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# Coupling electromagnetic and thermo-hydrodynamic simulations to optimize a vitrification furnace heated by direct induction

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**Abstract.** This study deals with the optimization of a cold crucible melter where electric currents are directly induced in a glass charge. Designs of experiments are used to determine the factors of the crucible design which have an impact on the efficiency, and result in an optimized configuration. Numerical tools are used to lead the experiments: a finite volume software, used to solve hydrodynamics and thermal equations, is coupled to a finite element software which computes the Maxwell equations. The innovation is the use to couple directly areas treated with surface impedance and volume formulations, in electromagnetic simulation. The optimized configuration is then studied comparing numerical simulations and experiments in an industrial unit.

Keywords: Coupling, design of experiments, optimization, sensitivity analysis

## 1. Introduction

Vitrification has been used since the 1970s for the treatment of high level activity nuclear waste. A direct induction process using the cold crucible technology is presently developed by the French CEA (Atomic Energy Commission) and AREVA NC (Nuclear Cycle) in order to widen the range of vitrifiable wastes. This process is characterized by currents directly induced inside the molten glass and by the cooling of all the crucible walls.

To further the electrical power into the glass charge, minimize the energy losses by Joule effect, and homogenize the temperature in the glass, the furnace design is optimized by numerical model. The high dependence of physical properties of glass with temperature requires a strong coupling study between electromagnetic, thermal, and hydrodynamic phenomena [1]. Moreover, due to intrusive elements in the crucible (thermocouples, mechanical stirrer . . .) that significantly perturb the Joule power distribution a three-dimensional model for the electromagnetism phenomena is necessary

In this article are presented numerical results from a design of experiments compared to experimental measurements acquired during experiments on a real vitrification unit. Experiments are realized in a cold

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Table I  
Formulations used for electromagnetic computations with Flux® [3]

Area type	Name of the formulation	Description
Air or Vacuum (with unmeshed coils)	MD3RED	Reduced scalar potential
Air or Vacuum	MD3VEC	Magnetic vector potential
Stainless steel	MD3ISAV	Surface impedance
Glass	MD3AV	Magnetic vector potential and Electric scalar potential

crucible melter of diameter 500 mm. The metallic structure is cooled by water. The present glass mass in the reactor is 100 kg. A multi-turn copper inductor is placed around the crucible. The temperature of the glass is regulated by action on the injected high-frequency power. This temperature is measured locally by two thermocouples. For a temperature fixed at 1250°C, the power injected in the molten glass load is 60 kW for a working frequency of 300 kHz.

## 2. Coupling strategy

An iterative coupling for simulation of the stirred molten glass is achieved by two dedicated software [1]. The commercial software Flux® is used to solve induction equations. Owing to the high value of the frequency, the quasi-steady approximation is made. The different formulations used according to the calculated areas are detailed in the Table I.

The possibility to couple directly areas treated with surface impedance and volume formulations, in electromagnetic simulation, opens up new horizons. Electric currents transfer between surface impedance and volume formulations areas can be simulated. The smaller numbers of mesh elements enable reduced time of calculation.

The MD3RED formulation is thrifty in resource of calculation and dedicated for magneto-harmonic calculations of non conductive areas, like air, with unmeshed coils (virtual current density source forced in the air) [3]. In Flux®, this formulation allows the use of infinite boxes for open boundaries and far fields computation while keeping a light study domain, and unmeshed coils to reduce the number of degrees of freedom [3]. The equations are established using the reduced magnetic scalar potential  $\Phi_r$  in relation of the magnetic field  $H_j$  generated by the coils [3]:

$$\vec{H} = \vec{H}_j - \vec{\nabla}\Phi_r \quad (1)$$

$$\vec{\nabla} \cdot \left( \mu \left( \vec{H}_j - \vec{\nabla}\Phi_r \right) \right) = 0 \quad (2)$$

With:  $\mu$  the magnetic permeability.

