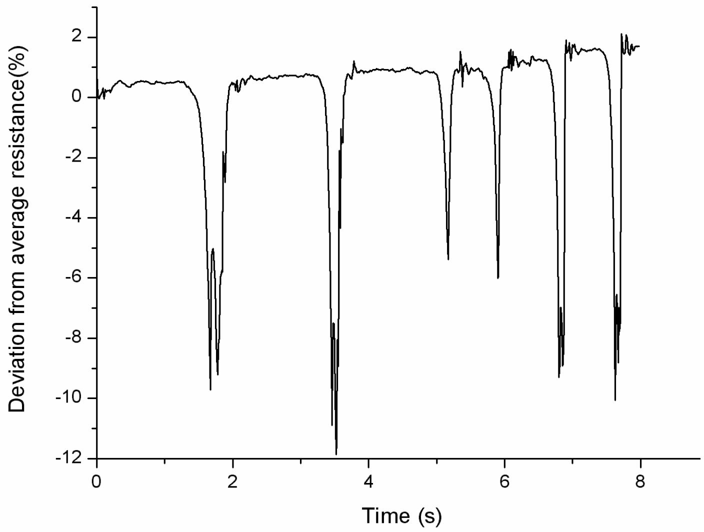

Figure 2: Fluctuation of the resistance during droplet departure without (t<4.5 s) and with horizontal magnetic field (t > 4.5 s).

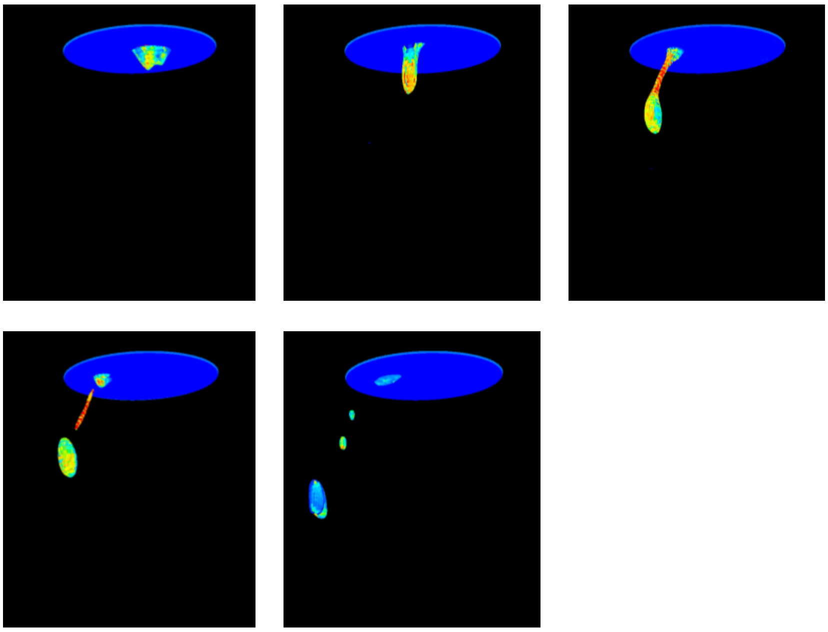

Figure 3: Droplet formation under the presence of a horizontal magnetic field. Surfaces are coloured with electric current density magnitude [10^5 -10^{11}Amp/m^2]

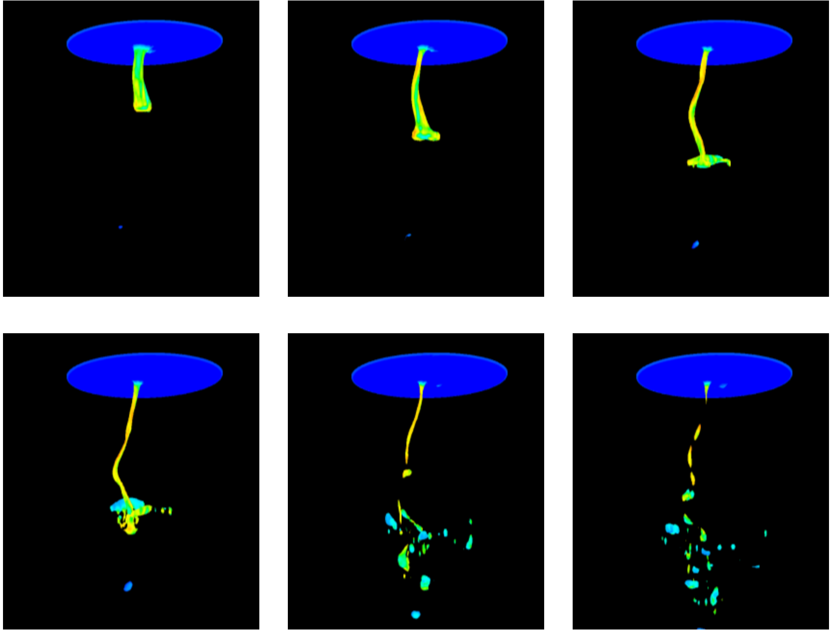

Figure 4: Atomisation of liquid metal faucet when the imposed current is suddenly increased by 30 %. Interface is coloured with the electric current density magnitude [10^5 -10^{11} Amp/m^2].

Small Surface Tension of 0.1N/m with no Additional Magnetic Field

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.

