Electromagnetic Processing from AC to DC field and Multiphysics Modeling: a Way for Process Innovation

M.Dumont[*1], R.Ernst [*2,3], Y.Fautrelle [2,3], J.Etay [2,3]

[1]EMDPI solutions, JAM, Grenoble, France [2]Univ. Grenoble Alpes, [3] CNRS, SIMAP, F-38000 Grenoble.
*Corresponding author: michael.dumont@emdpisolutions.com

Abstract:
Examples of Electromagnetic processes are presented: (1) cold crucible, (2) electromagnetic pump, (3) DC electromagnetic brake. A combined approach by using multiphysics modeling with Comsol and experimental validation is used in order to give some guidelines for process improvement and integration at industrial scale. A time-dependent 2D or 3D Multiphysics numerical model (electromagnetics and fluid mechanics) including an ALE deformed mesh technique was set up. New design of cold crucible with improved energetic efficiency was defined. MHD effects resulting from a strong coupling between fluid flow and electromagnetics is evaluated in a large annular linear pump for nuclear applications. In the frame of hot-dip coating, the control of zinc coating thickness by DC magnetic field resulting from braking of a liquid driven by an upcoming strip was demonstrated.

Keywords: cold crucible, electromagnetic pump, electromagnetic brake, MHD modeling

1. Introduction

Electromagnetic processing of Materials (EPM) is relatively well known and mature. This knowledge gives the possibility to improve such processes and to integrate them in specific application (aeronautics, automotive, nuclear sector, metallurgy, etc) at an industrial scale process. Thanks to a transverse and multiphysics approach which combined fluid dynamics, heat transfer, process metallurgy, solidification, it is possible now to define new innovative processes with the integration of new design of electromagnetic system. An association of more complex EM configurations can be realized: combination of AC and DC field, or two AC field [8, 9].

Future development of EPM technologies are in agreement with energy savings and CO2 reduction demand [1, 2]. In metallurgy industry, the integration of EPM technologies is more basically associated with productivity improvement, maintenance reduction and also safety consideration [2]. EM processing can be classified by type of magnetic field involved: from AC to DC field [3]. The choice depends on the desired action on the electro-conductive materials. These processes are suitable for heating, melting, flow and shape control, solidification control (stirring, pumping) but for each application a specific configuration needs to be defined, selected and optimized.

2. Numerical models

This paper gives some examples of EPM technologies applications for the development of new industrial process and main challenge to succeed in order to be relevant: (1) cold crucible technology, (2) electromagnetic pump, (3) DC electromagnetic brake. A combined approach by using multiphysics modeling with Comsol and experimental validation is used in order to give guidelines for process improvement or new design definition: concept, feasibility evaluation and potentiality for industrial integration. A time-dependent 2D or 3D multiphysics coupled numerical model (electromagnetics and fluid mechanics) including an Arbitrary Lagrange Eulerian (ALE) deformed mesh technique is set up which allows the deformation of the free surface.

2.1 Principle and geometry configurations

The main principle description and geometry configurations of three EM processes (Cold crucible, EM pump, EM brake) discussed in this paper are shown in Fig.1.

1-Cold crucible:

Levitation Melting cold crucible (LM-CC) is constituted by an assembly of sixteen water cooled copper sectors (hemispherical inner shape) separated by an air gap (0.5 mm) and surrounded by an induction coil. The metallic charge inside the crucible is melted thanks to Joule heating generated by eddy currents. The main dimension of the crucible is 100mm in inner diameter in order to melt 2kg of titanium alloy corresponding to small industrial pilot scale device. A current layer simulates the 3 turns of the induction coil with an effective rms current of 3.5 kA driven at 25 kHz. 3D model is necessary to describe properly the geometry and the 3D effect induced by the slit between each copper sector. Due to the periodicity, only a half copper segment and slit is considered in the model. Impedance boundary condition is implemented for copper segment description. This assumption is driven by the working frequency used which leads to small skin depth in the copper (less than 0.5mm).

