Numerical simulation of surface deformations in a three-fluid process stirred by low frequency magnetic field

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Abstract
A process allowing the treatment of solid low-activity nuclear wastes (metals and organic matter) is currently being developed by the CEA (French Alternative Energies and Atomic Energy Commission). During elaboration part of the process, some metal covered by conditioning glass is melted and stirred by low-frequency magnetic field. The pressure originating from Lorentz forces creates a steep dome on the surface of the metal, which can emerge from the glass. It is important to know the position of the interfaces between the fluids to determine heat and momentum transfers through them in order to get better insight for further development of the process. The goal of the presented numerical study is to obtain the positions of the three interfaces (glass-air, glass-metal and metal-air). It consists of a coupling between two commercial software: COMSOL Multiphysics to calculate magnetic field, and ANSYS Fluent for the three-phase flow (VOF). The results obtained have been validated by some measurements on the prototype.

Key words: numerical simulation, three-phase, electromagnetic stirring, low frequency, nuclear waste

Introduction

Each year, nuclear electricity production generates a large quantity of radioactive wastes. The larger volumes come from technological wastes (pumps, filters…) contaminated during the transformations and the handling of nuclear combustibles. Generally, these wastes are sorted in order to be treated in different ways: organic matter is incinerated then incorporated in melted glass, and metallic parts are often compressed and cast in concrete. The packages thus produced are then stored in underground sites in order to prevent the contamination of the environment [1]. The CEA is currently developing a process allowing the treatment of these two types of waste simultaneously. In the fusion part of this process, two immiscible materials are melted and stirred by low frequency electromagnetic induction: some glass in which are incorporated ashes of organic wastes, and the metal contained in the wastes.
The number of physical phenomena involved and the complexity of their coupling makes the operating of the prototype difficult. Hence, a numerical study is carried out to improve the understanding of these phenomena.
The major difficulty encountered when modelling this type of process is the representation of the deformation of the liquid surfaces by the electromagnetic forces. This phenomenon impacts directly the others physical phenomena like the fluid flow and heat transfers, and also the performance of the process by modifying the power repartition between the conductive elements. In this work, after a brief presentation of the process configuration and the physical phenomena considered, the numerical model developed to calculate the shape of the interfaces is presented and the results are compared with measurements on the actual prototype.

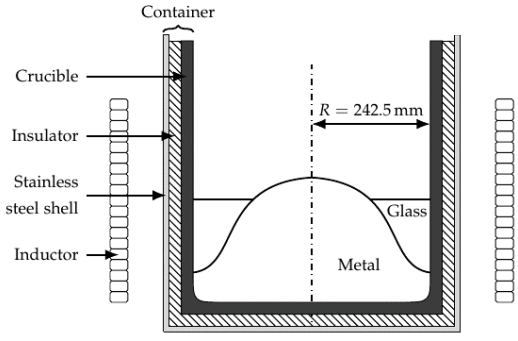

Fig. 1: Schematic of the process.

	Viscosity η (Pa.s)	Density ρ (kg/m³)	Electrical conductivity σ (S/m)
Glass	1.3	2500	20
Metal	6×10^{-3}	7000	10^6
Air	5×10^{-5}	1	0

Tab. 1: Physical properties of the fluids used in the numerical model.

Process configuration

The studied part of the process consists in a container composed of a ceramic crucible of internal radius R, some insulator and a stainless steel shell (Fig. 1). This container holds the liquids during the treatment of the wastes and is also the first barrier between radionuclides and the environment for the storage. The whole package is placed in a helical inductor powered by an AC generator producing a current intensity I in the range 2800−4200A and in the frequency range 30−50Hz. Tab. 1 regroups the physical properties of the liquids taken for this numerical study, estimated from the materials used on the prototype. The properties of the metal, composed of stainless steel and copper, are estimated using the mass ratio of these two components. Concerning the glass, it consists of a conditioning glass developed specifically for the process. The values are taken at 1350°C, corresponding to the average temperature measured during the operating of the prototype.

Hypothesis

As in many processes of this type, four principal physical phenomena are coupled during the operating of the process: electromagnetism, fluid flow, heat transfer, and the deformation of the interfaces between the fluids. Some of these phenomena can be neglected in the numerical model when focusing exclusively on the shape of the surfaces of the liquids. First of all, the geometry is considered to be 2D axisymmetrical (r, θ, z) because the helical aspect of the inductor is slight, and it can be assimilated to a stack of concentric rings. Second, due to the high thermal conductivity of the metal, the temperature in this phase is homogenous. Furthermore, measurements in the melted glass have shown that its temperature is also uniform at the exception of the area near the free surface, due to strong radiative transfers. It has been chosen to neglect this effect for this study, therefore, thermal gradients and their influence on the physical properties of the liquids are not modeled. Further approximations are obtained using dimension theory. The deformation of the surface of the liquids is defined by the pressure equilibrium at the interfaces between the fluids as:

$$P_{magnetic} + P_{dynamic} + P_{static} + P_{surface\ tension} = constant$$

$$\frac{B_t^2}{2\mu_0} + \frac{\rho U_t^2}{2} + \rho g z + \gamma K_c = C$$

Where B_t and U_t are components of the magnetic flux and fluid velocity tangential to the surface of the metal, respectively, μ_0 the vacuum permeability, g the standard gravity acceleration, γ the surface tension between the fluids, and K_C the mean curvature of the surface (sum of principal curvatures).