With a small surface tension of 0.1 N/m, it can be observed that the computed resistance (Figure 5) doesn't show the same behaviour than that found for a larger 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 break into droplets of about 0.5-4 mm diameter. Due to larger drag, smaller droplets fall at smaller speed than larger 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 linked to some relatively large droplets departure (larger than 2 mm).

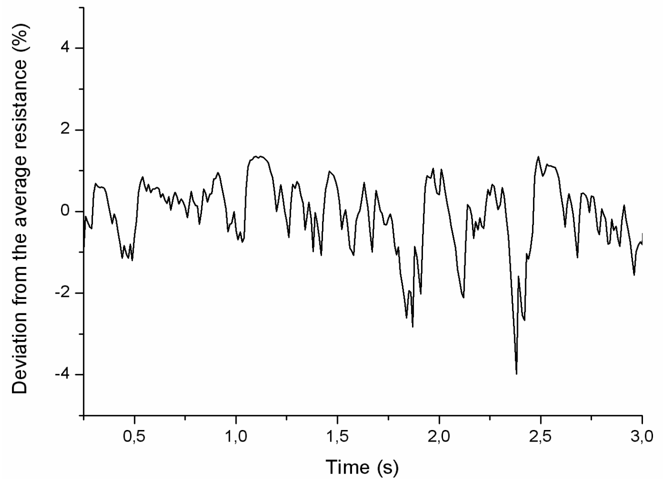

Figure 5: Fluctuation of the resistance during melting assuming a surface tension of 0.1N/m.

Since the liquid metal is not concentrated in a unique faucet, the electric current can choose several "metallic path" to flow downward. Thus the faucets experience smaller magnitude of electric current density (max $10^{9\text{-}10}$ Amp/m^2) than in the previous case (max 10^{11} Amp/m^2). This means that within the faucet, the actual Lorentz force magnitude is decreased by a factor of 10. 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.

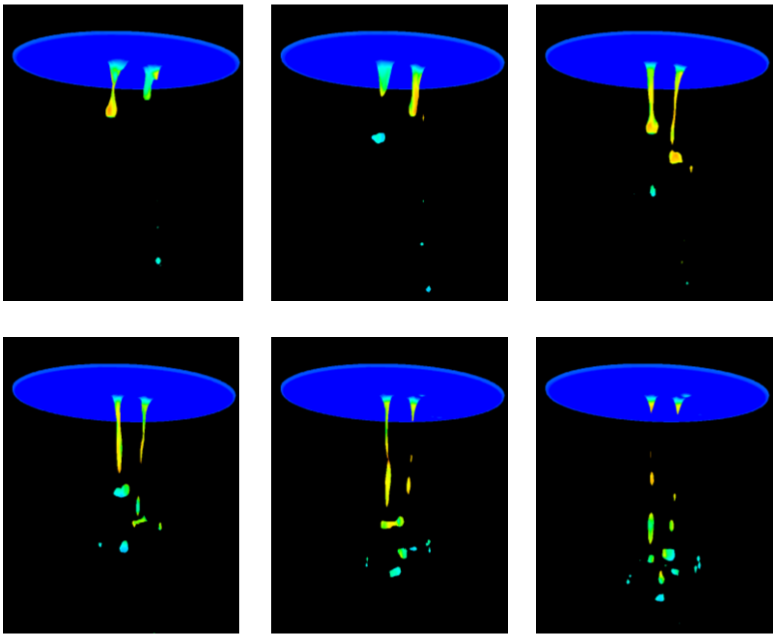

Figure 6: Droplet formation with small surface tension. Interface coloured with electric current density magnitude [10^5-10^9Amp/m^2]

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 interfacial 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 with smaller slag/metal interfacial tension. The results of the present DC investigation will be taken as a base for the exploration of melting under AC conditions.

References

1. Campbell, J., J. Metals 20 Nr.7, p23-35 ,(1970)
2.. K. Makropoulos and H. Winterhager, Arch. Eisenhuttenwes **47**, 211-216 (1976).
3. Y. KOJIMA, M. KATO,T. TOYODA, M. Inouye, Trans. ISIJ, Vol. **15**,1975
4. B.Korousic, Arch. Eisenhuttenwes **47**, 283-288(1976).
5. S. Ramesh Babu, Metall. Trans. **B**, Vol **17**.B, pp. 471–477,(1971).
6. Murgaš, M., Chaus, A.S., Pokusa, A., Pokusová, M., ISIJ International, **40**(10), 980-986(2000)
7. T. EI-Gammal and M. Hajduk, Arch. Eisenhuttenwes **49**, p235-239 (1978).
8. A. Kharicha, W. Schützenhöfer, A. Ludwig, R. Tanzer, M.Wu Process Metallurgy Steel research international 77 No.**7**. (2006)
9. B. Hernandez-Morales and A. Mitchell, Ironmaking Steelmaking **26** (6), pp. 423–438, (1999)
10. A.H. Dilawari and J. Szekely, Metall. Trans. B **8** (1997), pp. 227–236.
11. K.M Kelkar, J. Mok, S.V. Patankar and A. Mitchell, Phys. IV France 120 (2004) p 421-428
12. A. Jardy, D. Ablitzer and J. F. Wadier, Metallurgical and Materials Transactions B Vol p111-120 (1991)
13. M. Choudhary and J. Szekely, Metall. Trans. B **11** (1980), pp. 439–453.