The coupling between MD3RED and MD3ISAV formulation is not allowed [3]. The MD3VEC formulation treats the air areas around areas treated with MD3ISAV formulation [3].

$$\vec{B} = \vec{\nabla} \wedge \vec{A} \quad (3)$$

For metallic areas made of stainless steel, owing to a high electrical conductivity, electric currents penetrate only in a material thickness lower than 1 mm (skin effect) for our working frequency of 300 kHz. The MD3ISAV formulation using the surface impedance is dedicated for this type of elements. It allows to replace the numerical resolution in the conductor by a boundary condition on its surface.

$$\vec{E} \wedge \vec{n} = Z_S \vec{n} \wedge \left( \vec{H} \wedge \vec{n} \right) \quad (4)$$

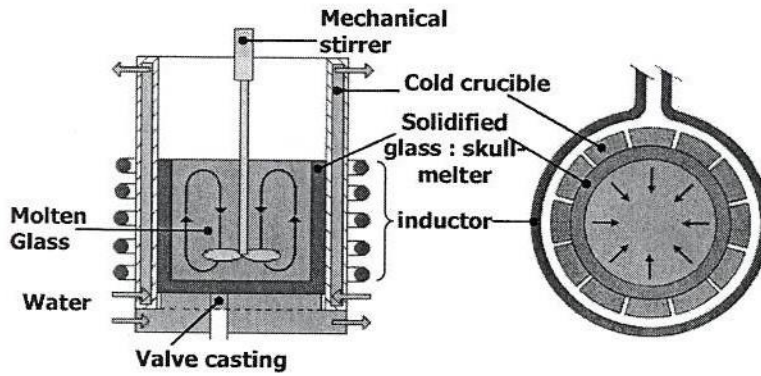


Fig. 1. Cold crucible device. (Colours are visible in the online version of the article; <http://dx.doi.org/10.3233/JAE-2011-1388>)

$$Z_s = \frac{(1 + i)}{\sigma \delta} \quad (5)$$

With:  $Z_s$  the surface impedance,  $\sigma$  the electrical conductivity, and  $\delta$  the thickness of electromagnetic skin.

The molten glass reaches values of electrical conductivity of about 0.01 to 0.1 ( $\Omega^{-1} \cdot \text{mm}^{-1}$ ) which is lower than the electrical conductivity of stainless steel. Thereby the skin thickness in glass is over 200 mm. The MD3ISAV is not conformed to this area. The magnetic vector potential formulation MD3AV is used. It gives better results, in a material with high gradient of electrical conductivity  $\sigma$  such as the glass, than  $t\text{-}\phi$  formulation. The equations of this formulation are:

$$\vec{\nabla} \wedge \left( \frac{1}{\mu_0} \vec{\nabla} \wedge \vec{A} \right) + \sigma \left( \frac{\partial \vec{A}}{\partial t} + \vec{\nabla} V \right) = \vec{0} \quad (6)$$

$$\vec{\nabla} \cdot \vec{j} = 0 \quad ; \quad \vec{j} = -\sigma \left( \frac{\partial \vec{A}}{\partial t} + \vec{\nabla} V \right) \quad (7)$$

With:  $\mu_0$  the vacuum permeability,  $\vec{A}$  the magnetic vector potential and  $V$  the electric scalar potential.

The thermo-hydrodynamic phenomena are computed by the software Fluent® which solves the Navier-Stokes Eqs (9) and thermal (10) equations [4]. Due to the high viscosity of the glass, the flow is assumed to be laminar. The terms coupling the electromagnetic and thermo-hydrodynamic equations are the non linear electric conductivity of the glass and the Joule power density  $Q_{th}$  induced into the molten glass Eq. (11). The main issue is to couple a finite element and volume finite based software. Mesh refinement requirements are different for the induction and hydrodynamic phenomena. Consequently, using a unique mesh is not possible and interpolations between the two meshes are done to minimize losses of precision. The convergence criterion for the iterative coupling is based on the square error between the old and new map of temperature. The temperature distribution evolution is slow compared to hydrodynamic and electromagnetic phenomena. The Joule power distribution is calculated every 20 seconds to 100 seconds. The time step for Fluent® is 1 seconds.

