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Numerical Study of the Hydrodynamics in a Two-Phase Induction Melter for Nuclear Waste Treatment Under Various Operating Parameters

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Abstract

This article presents the numerical modeling of an in-can melter containing a metallic and a glass phase. Low-frequency electromagnetic induction is used to melt and stir the metal, and the latter heats and drags the glass phase. A careful choice of operating parameters is required to prevent the solidification of the glass, and to increase the performances of the process. Numerical modeling helps in avoiding experimental trial and error method and in studying the effect of the operating parameters on the hydrodynamics. The main difficulty for the numerical modeling comes from the deformation of the interfaces, produced by the magnetic pressure. First, a theoretical estimation of this phenomenon is performed and compared with numerical and experimental results. Then, numerical results are presented for different power inputs, AC frequencies, and quantities of glass. One of the phenomena obtained numerically is air entrainment at the triple point, creating bubbles in the glass.

Keywords: MHD, Induction heating, Hydrodynamics, Three-phase flow, Vitrification, Nuclear wastes

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1. Introduction

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Mixed oxide nuclear fuel (MOx) production plants generate, each year, large quantities of technological wastes contaminated with uranium and plutonium due to the manipulation of the combustible in glove boxes. In France, today's solution to prevent the contamination of the environment is to enclose these wastes in hermetic packages for long-time storage in geological sites. To produce these packages, the wastes are compacted in order to reduce their volume by using different processes depending on their composition. Metallic parts are often compacted and cast in concrete [1] or melted in a can [2], while organic

- ¹⁰ materials are incinerated and then incorporated in melted glass, which is solidified afterwards. The latter process is called vitrification and mainly has two configurations, the first of which is based on the resistive heating technique and is in use in the United State, Japan, India, *etc.* [3]. The second vitrification technology, which has been developed by France, is based on the inductive heat-
- ¹⁵ ing of the glass bath and is currently in use in France, Great Britain, Korea, etc. [3].

In both vitrification technologies the melted glass containing the wastes is poured into the package where solidification occurs. Although these technologies are effective, their work-flow is rather slow mainly because of:

- The time needed to homogenize the irradiated matter in the glass, which is generally done with an air bubbling system [4] or a mechanical stirrer [5].
 - The time spent for the preliminary sorting of the wastes necessary for their further treatment. For the considered wastes, this step is substantial due to the fact that — even if they are sorted at the source — the wastes are sealed in welded PVC bags regardless of their composition, in order to ensure the containment of radioactive materials.

To allow the simultaneous treatment of unsorted organic and metallic intermediatelevel wastes, the PIVIC process [6–8] is currently being developed, under the

- ³⁰ collaboration agreement between the Orano company, Andra¹, and the CEA². This process belongs to the family of so-called "in-can melting" processes which were already proposed several decades ago [9, 10] and allows the crucible used for elaboration to become the final container. The whole treatment setup consists of two parts: the upper one serves as a combustion chamber for the organic
- ³⁵ part and is connected to the lower one which serves as a melter (figure 1). The latter is the subject of the present work. The melter is fed with metallic and incinerated organic wastes and glass frit, and the materials are melted due to electromagnetic induction. During the treatment, a phase containing the metallic parts from the wastes is formed in the container, along with a glass phase
- 40 containing the ashes of organic materials. Due to their physicochemical properties, the two phases are non-miscible and stratify because of differences in their density.

In addition to avoiding the sorting of preliminary wastes, the PIVIC process has another advantage directly related to the co-existence of electrically conducting and dielectric phases under the treatment. Indeed, the use of the AC electromagnetic field leads not only to the heating of the metallic phase, but also to its intense stirring. The glass is then melted and stirred via its contact with the metal, preventing the usage of another homogenization system.

However, to gain from benefits foreseen in the PIVIC process, its operational parameters should be carefully chosen. Regarding the processes in the melter, and without addressing the chemical interactions between the two phases, multiple questions arise about the electrical and mechanical behavior of the two phases. One of the crucial operational point is that the glass phase should be always stirred during the whole treatment, otherwise it will freeze and the package production will be interrupted. Consequently, the external AC electromagnetic field should not only penetrate the can, but also provide sufficient

heating and stirring for the melted metal to be further transferred to the glass.

²French alternative energies and atomic energy commission

¹French national agency for radioactive waste management



Figure 1: Sketch of the PIVIC process: the upper part serves as incineration chamber for organic materials, the lower part is for the processing of the liquid phases with their further solidification in place.

However, in such process configurations the electromagnetic induction produces not only the stirring of the bulk liquid, but also exerts a strong nonuniform
pressure on the surface of the metal. This may lead to the formation of a steep metal dome which can emerge from under the glass. The shape of the dome will affect the distribution of the glass over the metal's surface as well as the thermal and kinematic interaction between the two liquids.