2- EM pump:

The pumping of sodium in the duct is obtained thanks to a Travelling Magnetic Field (TMF) generate by three time-shifted phases with a specific arrangement based on asynchronous motor principle. A 2D axisymmetric geometry is considered. Two current sheets approximate the three phased double inductor. Each current layer is defined by the traveling wave of the line current $J_s(z,t)=J_0.\cos(\omega t-kz)$, where J_0=83.5 A/mm is the amplitude, $f=\omega/2\pi$=20 Hz is the frequency and k is the wave number.

3- EM brake:

EM Brake is constituted by an assembly of permanent magnets (Br=1T) which creates a transverse DC magnetic field (Fig.1-3). The mainly vertically moving liquid zinc with velocity v encounters the magnetic poles alternation (north to south) of the magnets producing the mainly horizontal (along x) B magnetic flux density, and hence "sees" a resulting magnetic flux variation according to Lenz's law. This gives a horizontal (along y) induced current density in the liquid zinc. This current density, coupled with the magnetic flux density B, produces a volume force density F_v mainly oriented in opposite direction to the strip motion with a module approximately equal to σvB^2. These forces tends to reduce the coating thickness in comparison with natural drag out by wiping the excess of zinc. A 2D Cartesian model perpendicular to the strip was set up.

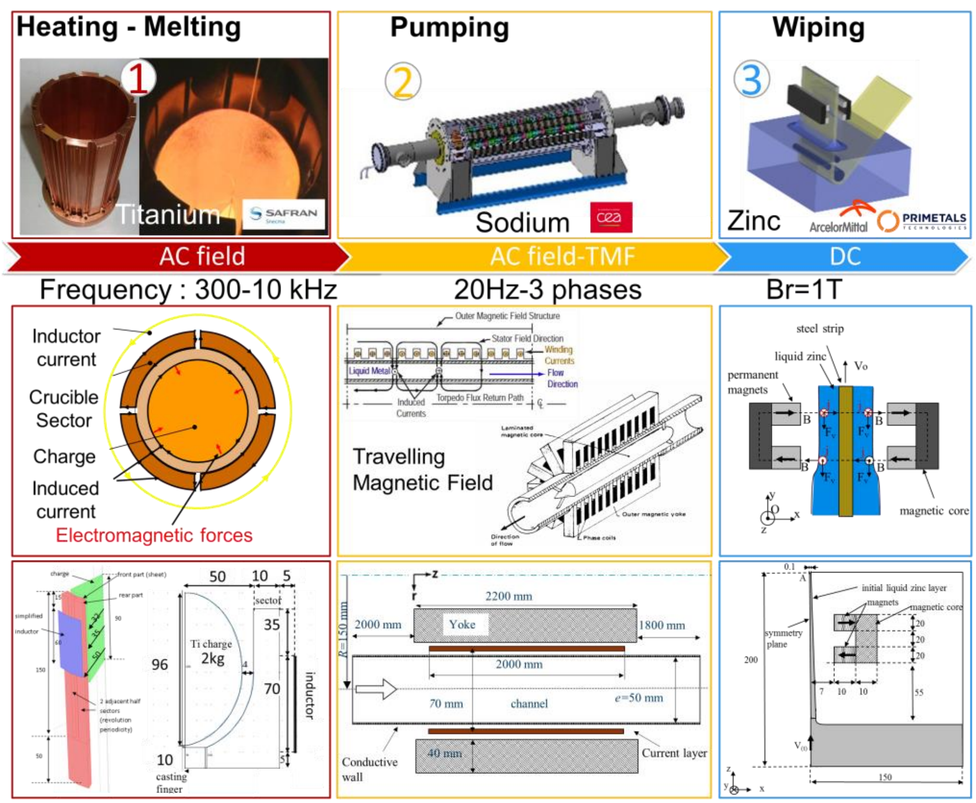

Figure 1. EM processes- design, principle and geometry: (1) Cold crucible for titanium alloy melting (2) EM pump for nuclear cooling circuit (3) EM brake for zinc hot dip coating

2.2 Governing equations

EPM processes are described with Comsol Multiphysics by using AC/DC, Navier-Stokes and moving mesh physics to make a coupling between electromagnetics and fluid flow with deformation of the free surface.