$$\vec{\nabla} \cdot \vec{u} = 0 \quad (8)$$

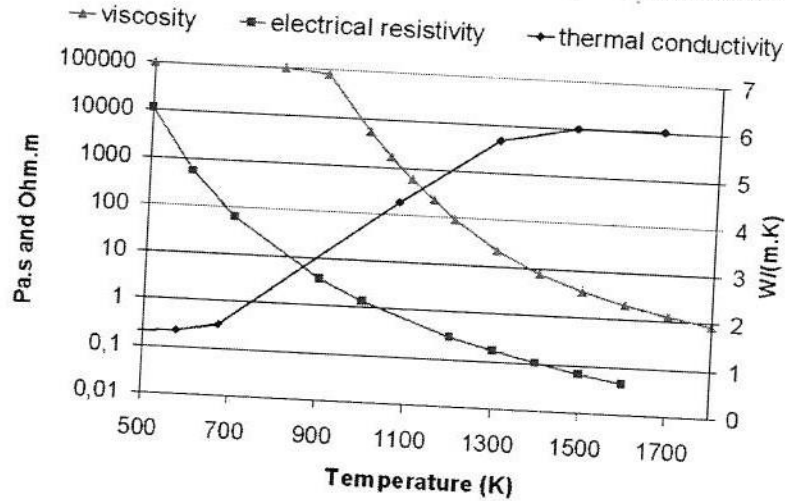


Fig. 2. High temperature characterization of glass. (Colours are visible in the online version of the article; <http://dx.doi.org/10.3233/JAE-2011-1388>)

$$\rho_0 \left( \frac{\partial \vec{u}}{\partial t} + (\vec{u} \cdot \vec{\nabla}) \vec{u} \right) = -\vec{\nabla} p + \vec{\nabla} \cdot \vec{\tau} - \rho_0 \beta (T - T_0) \vec{g} \quad (9)$$

$$\rho_0 \left( \frac{\partial C_p T}{\partial t} + (\vec{u} \cdot \vec{\nabla}) C_p T \right) = -\vec{\nabla} \cdot (\lambda \vec{\nabla} T) + Q_{th} \quad (10)$$

$$Q_{th} = \frac{|j|^2}{2\sigma} \quad (11)$$

With:  $\rho_0$  the density of the glass,  $\vec{u}$  the velocity,  $\vec{\tau}$  the stress tensor,  $p$  the modified pressure,  $\beta$  the thermal expansion,  $T$  the temperature,  $\vec{g}$  the gravity,  $C_p$  the specific heat capacity and  $\lambda$  the thermal conductivity.

The difficulty of this modeling is to consider glass physical properties variations: viscosity, electrical conductivity, thermal conductivity, density ... (Fig. 2).

### 3. Optimization method

The method chosen for this study is based on a design of the experiments. The main objective is to optimize the implementation of the mechanical stirrer in a glass melter strongly forced by its close environment. We shall retain that for reasons of free space, it was not possible to tilt the axis of the stirrer and that the maximal speeds of rotation did not have to exceed  $20 \text{ rd} \cdot \text{min}^{-1}$ .

The influence of geometric factors on the electromagnetic performances of the furnace is studied. In particular, we consider the inductor position, the thickness of the electrical insulator arranged on the structure of the furnace, and the number of metallic sectors which constitute the crucible. From a hydraulic point of view, we study the impact of the mechanical stirrer geometry which improves the thermal homogeneity of the glass.