Because of the strong coupling of the electromagnetic and hydrodynamic ⁶⁵ phenomena, the only way to understand the interconnections between the operational parameters, electromagnetism, and hydrodynamics of the system is numerical simulations. It should be noted that because of high temperatures, opacity of the materials, and the strong magnetic field, detailed measurements are hardly feasible.



The problem of simulations of magnetohydrodynamics coupled with the cal-

culation of the shape of the metallic charge is not new, and has been reported, for example, in metallurgy. Employed numerical methods were based on the mesh deformation [11–14] or used the volume of fluid (VOF) models [15–21]. Different numerical models were also used to represent the turbulent flow of

the metal in this type of processes. Mostly, models based on Reynolds averaged Navier-Stokes equations (RANS) are used — e.g. k-ε [13, 14, 19, 20, 22], k-ε RNG [15, 23], k-ω [11, 24], or k-ω SST [16, 17] — and sometimes Large Eddy Simulation (LES) is used [21, 23, 25, 26], despite the longer calculation times needed for this method. The calculations of the hydrodynamic and the
electromagnetic parts are often performed sequentially and sometimes with two different software [16, 20, 23, 25, 26], allowing the use of finite elements for the

electromagnetic part and finite volume for the fluid flow. It should also be noted that the shape of the metallic dome can be obtained

by solving the equation of mechanic equilibrium between the magnetic and hydrostatic pressure without accounting for the fluid flow [26–29].

Yet, all the publications cited above deal with single-phase systems. Simulations of two superposed liquids along with deformation of the interface between them were made by Courtessole and Etay [15]. However, the use of the electromagnetic field in the studied process was tuned in order to create mainly a stirring of the liquids and did not lead to a large deformation of the interface. The metallic phase remained always covered by the secondary liquid (molten salt) and the velocity also remains moderate.

In this paper, the specifications of the studied process and the order of magnitude of the characteristic parameters of the involved physical phenomena are ⁹⁵ firstly presented. The numerical model, which comprises EM calculation in COMSOL Multiphysics and hydrodynamics in ANSYS Fluent, and a coupling between them is described in the second part. In the third part, the shape of the surface of the liquids obtained in simulations is compared with some measurements realized on a prototype. Then, the impact of the operating parameters

¹⁰⁰ of the process on the stirring of the materials is studied, with attention to the flow of the glass.

2. Modeled process and associated physical phenomena

The melter (figure 2) consists of a multi-layered cylindrical container, of typical internal radius R, placed inside an electromagnetic inductor. Because of safety requirements, one of the layers is a metallic shell of 3 mm thickness responsible for retaining the melt in case of a breaking of the inner crucible. The inductor is powered by a generator delivering an electrical current I of a few thousands amperes at a low frequency ($f \approx 40 \text{ Hz}$) to ensure the penetration of the metallic layer of the container by the EM field. For a typical value of electrical conductivity of metals $\sigma = O(10^6 \text{ S/m})$, the value of the EM skin depth (equation 1) for the selected AC frequency is in the order of few centimeters, this means that the metallic shell is not entirely transparent for the applied EM field, and that it will dissipate a fraction of the EM energy.



$$\delta_B = \frac{1}{\sqrt{\pi f \mu_0 \sigma}} \tag{1}$$

Figure 2: Sketch of a meridional section of the melter containing the metal phase covered with the glass. A strong deformation of the shape of the surface of the metal due to electromagnetic pressure, and the formation of a dome emerging from the glass is shown on the right.

A dimensional analysis of the process is given below to provide some characteristic values of the process, and to explain further the chosen numerical approach. Yet, this analysis requires the knowledge of the physical properties of the processing materials. In the real process, the physical properties of these materials will depend on the composition of the wastes and may generally vary during the treatment. Hereafter the approximate values of properties corresponding to the materials used in the experiments with prototype at the

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corresponding to the materials used in the experiments with prototype at the average temperature of the melt $(1350 \,^{\circ}\text{C})$ are taken (tables 1-2). The properties of the glass in table 1 correspond to those of a glass which was formulated specifically for this process.

Table 1: Physical properties of the fluids used in the prototype.

	Viscosity	Density	Electrical
			$\operatorname{conductivity}$
	$\eta~(\mathrm{Pa}\cdot\mathrm{s})$	$\rho~(\rm kg/m^3)$	σ (S/m)
Glass	1.3	2500	20
Metal	$6 imes 10^{-3}$	7000	10^{6}
Air	$5 imes 10^{-5}$	1	0

Mir/metal
 Metal/glass
 Glass/air

 1.6 N/m 1.2 N/m 0.15 N/m

An order of magnitude for the velocity in the metallic phase U_m , produced by Lorentz forces, can be estimated using the notion of the Alfvén velocity U_A (equation 2), which comes from the balance between inertial forces and the rotational part of the Lorentz forces in the molten metal:

$$U_A = \frac{B_0}{\sqrt{\mu_0 \rho_m}} \tag{2}$$

with the subscript m corresponding to the metallic phase, and B_0 being a characteristic value of the magnetic induction. The latter was measured approximately to 0.13 T in an empty container for a typical operating current. In the presence of a load, this characteristic value will change.