Relevant equations are defined as followings:

-Maxwell's equations:

$$\nabla \times (\mu_0^{-1} \mu_r^{-1} (B - Br)) = J + Je \ , \ J = \sigma (E + u \times B)$$

$$\nabla \times E = -dB/dt$$

a time harmonic description is used for AC field:

$$(j\omega\sigma - \omega^2 \varepsilon_0 \varepsilon_r) A + \nabla \times (\mu_0^{-1} \mu_r^{-1} \nabla \times A) - \sigma u \times (\nabla \times A) = Je$$

$$\nabla \times A = B$$

-Incompressible Navier-Stokes (transient):

$$\rho \frac{\partial \vec{u}}{\partial t} + \rho (\vec{u}.\vec{\nabla})\vec{u} = -\vec{\nabla} p + \vec{F}_{em} + \nabla.\left[\mu_e (\nabla \vec{u} + (\nabla \vec{u})^T)\right]$$

$$\vec{\nabla}.\vec{u} = 0$$

where B is magnetic flux density, Je is external current density, σ is the electrical conductivity, μ is the magnetic permeability, Br is the remanent induction for DC magnet description. A is the magnetic vector potential. **u**=(u,v) is the fluid flow velocity, μ_e is the effective dynamic viscosity. The turbulence of the flow is taken into account via two descriptions: a simple turbulent approach by using a 1000 times enhanced effective viscosity, μ_e and a more complex *k-ε* model (EM Pump). Fluid flow is driven by the time-average Lorentz force: F_{em}=Re(JxB*/2) for time harmonic description. The braking velocity Lorentz terms u.B^2 can generate strong MHD coupling (Magnetohydrodynamics) more particularly with EM pump configuration.

3. AC field -Cold crucible

In metallurgical industry, further works have to be performed for induction melting processes in terms of energy savings and particularly with cold crucible. Cold crucible is a common device for melting high reactive alloys such as titanium, zirconium alloy, titanium aluminide, silicon and others with no pollution. But so far its industrial use at large scale remains limited due to poor energetic efficiency [4]: low superheat typically around 20 to 50°C which is very restrictive for investment casting and technological difficulties for upscaling. For these industrial applications, cold crucible design presents a size limitation around 10 liters of metallic alloy and require high power source around 1000kW. A better comprehension of this process was achieved due to recently improved multiphysics modeling tools and experimental measurements. It gives some guidelines for experimenting new kinds of cold crucibles. Numerical modeling and first tests operated on a thin shaped straight cold crucible dedicated to continuous casting gives very promising results concerning the power efficiency (Fig. 2, see previous paper [5]).

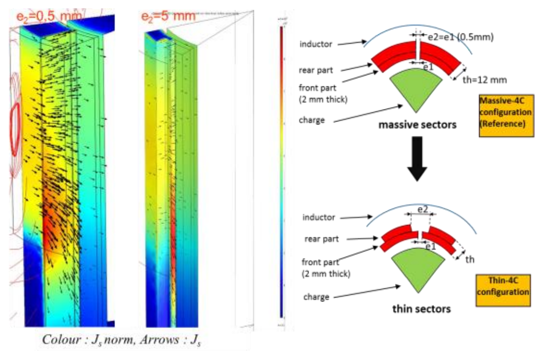

Figure 2. Continuous casting cold crucible - EM modeling (Surface current density A/m) on solid Ti charge - Comparison between massive and thin shape design- f=60kHz [5].