Designs of experiments are useful to minimize the number of experiments. Their results allow us to determine the influence of each factor, and to predict the response of the system in some cases. This

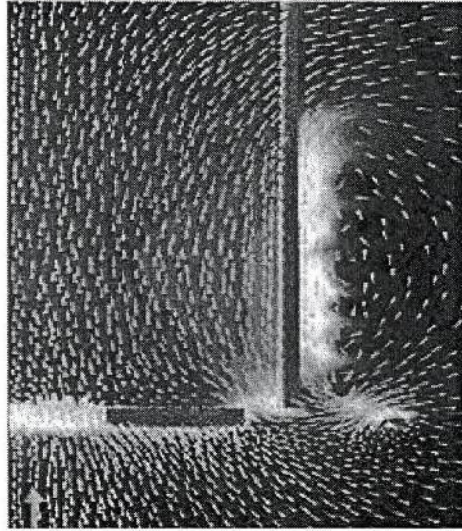


Fig. 3. Magnetic field computed around the empty glass crucible. Scale: [0; 3500] A/m. (Colours are visible in the online version of the article; <http://dx.doi.org/10.3233/JAE-2011-1388>)

study shows the effects of thirteen different parameters, each of them with three levels. Finally, the system is determined by the Taguchi table [5] and described with 27 simulations.

A mesh composed of 750 000 elements is used for the thermo-hydrodynamic simulations. To simulate the mechanical stirrer rotation, the “multiple reference frame” and the “sliding mesh” methods are combined. In these configurations, each simulation requires approximately 24 hours.

#### 4. Results

The presented results concern the optimal configuration resulting of the design of the experiments. It was necessary to obtain at the same time significant surface velocities while limiting the energy losses to structures.

The whole simulations lead us to understand the physical phenomena, in particular the magnetic field distribution repartition in the furnace (Fig. 3), and to appreciate the impact of each geometric factors on the system (Fig. 4). In this graph, we can see that the rotational speed of the stirrer ( $V_{max}$ ) and its wingspan (P1) are predominant factors on the homogeneity of the temperature, compared to the other geometric factors.

Designs of experiments led us to an optimized configuration of the whole system. We then studied this configuration comparing simulations with experiments.

In an industrial unit it is difficult to chart the electromagnetic field continuously throughout the system. It is easier to take advantage of cooling to access to Joule losses in the structures.

We observed three specific quantities: the heat exchange, the field of velocity and the temperature in the glass melt. Concerning the validation of the field of velocity, the comparison between the experimental and numerical results is possible only on free surface. It is obtained by the follow-up by camera of millimeter-length tracers deposited on surface during experiments (Fig. 5).

The hydrodynamic aspects were validated, the experimental method described here above confirmed the azimuthal character of the flow on the surface. Concerning the heat aspects, during the computation

Table 2  
Temperature in the glass load and power exchange for a rotational speed of 20 rd.min<sup>-1</sup>

N = 20 rd.min <sup>-1</sup>	Measurements	Computation
Maximum temperature (K)	1623	1700
Thermal power (kW)	14	12.2

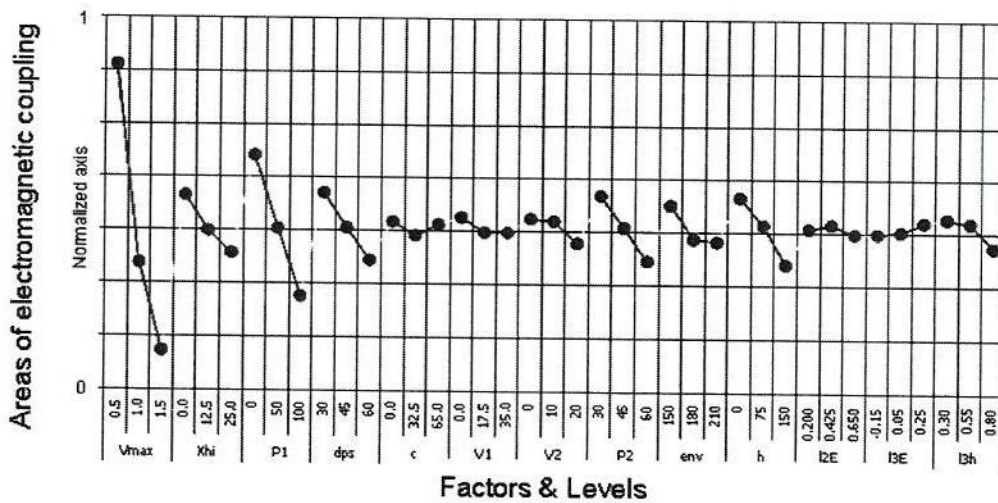


Fig. 4. Example of the influence of the factors on the areas of electromagnetic coupling. (Colours are visible in the online version of the article; <http://dx.doi.org/10.3233/JAE-2011-1388>)