Using the experimental results of Fautrelle *et al.* [30], U_m can be approximated to $0.2U_A$ in the frequency range of this study. This gives $U_m = 0.28 \text{ m/s}$ for the velocity of the molten metal. With the estimation of the magnetic Reynolds number $Rm = R\mu_0\sigma_m U_m$ which gives approximately 0.09, one can conclude that advection of the magnetic field by the flow is negligible.

The estimation of the regime of the liquids' flow is done with the Reynolds number $Re = U\rho R/\eta$ which represents the ratio of the inertial and viscous forces. Taking the value of U_m as a characteristic velocity for both liquids (thus overestimating it for the glass), $Re_m = 8 \times 10^4$ and $Re_g = 130$ is obtained for the metal and the glass respectively. This predicts a turbulent flow in the metallic phase, which corresponds to earlier observations in the literature. However, the glass flow is laminar, which is in agreement with the observations of its free surface in the prototype, as discussed later.

The next estimation is related to the deformation of the surface of the molten metal due to the magnetic pressure $B_0^2/2\mu_0$ produced by the irrotational component of the Lorentz forces and counterbalanced by the hydrostatic pressure. The height of the dome h_m , defined as the difference of height between the highest point and the lowest point of the metal surface (see figure 2), can be estimated using the pressure equilibrium between these two points. Neglecting the effects of surface tension and of flow, for a dome emerging from under the glass such that its highest point at the axis of symmetry is not covered with the glass, the pressure equilibrium is given as:

$$h_m \rho_m g = \frac{B_0^2}{2\mu_0} + h_g \rho_g g$$
 (3)

where h_g is the thickness of the glass free surface at the crucible wall and g the gravity acceleration. Assuming that the dome shape is parabolic, i.e. its surface is given as $z(r) = h_m(1 - r^2/R^2)$, one can relate h_g with the total mass of the glass in the crucible M_g :

$$h_g = \frac{1}{R} \sqrt{\frac{2M_g h_m}{\rho_g \pi}} \quad \text{for} \quad h_g \le h_m \tag{4}$$

Furthermore, the critical charge of the glass before the coverage of the metal $M_{g,cr}$ can be found from equations 3 and 4 with a condition that the height of the dome is equal to the height of the glass $h_m = h_g$ that means that only the dome's apex is not covered. Note that in this case the equation 5 defines the

dome's height and this relation holds also for a dome completely covered with any quantity of glass [15], i.e. for $M_g \ge M_{g,cr}$.

$$h_{m, max} = \frac{B_0^2}{2\mu_0 g(\rho_m - \rho_g)} \quad \text{if} \quad M_g \ge M_{g, cr} \tag{5}$$

$$M_{g,\,cr} = \frac{R^2 \rho_g \pi B_0^2}{4\mu_0 g(\rho_m - \rho_g)} \tag{6}$$

For $B_0 \approx 0.13$ T obtained by the measurements on the prototype, given relations lead to the critical glass charge of approximately 35 kg. Yet, in the experiments performed within the prototype, the surface of the metal was visible up to the use of 50 kg of the glass, which exceeds significantly the estimated value. Consequently, the height of the metallic surface depending on the total mass of the glass introduced in the crucible is one of the subjects of the numerical study.

Accounting for the fact that the properties of the materials, especially glass, may strongly depend on temperature, yet, not aiming to do its calculation at this stage of the process study, the following argumentation was accepted. First, the temperature in the metal can be considered constant due to its high thermal conductivity ($\approx 17 \text{ W/(m \cdot K)}$), the turbulent flow, and the thermal insulation produced by the glass. Secondly, on the prototype, the insertion of thermocouples in the melted glass showed that its temperature was homogeneous in the bulk, yet, there is a stronger temperature variation close to its free surface due

to the important heat losses by radiation. Consequently, neglecting the thermal effects on material properties one may underestimate the viscosity of the glass near its free surface that can provide a higher velocity of the latter. Otherwise, temperature distribution in the system has no significant effect on the flow and formation of the metallic dome.

