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Numerical modelling of natural convection in molten glass heated by induction

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Abstract

A new vitrification process based on a cold crucible heated by direct induction has been developed by CEA. This process is characterized by the cooling of all the walls and by currents directly induced inside the molten glass. This paper presents a global modelling of phenomena which take place in vitrification in a cold crucible. Electromagnetic, thermal and hydrodynamic phenomena are modelled within the molten glass. The thermohydrodynamic aspects are solved by FLUENT software (distributed by Fluent France) and the electromagnetic aspects by OPHELIE (EPM program based on integral methods). The numerical studies are validated using experimental results obtained from pilot vitrification facilities.

Keywords: Coupled modelling; Electromagnetism; Thermohydrodynamics; Thermal convection; Vitrification

1. Introduction

Since the late 1950s, many research and development programs have focused on the problem of nuclear waste reprocessing and containment. Vitrification has shown its capability for safe long-term conditioning of high-level radioactive waste. This process consists of incorporating the ultimate waste in molten glass. However, the continuous vitrification process used by Cogema at La Hague in France is not suitable to meet new needs, including the vitrification of other types of waste and the reduction of waste volumes. Vitrification materials and processes must be adapted to handle waste with higher fuel burnup values and liquid solutions from the reprocessing of legacy fuel. Direct-induction cold-crucible vitrification would appear to offer a possible solution. This technology is under investigation at Marcoule and is intended to replace metal pots in one of the six vitrification lines of the plant at La Hague. The direct-induction cold-crucible process is distinguished by an inductor supplied by a sinusoidal current and by the cooling of all the walls (Fig. 1). For a cold crucible with a 650 mm diameter, the inductor surrounding the crucible is connected to a high-frequency current generator putting out 400 kW at a frequency of 300 kHz. The process is based on the induction of electric currents directly in the glass. The energy dissipated by the induced currents due to the Joule effect melts the glass. The advantages of the cold crucible are mainly related to the formation of a thin layer of solidified glass. This solidified glass forms a "skull melter" that insulates the cold melter walls from the molten glass. Thus, the crucible walls are not corroded by the molten glass and in turn the molten glass is not contaminated. Cold-crucible vitrification greatly extends the service life of the melter, thereby decreasing the production of secondary technological waste.

Numerical modelling is extremely useful in the operation and optimization of the vitrification facility. In fact, it is necessary to understand the phenomena taking place in vitrification in order to control the distribution of thermal gradients and convection zones within the bath. Until now, only a few studies have been devoted to finding numerical solutions to this process. The main difficulty encountered is related to the large thermal variations of the physical properties of the glass, requiring coupling of the electromagnetic, hydrodynamic and thermal aspects. In their study, Servant et al. [1] did not take fluid flow into account and only thermal and electromagnetic phenomena were coupled. Schiff [2,3] modelled all three aspects but electromagnetic modelling neglected border effects. Modelling of the forming process of TV-panels is presented by Op Den Camp and Aume [4] but the glass is not heated by direct induction. A heat flux distribution is used to describe combustion over the glass surface. In the present study, the thermohydrodynamic and

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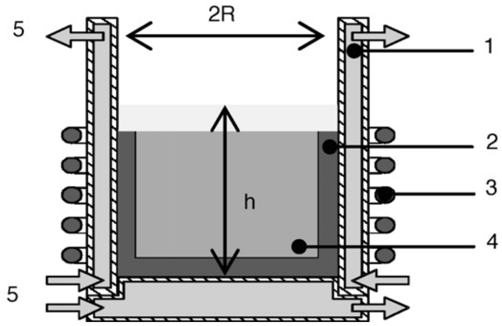

Fig. 1. Cold crucible: 1, water-cooled segment; 2, solidified glass; 3, inductor; 4, molten glass; 5, cooling water; *h* height of the glass bath; *R* radius of the glass bath.

electromagnetic models are coupled and a complete modelling is obtained. In addition, because of the complexity of the vitrification process in a cold crucible and due to the lack of sensors and accurate analysing techniques to measure temperature and velocity field within the glass bath, no quantitative description has been carried out so far. In this paper, the validation of the numerical results using experimental results obtained from pilot vitrification facilities is presented.