An order of magnitude for the magnetic flux (B_0) can be estimated using Biot-Savart law applied to a point at the center of a coil. In the functioning range of the generator $B_0 \sim 10^{-1}$ T, giving a magnetic pressure of approximately 10^3 Pa.

A characteristic velocity of the liquid metal U_0 can be determined using Alfvén velocity along with experimental results from Fautrelle et al. [2]:

$$U_0 = \frac{0.2\ B_0}{\sqrt{\mu_0 \rho}}$$

This equation gives estimates the order of magnitude of the velocity to 10^{-1} m/s, leading to $P_{dynamic} \sim 10^1$ Pa which is negligible in comparison with the magnetic pressure. This characteristic velocity also gives a magnetic Reynolds number $Rm = R\mu_0 U_0 \sigma$ smaller than unity, so the advection of the magnetic field by the metal flow is negligible.

For this study, surface tension effects are also neglected because the surfaces are wide (few decimeters) compared to the curvature radius necessary to obtain a significant pressure (few millimeters).

In this frequency range, the electrical conductivity of the glass makes it transparent to magnetic field. With the assumptions made above, only static pressure determines the shape of the free surface of this material and it is therefore expected to be flat ($\rho g z = constant$).

Numerical model

The numerical model developed to calculate the shape of the interfaces between the fluids consists in a coupling between two commercial software. Electromagnetic induction is modeled in COMSOL Multiphysics (finite element) using harmonic magnetic potential equation. The glass being unaffected by the magnetic field, only the metallic phase is represented in this model. Incompressible transient Navier-Stokes equations are modeled with ANSYS Fluent based on finite volume. Volume of fluid (VOF) method is used to determine the deformations of the interfaces of the liquids [3-5]. The principle of this method is to represent materials by their volume fractions α in each mesh cell, allowing to solve a single set of Navier-Stokes equations for all the phases. The physical properties of the mixture are proportional to α, e.g. $\rho = \sum \alpha_i \rho_i$, and a continuity equation is solved for the volume fractions in order to track the interfaces.

Since the shape of the surfaces is supposed to be independent from the fluid flow, the viscosity of the fluids has been increased artificially in the model to reduce the time necessary to reach the stabilization of the surface and avoid using a turbulence model. The viscosity has been taken to 60 Pa.s for the metal and 10^{-2} Pa.s for the air.
For each time step, the two programs calculate their part simultaneously, and exchange metal volume fraction and time averaged Lorentz force density at the end of the step. This allows to optimize transfer time between the programs by realizing data transfer and the interpolations between the meshes on COMSOL's side because the computing time is shorter than in Fluent. With this parallel operating, there is always a lag between the two programs: the calculation of Lorentz forces uses the position of the metal surface from previous time step and not current time step, and it is the same for the calculation of the position with the forces. Therefore, the time step has been chosen to 5 ms to have only little variations between two consecutive steps and thus ensure stability.
At the beginning of the calculation the current intensity in the inductor is increased from zero to the aimed value I_s to avoid oscillations of the surfaces caused by the quasi instantaneous deformation in response to the magnetic field. The height of the metal surface being function of the square of the magnetic field, which is itself proportional to the current in the inductor, the intensity is increased as the square root of the time to produce a smooth rising of the surface:

$$I = I_s \cdot \begin{cases} \sqrt{t/t_r} & \text{if } t < t_r \\ 1 & \text{otherwise} \end{cases} \quad (1)$$

The duration of the ramp t_r was chosen to 4s to completely avoid oscillations of the metal surface during the calculation in most cases (see Fig. 2). In addition to the convergence of hydrodynamic equations estimated with the residuals calculated by Fluent at each iteration, another ,convergence C criterion has been implemented to monitor the stabilization of the metal surface and to stop the calculations. It represents the average rate of variation of the metal volume fraction repartition between iteration $N-1$ and N:

$$C_N = \frac{\sum|\alpha_N - \alpha_{N-1}|}{Nb\ cells\ \cdot\ \Delta t} \quad (2)$$

Large oscillations on the convergence plot (Fig. 3) corresponds to global movements of the metal surface, and the little ones are due to the small fluctuations created by the glass moving off of (slipping down) it. The square root case seems to converge as fast as the case with no ramp but allows to prevent the metallic phase to possibly reach the top of the computational domain.