3. Numerical modeling

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As explained above, the aim of the numerical modeling is to provide the detailed information about the hydrodynamics of the process which is governed by the operational parameters, such as input current and its frequency, and also by the amount of glass frit loaded into the melter. For the present study we choose a 2D axisymmetrical geometry neglecting the slight helicity of the inductor. Based on the estimation of the height of the metallic dome, the height of the calculation domain was limited to Z = 300 mm, i.e. the upper part of the PIVIC setup (combustion chamber) was excluded. The modeling approach is similar to the one adopted in [16, 20, 23, 25, 26] and consists of a coupling between the electromagnetic simulations performed in COMSOL and modeling of hydrodynamics performed with ANSYS Fluent. The fundamentals

of the two models and the main difficulties are briefly described below. Coupling of two software gives more flexibility in the construction of the

- 175 calculating meshes, as explained below. Indeed, a fine mesh is required for the simulation of the fluid mechanics while a large domain is needed for the electromagnetic calculations to treat properly a natural decrease of the intensity of the electromagnetic field. An attempt to combine both requirements using only one calculating mesh usually leads to a large number of cells and requires
- ¹⁸⁰ more calculation time as well as more computational resources. Furthermore, the use of a finite element based software is natural for the computations of the electromagnetic phenomena due to employed projection and interpolation methods while a larger number of models for the fluid mechanics is proposed for the finite volume spatial discretization. It should be noted that other software,
- such as OpenFOAM and Elmer [31] which are open source, can be used in a similar way as presented below.

3.1. Electromagnetic model in COMSOL

For AC electromagnetic induction applications, the electromagnetic equations are formulated using the magnetic and electric potential A-V, with complex harmonic presentation. The equations are formulated in a cylindrical coordinate system (e_r , e_{θ} , e_z). In the case of axial symmetry, the electric potential has a trivial constant solution and the magnetic potential has only an azimuthal component θ . This leads to a one equation system:

$$i\mu_0 \sigma \omega A_\theta - \boldsymbol{\nabla} \times (\boldsymbol{\nabla} \times A_\theta) = \mu_0 js \tag{7}$$

here $(i^2 = -1)$, and the azimuthal source current density js is non zero in the inductor only, where it is equal to the total current I divided by the cross section area of a wiring. Then, the time averaged Lorentz force density is expressed as:

$$F_{e} = \frac{1}{2} \mathbb{R} \left(\boldsymbol{j} \times \overline{\boldsymbol{B}} \right)$$
with
$$\boldsymbol{B} = \boldsymbol{\nabla} \times (A_{\theta} \boldsymbol{e}_{\boldsymbol{\theta}})$$
and
$$\boldsymbol{j} = i\sigma \omega A_{\theta} \boldsymbol{e}_{\boldsymbol{\theta}}$$
(8)

j is the electric current, \overline{B} the complex conjugate of B, and \mathbb{R} the real part of the value.

The domain treated with COMSOL includes the container with the liquids, the inductor, and some surrounding air of size $10Z \times 10R$ in order for the magnetic lines to close without constraints. The largest gradients of A_{θ} are concentrated in the electromagnetic skin, so the size of mesh cells in the fluid domain must be small compared to δ_B (equation 1). Therefore, this domain is meshed by squares of 4.85 mm sides.

3.2. Modeling of hydrodynamics and configuration in Fluent

The calculation domain in ANSYS Fluent also has a 2D axially symmetric geometry with the size $Z \times R$. The model in Fluent is in charge of simulating the flow and calculating the shape of the interfaces between the fluids. To be able to handle the appearance of a new surface due to the emergence of the metallic dome, we choose a three-phase Volume of Fluid (VOF) model. The principle of the latter is to use a single set of momentum equations for all fluids and to track the volume fraction α of each of the fluids throughout the domain in each mesh cell. Consequently, any physical property ξ in a calculation cell of a domain is presented proportionally to the value of this property for each fluid ξ_i and the volume fraction α_i of the latter:

$$\xi = \sum_{i=1}^{3} \alpha_i \xi_i \quad \text{with} \quad \sum_{i=1}^{3} \alpha_i = 1$$
(9)

For further treatment, one of the phases is considered as a primary one while others are secondary phases. Then, the system of equations consists of the continuity equation for a unique velocity field U, incompressible transient Navier-Stokes momentum equation, and continuity equations for the secondary phases that are presented as follows:

$$\nabla \cdot \boldsymbol{U} = 0$$

$$\rho \left(\frac{\partial \boldsymbol{U}}{\partial t} + \boldsymbol{U} \cdot \nabla \boldsymbol{U} \right) = -\nabla P + \nabla \cdot (\eta + \eta_t) \nabla \boldsymbol{U} + \boldsymbol{F}_e + \boldsymbol{F}_s - \rho g \boldsymbol{e}_{\boldsymbol{z}} \qquad (10)$$

$$\frac{\partial \alpha_i}{\partial \alpha_i} + \boldsymbol{U} \cdot \nabla \boldsymbol{U} = 0 \qquad (11)$$

$$\frac{\partial \alpha_i}{\partial t} + \boldsymbol{U} \cdot \boldsymbol{\nabla} \alpha_i = 0 \quad \text{with} \quad i \in \{2, 3\}$$
(11)