A potential improvement of the energetic efficiency was evaluated by combining modeling approach and experimental evaluation. The power efficiency η (power injected in the charge compare to total power input needed) is increased: η=52% with a thin shape design compare to 36% for a massive reference configuration resulting from power losses reduction in the cold crucible.

To go further, the same approach was used for Levitation Melting cold crucible (LM-CC). A thin LM-CC is studied with a 2 mm thin copper sheet for cold crucible segments.
The numerical modeling of each configuration is shown in Fig 3 with same induction Ampere-turns. The steady state shape is clearly different between a massive and thin LM-CC which tends to prove that a better levitation can be obtained with this new design and possibly higher level of superheat. The fluid flow is also more intense with thin shape. Typical Velocities are about 0.5

m/s for thin LM-CC and 0.3 m/s for massive LM-CC (downward located in the bottom of the charge).

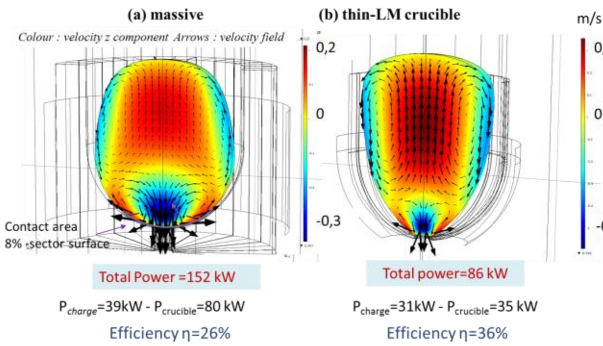

Figure 3. Numerically calculated steady state shape of a liquid titanium charge for a massive and a thin LM-CC with same induction ampere-turns and power repartition evaluation.

A large contact area with the inner surface of the cold crucible is obtained with massive LM-CC (8% of the global copper segment inner surface). It is characteristic of a poor levitation behavior and contribute to add supplementary power losses during the melting process due to the contact with water cooled copper sector.

For LM-CC design, the contact area is very limited. The integration on whole volume of the electromagnetic force along z axis is about 19.5N, the same order than the force resulting from the charge load 20N. A complete levitation seems achievable by optimizing the design and modifying inductor configurations [6, 7].

The conventional massive LM-CC presents very low efficiency: 25% of the power input is effectively injected in the charge. In massive LM-CC, a lot of power is loss in copper segments by Joule heating and more precisely 70% of these power losses are located on the slit surface (in front the air gap between each copper sector). It is resulting from 3D effect of the current distribution and link with the shape of the slit surface and function of the position and shape of the charge in the crucible (Figure 4).

In thin LM-CC, power losses are drastically reduced in the copper segments (more than 2 times lower).The power input needed to melt the charge is divided by two : 85kW compare to 150 kW. The power efficiency is also improved. Only 50% of the power losses in the cold crucible are located on the slit surface but higher current density was observed. The maximum current density is 3 times higher than massive design.

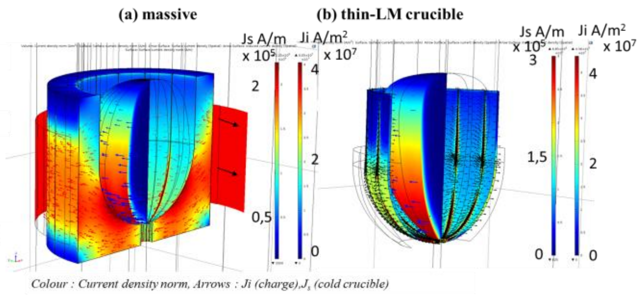

Figure 4. Current distribution around copper sector of the cold crucible (Js) and the charge (Ji) for thin or massive Levitation Melting crucible.

