

Flux - Fluent Iterative Coupling for a Full 3D Simulation of Molten Glass Heated by Direct Induction.

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The aim of this study is to perform numerical simulation of a vitrification process of nuclear waste produced by the French atomic commission over a period of 35 years. This process uses direct induction technology in a cold crucible to melt specific glass at high temperature (~1250°C). The walls of the crucible are cooled by internal water circulation which protects them from corrosion and allows higher molten glass temperatures. Additionally, a mechanical stirrer and an air bubbling system promote good homogeneity of the melt. Consequently, the lifetime of the process as the incorporation rate of the nuclear waste is increased.

Numerical simulation of this process requires a coupled approach of the different phenomena: induction, thermal and hydrodynamic. Indeed, those three phenomena are closely coupled because of the temperature dependence of the glass properties. For example, the hotter the molten glass, the higher the electrical conductivity.

electrical conductivity as a function of temperature. The crucible as well the inductor are not modelled, but are approximated by a current sheet around the glass. In this coil, an alternative current ($I_{eff} = 1500$ A and 280 kHz) is imposed. Owing to the high value of the frequency, a quasi-steady approximation is made. Different formulations for induction equations are available. The A-V formulation (magnetic vector potential – electrical scalar potential) gives best result in a material with a high electrical conductivity gradient. The coil is not meshed, so a reduced scalar potential formulation is used. The domain is discretised with approximately 200,000 first-order elements.

and file data transfers. Each software interpolates the chosen field on the computing nodes of the other software. A C-shell script supervises the two softwares and launches them when the other is finished.

The general algorithm is shown in figure 3. In an initial step, each software reads the computing nodes of the other software and stores them in its memory. For Flux, this solution is available since version 10.2. Fluent mesh is read as a 'Support_Multipoint' on which Flux will compute Joule power density values. On the other hand, specific 'user-defined functions' (UDF) have been developed to allow Fluent to read Flux nodes in a file, to localize them in its mesh and to keep the link in memory. Then, when Fluent computation is over, it does a first-order interpolation of the temperature value on Flux nodes using the temperature and the gradient of temperature values of the cell centre. All these UDFs are compatible with parallel processing which allows faster hydrodynamic computation. Thanks to these pre-localizations, transfers time are negligible compared with convergence times of Flux or Fluent. Moreover, this coupling performs accurate interpolation between the two computational grids, so very small precision losses are noted. Another issue is to determine the appropriate number of iterations between the two softwares. Unstationary resolution is used by Fluent. Flux updates the repartition of Joule power losses every 20 physical seconds. This time has been chosen as it is less than the diffusion and convection times in the glass bath, at around 1000s.

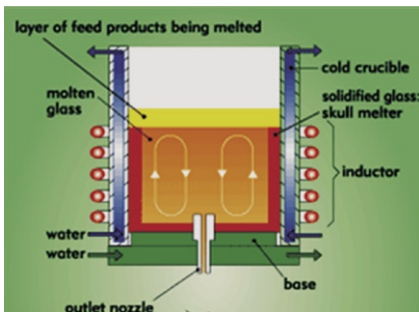


Fig. 1: Overview of the vitrification process.

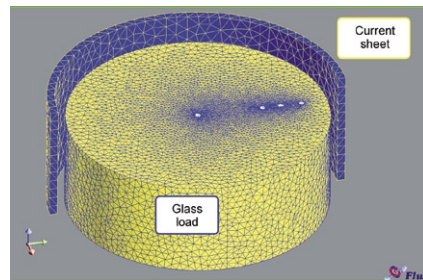


Fig. 2: Flux mesh.

How to couple Flux with Fluent?