Here the density ρ and the dynamic viscosity η in each calculation cell is estimated according to equation 9. The turbulence of the flow is accounted for by introducing into equation 10 the turbulent dynamic viscosity η_t . Among the multiple models which are at disposal for the calculation of the latter, we chose the k- ϵ realizable turbulence model [32] for its stability. The term F_e corresponds to the EM force calculated in COMSOL and is given by equation 8. The second force F_s interprets the pressure jump originating across the interface between the fluids i and j because of surface tensions between them $\gamma_{i/j}$. It is determined using the curvature κ of the interface:

$$\boldsymbol{F}_{s,i/j} = 2\gamma_{i/j} \frac{\alpha_i \rho_i \kappa_i \boldsymbol{\nabla} \alpha_j + \alpha_j \rho_j \kappa_j \boldsymbol{\nabla} \alpha_i}{\rho_i + \rho_j}$$
(12)

with
$$\kappa_i = \nabla \cdot \frac{\nabla \alpha_i}{|\nabla \alpha_i|}$$
(13)

The VOF formulation is supposed to be conservative and this holds for the two phases. However, in the problem under study, a volume deviation may occur during the calculations because of the cells containing a fraction of the three fluids. Indeed, the VOF algorithm requires a reconstruction of the interface to further calculate the respective mass fluxes for each phase at the cell faces. Yet, since this reconstruction is done separately for each secondary phase, some interfaces can overlap in these cells and errors may occur as illustrated in figure 3.

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One of the ways to overcome this problem is to use small cell mesh size to reduce the quantity of cells containing three phases, but the duration of the



Figure 3: Illustration of the possible error of interface reconstruction in 3-phase Volume Of Fluid (VOF) approach (right), compared to the real interfaces (left).

calculation will highly increase. For the presented study, the domain is decomposed in square mesh cells of 1.25 mm of side and results of the calculations obtained with a final volume deviation of less than 1% were accepted. This value produces an average error of \pm 1.5 mm for the height of the metal surface, corresponding to approximately 1% of the typical h_m .

4. Results and discussion

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For this study, we chose to fix the total Joule power in the metallic phase Q_m (equation 14) and to adapt the current intensity in the inductor in order to obtain the aimed value Q_m^* . This strategy means that the glass/metal system is approximately at the same thermal conditions for simulations performed with the same Q_m^* , and therefore, we can consider a similar viscosity of the glass.

$$Q_m = \frac{\pi}{\sigma_m} \int_0^Z \int_0^R r \, |\mathbf{j}|^2 \, dr \, dz \tag{14}$$

For a given position of the metal, Q_m is proportional to I^2 and changes with the displacement of the free surface of metal. To obtain a desired power Q_m^* , the current intensity in the inductor is therefore corrected during the calculation as:

$$I_{corr} = \sqrt{\frac{Q_m^*}{Q_m}} I \tag{15}$$

4.1. Shape of the interfaces

Figure 4 shows the calculated height of the metallic dome for several values of the total mass of the glass charged in the crucible and a fixed value of $Q_m^* =$ 35 kW and f = 40 Hz, which gives a value of B_0 around 0.13 T, varying with the shape of the dome. The values of h_m and h_g calculated by the numerical model are relatively close to the estimation made with the analytical formula (see section 2), the largest errors come from the fact that B_0 is not exactly constant

- on the numerical model due to the variation of the shape of the load (higher for cases with lower M_g and lower for cases where the metal is covered). As indicated above, starting from $M_{g, cr} = 35$ kg the dome's height in the analytical model is at its maximal value $h_{m, max} = 152$ mm and the surface is completely covered with glass. Yet, in the simulations the free surface of the glass is higher than the top of the metallic dome but does not cover it, as shown with the diagrams in figure 4. This phenomenon is due to the entrainment of the glass
 - by the metal, pushing it downwards and preventing the covering of the dome. Due to this phenomenon, the critical mass of the glass to cover the dome is 52 kg instead of the 35 kg estimated analytically.



Figure 4: Height of the metallic dome and the glass as a function of the mass of glass in the crucible for $Q_m^* = 35 \,\mathrm{kW}$ and $f = 40 \,\mathrm{Hz}$ giving $B_0 \approx 0.13 \,\mathrm{T}$. Solid and dashed lines correspond to the analytical solutions of equations 3 and 4, the markers are for the numerical results. The vertical lines indicate the transition between the different surface geometries on the numerical model, as shown schematically in inserts.