First trials were made to build this kind of thin LM-CC. A first small scale (8 sector-50 mm in diameter) was realized (Fig. 5) and compare to massive configuration. Power repartition measurements with a titanium solid charge (impedance meter method, [4]) demonstrates the gain in efficiency in good agreement with modeling results. Power dissipated in the cold crucible are divided by two and the global efficiency is increased significantly: 25% for thin design compare to 12% for massive design at a working frequency of 80 kHz. A titanium charge (200g) was melted successfully with less than 15 kW of power input.

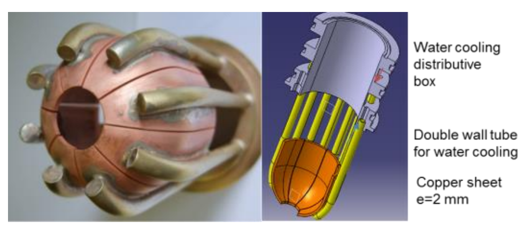

Figure 5. Thin Levitation Melting cold crucible design (50mm inner diameter).

The main challenge is actually to solve technical difficulties in order to construct these more complex thin designs by maintaining efficient water cooling of each copper segment of the cold crucible. More works by coupling experimental design and modeling is needed to improve levitation at the bottom and define new technical solution, more particularly if we want to use at industrial scale bottom pouring device to transfer the melt into the mold.

4. AC field-TMF-Electromagnetic pump

Another challenging aspect in nuclear application concerns the development of 4th generation of nuclear power plant. The French Atomic Commission (CEA) is now engaged in the development of the pilot plant ASTRID, a prototype of Sodium Cooled Fast Breeder Reactor. There is a recent interest on the development of large-size Annular Linear Induction Pump (ALIP) for nuclear engineering applications [10]. The potential use of large electromagnetic pump as circulating pump for the sodium contained in the secondary circuit in replacement of classical mechanical pumps is studied. To ensure a sufficient heat transfer through the secondary circuit, EMP needs to generate very high flow rate (2-4m^3/s). EMP presents different technological advantages like simplification, maintenance reduction and safety improvement since no mechanical parts are in contact with sodium, and there is no cooling water circuit. First modelling study was needed to consider MHD effects resulting from the strong coupling between electromagnetic and fluid flow in order to evaluate the pump efficiency and potential instabilities generated by the ALIP pump [11]. In parallel an instrumented facility (PEMDYN prototype 2m length) is under construction at CEA to get data for validation and give guidelines for upscaling at larger size.

Due to convection (high Reynolds magnetic number), significant ends effects are observed for large velocities with entrainment of magnetic field line outside the pump (Fig. 6). This leads to the existence of regions where the axial force is negative at high velocities (Fig. 7). Another phenomenon is the Hartmann effect which occurs near the walls at high fluid flow velocity. It leads to an expulsion of the electric current and the corresponding forces near the wall in a thin layers due to the strong coupling between velocity and magnetic field.

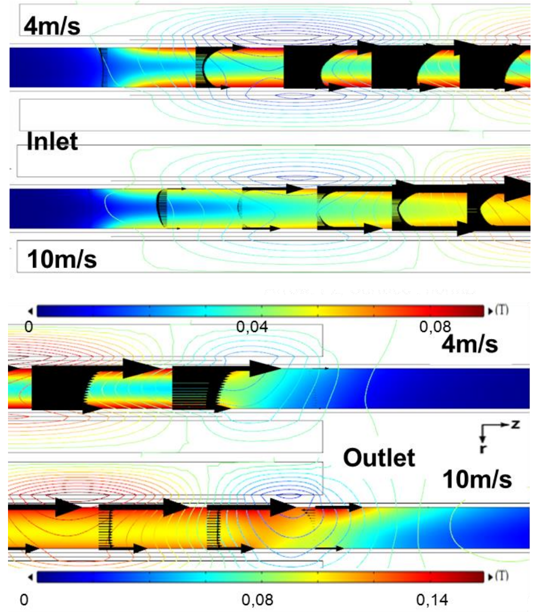

Figure 6. Distribution of the magnetic field and the axial electromagnetic force component in the channel for two mean velocities, U = 4 and 10 m.s-1 [12].