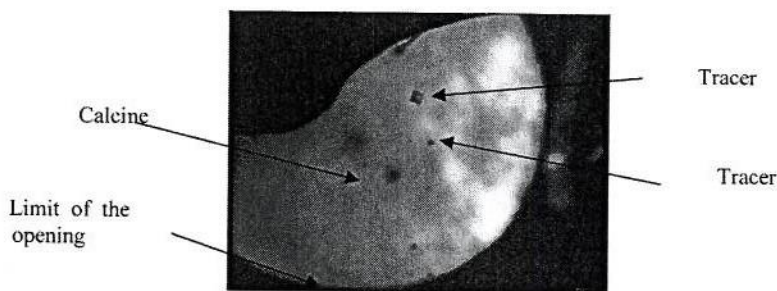


Fig. 5. Photograph of tracers deposited on surface. (Colours are visible in the online version of the article; <http://dx.doi.org/10.3233/JAE-2011-1388>)

the total power injected into the glass is in accordance with experimental results 60 kW. The heat losses matches with the experiments (Table 2). Thus, the choice of boundary conditions in the calculations seems to meet the experimental conditions. Regarding the temperatures, the magnitudes of the temperature are identical numerically and experimentally, the relative differences do not exceed 10% (Table 2). Finally, the numerical and experimental results show good agreement for all the compared variables.

Distributions of the glass speed and the temperature once the steady state is reached are presented in a horizontal plane intersecting the stirrer here below (Fig. 6). We can see that the temperature is homogeneous throughout the crucible until the cooled walls.

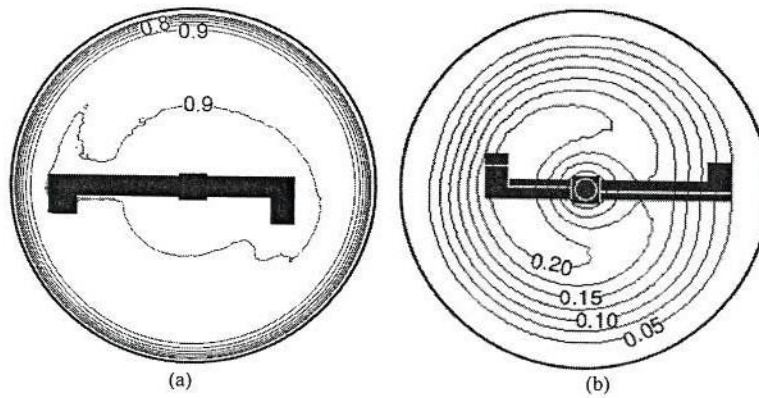


Fig. 6. Distribution in a horizontal plane intersecting the stirrer: (a) of dimensionless temperature (b) of distribution of the glass speed.

## 5. Conclusions

Electromagnetic, thermal and hydrodynamic phenomena are modeled within the stirred molten glass that is heated by direct induction. Use the coupling AV formulation with surface impedance boundary condition enables the simulation of complete and elaborate case. This study details how the coupling is achieved. A design of experiments has been carried out (13 parameters with 3 levels, a global of 29 configurations). It provides valuable information for the design of the stirrer and for the choice of the locations of the measurement devices used to control the process.

Despite the experimental difficulty for assessing the electromagnetic quantities, the coupling with thermics permits to estimate the electromagnetic state of the system satisfactorily. A comparison between numerical and experimental data has confirmed the validity of the model since it has shown a good agreement between all the compared quantities. The coupling directly areas treated with surface impedance and volume formulations enables the simulation of complete and elaborate case. The device optimization is based on this simulation.

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