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In order to validate the shape of the interfaces obtained with the numerical

model, it is necessary to measure these shapes on the prototype of the process. The use of the contact probe method [33–35] is not feasible in this case due to the high temperature of the melt, and neither are the methods based on light projection [17, 20], due to the presence of the opaque glass phase above the

- ²³⁵ metal. Also, measurements based on the melting of a material in the liquids [11, 28] are ineffective to measure the shape of the surface of the metal, because the materials will melt in the glass. Therefore, the shapes were measured by manually immersing a metallic rake in the liquids. The rake is made of stainless steel because of its melting point (≈ 1500 °C) which is higher than the temperature of the melt. Due to instantaneous cooling, the liquid metal or glass
- solidifies on the rake's fingers leaving traces. The latter allowed us to estimate the positions of the fluid interfaces (figure 5). Due to the low frequency of the electromagnetic field, the perturbations of the magnetic field in the air and the glass provoked by the rake are low since δ_b (equation 1) for the stainless steel

is large compared to the diameter of the fingers. The use of stainless steel also prevents the modifications of the magnetic flux inside the metal because the electrical conductivity of both materials are very close. Furthermore, even if the insertion of the rake modifies the flow of the liquids near the fingers, the measured shape must not be affected since the dynamic pressure is supposed to be negligible for the deformation of the surface of the metal. In figure 6, the

comparison between the results of the numerical model and the measurements made with the rake for $M_g = 25$ kg is shown.

The mean absolute error on the metal height is 6.5 mm which is relatively low compared to $h_m \approx 160 \text{ mm} \ (\approx 4\%)$. The largest errors are localized at the interface between the metal and the glass, because of the large dispersion of measurements in this area. As noticed above, the free surface of the glass obtained with the numerical model is not flat due to the flow of this material. The local decrease of the fluid velocity provoked by the insertion of the rake may be the reason why this phenomenon is not observed on the measurements.



Figure 5: Rake after a measure of the dome shape on the prototype for $M_g=25\,{\rm kg},~f=40\,{\rm Hz},~Q_m^*pprox 60\,{\rm kW}.$

²⁶⁰ 4.2. Operating parameters affecting prototype performance

The data given in the section Shape of the interfaces were obtained for a fixed Joule power dissipated in the metallic phase Q_m^* . Since $Q_m^* \propto I^2$, $B \propto I$, and $h_m \propto B^2$ the height of the dome is supposed to increase linearly with the Joule power in the metal, and the numerical model confirms this estimation.

The effect of the frequency on the deformation of the metallic surfaces was studied by Bojarevics *et al.* [24] who pointed out that the deformation of the material should decrease when the frequency increase for a given Q_m^* . This is confirmed with our studies, although these variations were found small compared to the total deformation. Thus, for a frequency variation between 20 and 60 Hz, the variation of h_m was found about 12 mm.

However, the variation of the frequency modifies the repartition of the Joule power in the set-up and its efficiency. Indeed, Joule power dissipated in the metallic shell Q_{shell} increases with higher frequencies due to the increase of current density originating from the reduction of δ_B according to equation 1. On the other hand, the use of lower frequencies increases the electrical current in the inductor in order to maintain a required Q_m^* in the molten metal. Due to the electrical resistance of this part, the increase in I produces more heat losses



Figure 6: Comparison of the shape of the surfaces of the liquids between a measurement on the prototype and the numerical model for $M_g = 25 \text{ kg}$, f = 40 Hz, $Q_m^* \approx 60 \text{ kW}$.

in the inductor $Q_{inductor}$ (figure 7). For further estimations, the resistance of the inductor coils was extracted from the data of the cooling flux and the electrical current measured in the prototype. Using it, a maximal system efficiency E was calculated for a frequency range of 20 to 80 Hz for the mass of the glass charge 25 kg (equation 16). The obtained results show that near 50 Hz, the dissipation of the Joule power is equilibrated between the metallic shell and the inductor and the efficiency has its maximal value.

$$E = \frac{Q_m}{Q_m + Q_{shell} + Q_{inductor}} \tag{16}$$

The same tendency is observed for other glass charges. Moreover, the efficiency of the system increases with the increase of M_g , as well as with the decrease of Q_m^* for a fixed frequency. This is due to the variation of the dome's shape that brings the metal closer to the inductor, increasing the coupling.

275 4.3. Liquids flow

The figure 8 presents the vector field corresponding to the rotational \mathbf{F}_R and irrotational \mathbf{F}_{IR} parts of the Lorentz force density, given by equations 17-18, for two different frequencies and $Q_m^* = 35 \text{ kW}$, and $M_g = 50 \text{ kg}$.