2. Mathematical models

2.1. Thermohydrodynamic model

2.1.1. Hypothesis and equations

The thermohydrodynamic aspects are solved only within the glass bath. The Rayleigh number $Ra = g\beta\Delta Th^3/\nu\alpha$ does not exceed 10^5 and the Prandtl number $Pr = \nu/\alpha$ is 10^3. The flow is therefore assumed to be laminar and steady by analogy with flow driven by thermal convection in enclosures. The steady flow hypothesis is discussed in Section 3. The Boussinesq assumption is used to model buoyancy. This model treats density as a constant value in all solved equations, except for the buoyancy term in the momentum equation where ρ is defined by $\rho = \rho_0(1 - \beta(T - T_0))$. This approximation is accurate because changes in actual density are small; specifically, the Boussinesq approximation is valid because $\beta(T - T_0) \ll 1$. All the other physical properties (viscosity, specific heat, electrical and thermal conductivities) are defined by temperature dependence based on a piecewise-linear function. Laplace forces due to induced currents and electromagnetic field in the glass are neglected. The magnitudes of these forces are low compared with the forces generated by thermal convection [5]. The modelled glass show strong absorption, it is almost completely non-transparent even for thin layers. The heat transfer inside the glass is therefore only determined by heat conductivity, the internal radiation in the glass bath is neglected. The fluid is assumed to be Newtonian. Experimental studies show that glass behaves as a Newtonian fluid at high temperature but below the glass transition region its rheological behavior is complex. However, this assumption is not very restrictive because velocities are very small in the cold regions. The equations for laminar steady flow are the continuity (1), the Navier Stokes (2) and thermal energy (3) equations:

$$\vec{\nabla} \cdot \vec{u} = 0, \tag{1}$$

$$\rho_0(\vec{u} \cdot \vec{\nabla})\vec{u} = -\vec{\nabla} p^* + \vec{\nabla} \cdot (\mu \vec{\nabla} \vec{u}) - \rho_0 \beta (T - T_0)\vec{g}, \tag{2}$$

$$\rho_0 \vec{\nabla} \cdot (C_p T \vec{u}) = \vec{\nabla} \cdot (\lambda \vec{\nabla} T) + Q_{\mathrm{th}}, \tag{3}$$

where p^* is defined as $p^* = p + \rho_0 gz$. The source term Q_{th} in the thermal energy equation represents the density of the Joule power. It is calculated by the electromagnetic code according to the relation:

$$Q_{\mathrm{th}} = \frac{|j|^2}{2\sigma}, \tag{4}$$

where $|j|$ denotes the modulus of current density.

2.1.2. Boundary conditions

Concerning thermal boundary conditions, radiative and convective heat transfer is taken into account at the free surface. The heat flux through the free surface is calculated as

$$\varphi = \varepsilon \sigma_{\mathrm{sb}} (T_{\mathrm{s}}^4 - T_{\mathrm{a}}^4) + h_{\mathrm{s}} (T_{\mathrm{s}} - T_{\mathrm{a}}). \tag{5}$$

Heat losses through the walls (crucible and base) are expressed by the following equation:

$$\varphi = h_{\mathrm{w}} (T_{\mathrm{w}} - T_{\mathrm{c}}), \tag{6}$$

Eq. (6) includes the contact resistance between the glass and the walls and the heat exchange between the walls and the cooling water.

The velocity boundary conditions are chosen to correspond to the physical model, i.e. no-slip boundary conditions along solid boundaries and a slip boundary condition on top of the glass bath.

2.1.3. Numerical method

The thermohydrodynamic aspects has been modelled using the FLUENT CFD software, and its accompanying mesh generation software, Gambit. The governing equations are solved sequentially with a finite-volume discretization process. In this segregated solution method each discrete equation is linearized implicitly with respect to that equation's dependent variable. For the convection terms of each equation (momentum and energy) a second-order discretization is used. The diffusion terms are central-differenced and second-order accurate. The interpolation of the pressure terms is preformed by the PREssure STaggering Option (PRESTO) scheme. The semi-implicit method for pressure-linked equations consistent (SIMPLEC) algorithm is used for introducing pressure into the continuity equation [6,7].

2.2. Electromagnetic model

2.2.1. Hypothesis

From Ohm's law and Ampere's law for a non-magnetic medium we have

$$\vec{\nabla} \wedge (\vec{\nabla} \wedge \vec{A}) = \mu_{\mathrm{e}} \vec{j} = -\sigma \mu_{\mathrm{e}} \left(\vec{\nabla} V + \frac{\partial \vec{A}}{\partial t} - \vec{u} \wedge (\vec{\nabla} \wedge \vec{A}) \right) \tag{7}$$