The main issue is to couple a finite element and a volume-finite software. Moreover, mesh refinement requirements are different for induction and hydrodynamic phenomena. Consequently, using a single mesh is not possible and data transfers between the two meshes are necessary. This coupling is based on interpolations

Numerical model

Fluent® software solves the Navier-Stokes and thermal equations on a 1.5 million element grid. The flow is assumed to be laminar due to the high viscosity of the glass. A source term is added to the thermal equation corresponding to the Joule power density which is a function of the induced current computed by Flux. Convection is driven by two phenomena: buoyancy and Marangoni convection corresponding to the variation with temperature of density and surface tension respectively. Laplace forces are negligible because of the high density and high viscosity of the glass. Flux® commercial software is used to solve induction equations with

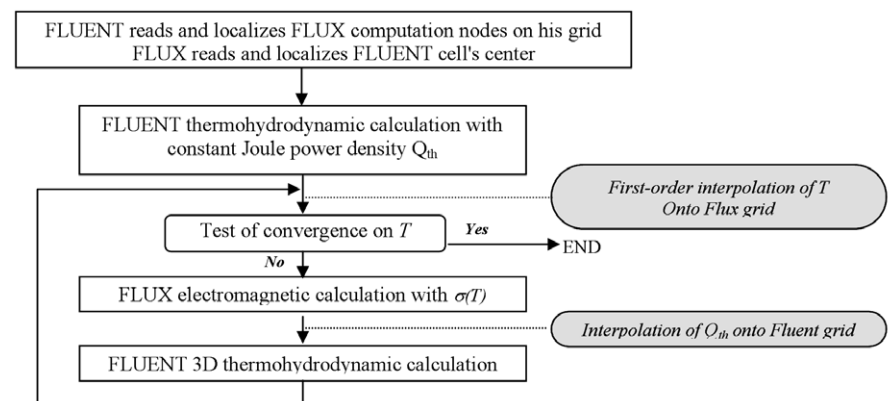


Fig. 3: Iterative algorithm for the Flux-Fluent coupling.

(see continued on page 9)

Flux - Fluent Iterative Coupling for a Full 3D Simulation... (continued)

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Application

Coupling is used to model the glass bath heated by induction. The first result is that the maximum Joule power density is located in the hot parts of the bath which have better electrical conductivity. But the hotter the molten glass, the faster it moves. This mechanism leads to an unstable flow configuration showing Bénard-Marangoni cells at the free surface. (cf. fig. 4). This instability is fully time-dependent, the number of convection cell numbers oscillating between 5 and

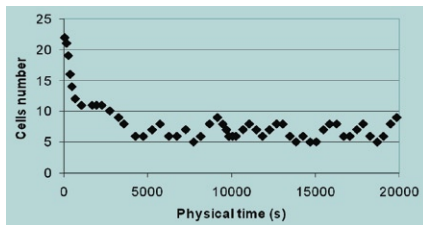


Fig. 5: Time evolution of the number of convection cells.

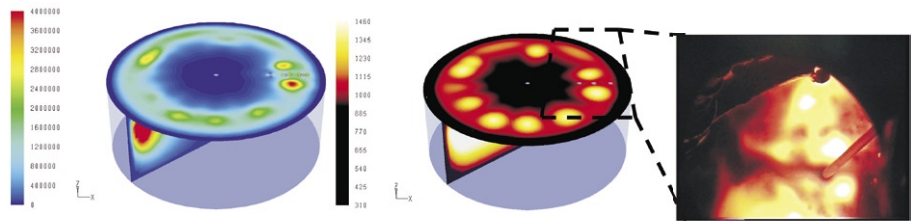


Fig. 4: Numerical Joule power density isocontours (left), temperature isocontours (middle) at the free surface and in a crossing vertical plane. Scales are respectively $[0;4.106]W.m^{-3}$ and $[310;1450]K$. Experimental view of the free surface (right).

9 (cf. fig. 5).

These instabilities have been experimentally observed (cf. fig. 4). Wave numbers and sizes are reasonably compatible with the experimental ones. Former results using a simplified (axisymmetric) induction model lead to stationary glass flows.

Conclusion and prospects

A home-made iterative coupling between Flux and Fluent was

performed.

Induction of molten glass is fully 3D-modeled. The concentration of Joule power in the hottest zones of the glass has an influence on flow configuration. Unstable flow was found which has never been numerically described before.

Future work will use the existing 64bits version of Flux to model more complex geometry, including the complete inductor or the cold crucible.

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