Figure 7: Power losses in the inductor (\blacksquare), the metallic shell of the container (×), and efficiency of the process as a function of the frequency for $Q_m^* = 35 \text{ kW}$ and 25 kg of glass (with linear interpolation).

$$\boldsymbol{F}_{IR} = -\boldsymbol{\nabla} \frac{\boldsymbol{B}^2}{2\mu_0} \tag{17}$$

$$\boldsymbol{F}_{R} = \frac{1}{\mu_{0}} \boldsymbol{B} \cdot \boldsymbol{\nabla} \boldsymbol{B}$$
(18)

Because δ_B is of order of several centimeters, the penetration of both components of the Lorentz forces is rather deep. Also, F_{IR} is not completely perpendicular to the surface of the metal, and affects the motion of this material. Similarly, F_R is not tangential to the surface, and introduces additional pressure impacting the shape of the surface. With the increase of the frequency, the penetration of both components diminishes and the ratio $|F_{IR}|/|F_R|$ increases, especially at the surface of the metal.

The flow of the metal is composed of two vortices (figure 9), which is a type of pattern usually observed in metals stirred electromagnetically. Rather often, these vortices are of comparable size, yet in the present case the bottom vortex is very small and rotates with a higher speed compared to the larger vortex due to the stronger Lorentz force near the inductor. The larger vortex involves the metal from the dome's apex till the bottom of the crucible and makes the



Figure 8: Distribution of the rotational (\mathbf{F}_R) and the irrotational (\mathbf{F}_{IR}) parts of the Lorentz force density with two operating frequencies for $Q_m^* = 35 \text{ kW}$ and $M_g = 50 \text{ kg}$.

surface of the melt move. Two zones with nearly zero velocity exist in the melt where the two vortices meet near the metal surface and diverge at the bottom. Furthermore, due to the viscous interaction with the metal, the glass is also put in motion and presents one vortex, aligned with the largest one in the metal.

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Figure 9: Velocity field in the liquids for two glass fillings ($Q_m^* = 35 \,\mathrm{kW}, \, f = 40 \,\mathrm{Hz}$).

Thereafter, the volume averaged value of any variable ξ in the fluid *i* is

calculated as:

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$$\langle \xi_i \rangle = \frac{2\pi\rho_i}{M_i} \int_0^Z \int_0^R r\alpha_i \xi \, dr \, dz \tag{19}$$

For $Q_m = 35 \,\mathrm{kW}$ the volume averaged velocity in the metal $\langle U_m \rangle$ is about 0.17 m/s and the maximal velocity is about 0.58 m/s. These values are close to the value estimated velocity of the metal using Alfvén velocity. The velocity magnitude of both liquids intensifies with a higher Joule power dissipated in the metal. Compared to increases in the frequency and glass mass, this phenomenon has the higher influence on the velocities.

The velocity of the glass at its free surface varies from zero to 10 or 15 cm/s depending on the mass of glass introduced in the crucible. The order of magnitude for the glass velocity can be verified using optical observations on the prototype. They revealed that air bubbles appear somewhere inside the glass and are transported to the free surface where they disappear. Beneath the surface of the glass, these bubbles appear as dark spots. Their motion was tracked by video recordings which provided an estimation for the glass velocity about

³¹⁰ 10 cm/s, i.e. the same order of magnitude as in the numerical results. The optical observations also confirm the existence of the stagnation zones on the surface of the glass and measurements give a lower temperature in this zone than at the rest of the surface. The solidification of the glass free surface which was observed during some experiments may have been triggered by this phenomenon.

315 4.3.1. Air entrainment

An interesting phenomenon observed in simulations is the air entrainment between the glass and the metal at the point of contact of the three fluids. The captured air follows the interface between the metal and the glass and is transformed into bubbles at the point where the two large vortices in the ³²⁰ metal and in the glass diverge (figure 9). Some bubbles rise toward the free surface through the glass, whereas, a smaller fraction of the air is dragged to the surface through the bulk metal. Numerical modeling shows also that the bubbles contribute to the stirring of the glass when rising up through the latter, yet, their exact contribution is difficult to quantify.

- One can suppose that this phenomenon is a numerical artifact related to the reconstruction of the interface in the VOF model. To verify this, several simulations with finer meshes were performed and showed that the bubble production decreases, whereas their number increases, *i.e.* the numerical phenomenon persists.
- It is quite complicated to judge at what extent the numerical results represent the real situation regarding bubbles' formation. Indeed, on one hand, the bubbles trapped and entrained by the glass are observed during material processing in the prototype. Yet, on the other hand, the origin of the bubbles in the prototype experiments can also be due to some gas produced by a chemical reaction at the glass-metal interface, which is not taken into consideration in the present numerical model.