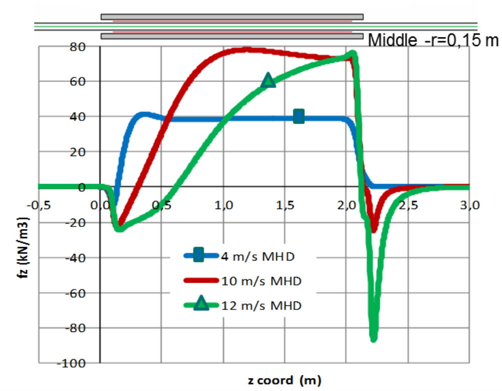

Figure 7. Profiles of the axial component of the electromagnetic force along the channel centerline for various mean velocities [11]

5. DC field-Electromagnetic brake

In automotive sector and more particularly for galvanizing lines, a challenge is to be able to increase the line productivity by increasing strip velocity (two times faster) while maintaining thin coating layer of zinc for corrosion protection. Different types of electromagnetic processes were evaluated and tested in the past with no success due to galvanealing (with HF inductor), stability and homogeneity of the coatings. A new innovative approach developed in collaboration with Primetals Technologies (formerly Siemens SVAI) and Arcelor Mittal is based on a DC device for controlling zinc coating thanks to braking effect generated by magnets [13].

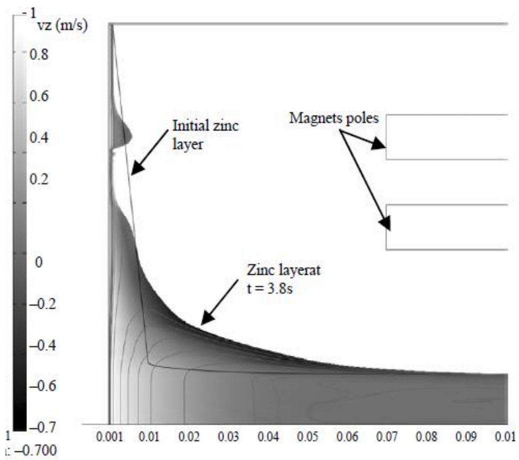

Figure 8. Free surface and velocity field (streamlines) with magnetic field at t=3.8s [13].

In hot dip galvanizing lines, zinc coating thickness control is realized by using gas knives wiping device. But for high velocities (> 3 m/s) a strong liquid zinc splash risk exists due to the necessity to increase the gas pressure for maintaining the same coating thickness. This is why an alternative approach with a complementary electromagnetic wiping system was studied based on the use of a DC field electromagnetic brake (EMB) system built with permanent magnets (Fig. 1-3). The wiping effect on the liquid zinc was proved and is in good agreement with models descriptions (Fig. 8). The main advantage of such device is a compact design and no overheating of the strip. This seems promising for an implementation on industrial line.

6. Conclusions

This paper gives an overview of Electromagnetic processes from AC to DC field thanks to examples of innovative industrial processes. They are developed by using a transverse and multiphysics approach. The use of Comsol Multiphysics for MHD modeling gives interesting guidelines for industrial processes improvement or definition of new solutions: concept and feasibility evaluation, design and optimization for industrial integration.

To enlarge the application of cold crucible at industrial scale in metallurgy industry, the main challenge is to improve its energetic efficiency and superheat level. A thin-shape cold crucible is a good candidate to improve significantly these two points.

EM pump is a promising candidate for use in secondary nuclear cooling circuit. Further study of the full MHD coupling with validation on prototype is needed to confirm its potential and evaluate fluid flow instabilities of large EM pump.

EM brake seems to be an interesting way for increasing line speed on galvanizing lines by adding a complementary EM wiping system for the control of zinc coating thickness.

7. References

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