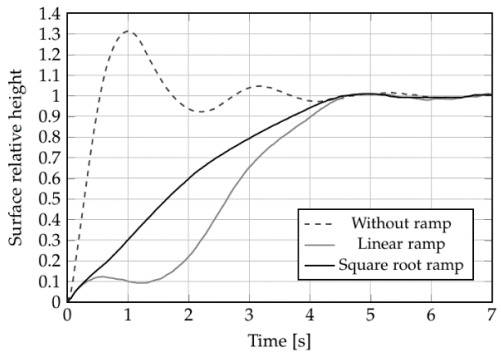

Fig. 2: Total height of the metal surface as a function of the ramp on the intensity at the beginning of the calculation.

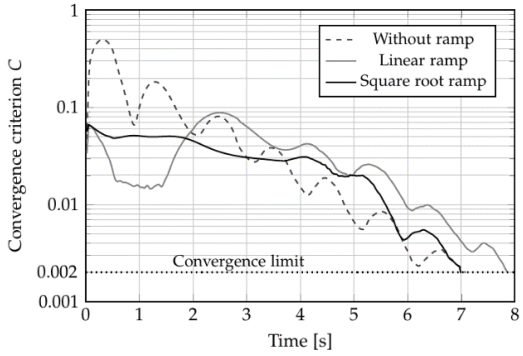

Fig. 3: Evolution of the convergence criterion during the calculation (Equation 2).

Comparison with experimental results
The shape of the metal surface was measured on the prototype by manually immersing a metallic rake in the liquids during three different experiments. The cooling provoked by the rake solidifies a layer of liquid on its fingers and it is then possible to measure the height of the marks left. It is impossible to know if the rake reached the bottom of the crucible, therefore, the measurement is corrected to obtain the same maximal height as the model, and the comparison is made on the relative height only.
The results of the second measurement are shown in Fig. 4. The average error on the height is approximately 6.5 mm for this case, and the average relative error (absolute error divided by the height of the deformation) are about 5.9 %,

4 %, and 3.8 % for the three measurements respectively. It has been observed that the maximal errors are located at the interface glass-metal, and probably comes from the large dispersion of the measurements in this area.
The numerical model has also been validated using experimental results from M. Kirpo Ph.D [6]. This case contains one liquid only (Wood's metal) but the measurements are much more precise than those with the rake on the prototype. The results of the numerical model are very close to the experimental values, the error close to the crucible may be explained by the approximations made on some parameters like the thickness of the crucible (Fig. 5). For this case, the average absolute error is about 0.65 mm leading to a relative error of 3.6 %.

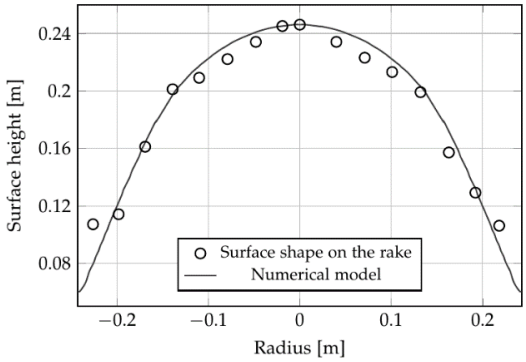

Fig. 4: Comparison between the numerical model and a measurement on the prototype.

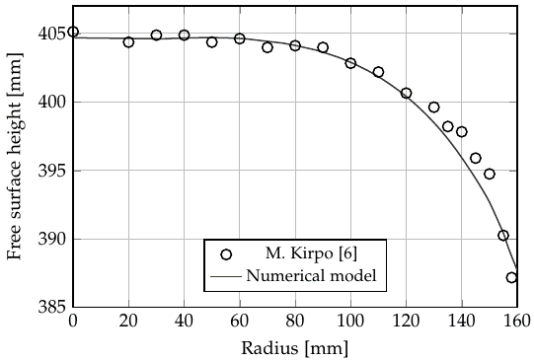

Fig. 5: Comparison between the numerical model and a case from the literature [6]

Conclusion

A model allowing the calculation of the position of the interfaces between the fluids in a process containing melted metal and glass under alternating magnetic field has been developed. It consists of a coupling between COMSOL Multiphysics – solving harmonic magnetic potential – and ANSYS Fluent – for the three phase flow using VOF method. The shape of the surfaces has been assumed to depend only on the magnetic and the static pressure, therefore some assumptions were made, including the artificial increasing of the fluids viscosity. A convergence criterion has been set up to end the calculation, based on the movement of the metal phase. The model has been validated with some measurements on the prototype of the process, and the results were found precise concerning the shape of the metal surface (relative error of approximately 4 %). Concerning the glass, comparisons are difficult due to the formation of air bubbles in this material. To characterize this phenomenon, a model taking turbulence into account, real viscosities of the fluid, and with a 3D geometry will be developed.

Acknowledgments

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