It should be noted that the air entrainment by an inclined jet falling into a liquid pool is a well-known hydraulic phenomenon which may be observed at a large scale in nature (waterfalls, waves, *etc.*) as well as at a small scale

- in the laboratory experiments with water [36]. Turbulent vortices inside the jet are at the origin of this phenomenon by causing small perturbations at the surface of the flow. If the velocity of the liquid in the pool is lower than that of the jet, its surface cannot adapt to the disturbances of the jet. Consequently, some air enters at the inception point. One can easily see that the experimental
- and numerical conditions in the process qualitatively reproduce such physical situation. Indeed, the flow of the metallic phase is turbulent whereas the glass flow remains laminar, and, due to the formation of the dome, the metals arrives to the glass pool similar to a jet. Thus, the bubbles can form according to the mechanism explained above. However, the analytical analysis used elsewhere
- [36] cannot be easily transposed to the case of three different fluids involved in the process. It is foreseen to study the observed phenomena in details in further simulations. It should be noted also that it would not be possible to compare experimental and numerical results related to the bubbles and their effects if simulations are performed in 2D axisymmetric geometry since, in this case, the
- ³⁵⁵ surface of each modeled bubble would be a toroidal volume instead of a spherical

one. Consequently, such studies should be performed using a 3D model.

4.3.2. Effect of the glass charge

It could be expected that a higher filling of the glass produces lower overall velocity of the melt. Yet, the average turbulent viscosity of the metal is lower for cases with more glass, approximately 10% lower between 25 kg and 50 kg of glass (figure 10). This phenomenon is probably due to the damping of the turbulence provoked by the glass at the glass-metal interface, because we notice that the Lorentz forces in the metal does not vary significantly with the change in the shape of this material. The turbulent kinetic energy (k) of the metal is 5.5% lower in the bulk and about 12% lower at the surface, comparing the cases with 50 kg of glass with the cases involving 25 kg. This phenomenon produces

an increase in the average velocity of this material (figure 10).



Figure 10: Volume averaged velocity $\langle U_m \rangle$ and turbulent viscosity in the metal $\langle \eta_{t,m} \rangle$, as a function of the mass of glass in the crucible $(Q_m^* = 35 \text{ kW}, f = 40 \text{ Hz}).$

This intensification of the metal velocity increases slightly the velocity of the glass $\langle U_g \rangle$ up to a certain mass after which the viscous losses becomes predominant and the velocity decreases (figure 11).

4.3.3. Effect of the frequency

By imposing the Joule heating in the metal only and not in the whole load, it is possible to see the effect of the frequency on the liquids, independently of



Figure 11: Volume averaged velocity of the glass, as a function of the mass of this material in the melter ($Q_m^* = 35 \,\text{kW}, f = 40 \,\text{Hz}$).

the damping caused by the metallic shell. For the same Q_m^* , the magnitude of the average velocity of the metal is slightly lower when using a higher frequency. However, when the frequency is increased, the magnitude near the surface and near the side of the crucible is magnified, due to concentration of Lorentz forces in these areas (figure 12). The intensification of the velocity at the glass-metal interface also induces a higher velocity of the glass.



Figure 12: Average velocity of the metal in the bulk and at the surface along with volume average of glass velocity, as a function of the frequency $(Q_m^* = 35 \text{ kW}, M_g = 25 \text{ kg})$.

380 5. Conclusion

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Interesting phenomena were observed during the numerical study of the stirring of melted metal and glass in an in-can melter under low frequency AC induction. A simple analytical model proposed for the description of the shape of the surface of the metal phase underestimates the critical mass of the glass before covering the metal, due to dynamic effects. Also, we suppose that the effect of the rotational Lorentz forces term also affects the shape of this surface.

To account for the most important effects, a numerical model of the process has been developed. The calculation is achieved by an iterative coupling between COMSOL Multiphysics and ANSYS Fluent solving harmonic magnetic ³⁹⁰ potential and turbulent three phase flow (VOF) respectively. The calculations of the shape of the surface of the metal were validated with measurements on a prototype of the process using a metallic rake. Using recorded videos of the free surface of the melt, the average velocity of the glass was estimated and compared with the one obtained with simulations.

The results of the numerical model show that the height of the glass can be higher than the top of the metal dome without covering it, explaining the difference for the critical glass charge obtained with the analytical approach.

A parametric study was conducted to examine the influence of the power injected in the metal, the quantity of the glass in the crucible, and the frequency on the stirring of the liquids. An increase in the amount of glass introduced results in a larger volume averaged velocity of the metal, provoked by the damping of the turbulence. Regarding the frequency, it is shown that it has little impact on the stirring and can therefore be taken to an optimal system efficiency (\approx 50 Hz).

The results also pointed out an eventual trigger for the solidification of the free surface of the glass: a dead zone near the crucible and this surface. Further investigations of this phenomenon must be performed by adding heat transfer in the model.

It was found that the air is entrained at the triple line, yet it is not clear

⁴¹⁰ if this is a numerical artifact or a physical phenomenon. Some arguments for both points were proposed. For further study of the formation of air bubbles in the liquids, the geometry of the model can be replaced by a 3D one to obtain physically accurate bubble shape, moreover, the algorithm for the reconstruction of the interface should probably be changed.

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