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Numerical modeling of coupled phenomena in a mechanically stirred molten-glass bath heated by induction

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Abstract

A mechanically stirred molten-glass bath heated by direct induction in a cold crucible was numerically modeled. The aim of the study was to develop numerical tools to understand thermal, hydrodynamic and electromagnetic phenomena that occur in the bath. Models and coupling between these phenomena are described. This coupling and the high content of elements in the 3D mesh result in a long calculation time. The study demonstrates how to couple programs to yield the highest degree of accuracy in the shortest calculation time possible. Numerical studies are also used to characterize the fluid dynamic behavior and heat transfer in an industrial-size tank. Classical correlations commonly used to characterize stirrer efficiency and heat transfer for fluids with constant physical properties were adapted for molten glass. The power number N_p and the Nusselt number Nu are used as macroscopic indicators. The results of these global studies will be useful for the operation and optimization of the vitrification facilities.

Keywords: Mechanical stirrer; Molten glass; Induction; Computation; Chemical processes; Laminar flow; Mixing

1. Introduction

Since the late 1950s, many research and development programs have focused on the problem of nuclear waste reprocessing and containment. Vitrification is suitable for safe long-term conditioning of high-level radioactive waste. The process involves incorporation of the ultimate waste in molten glass. Waste results from spent-fuel reprocessing and is composed of minor actinides and fission products. The amorphous structure of glass makes it possible to contain such waste by integration of all the elements of fission-product solutions within the matrix at the atomic scale, resulting in true containment rather than encapsulation. To ensure the long-term stability of the waste package, the chemical, mechanical and thermal properties of the glass must not change with time. A continuous two-step vitrification process was set up by AREVA NC on six vitrification lines at La Hague (France) in 1989. This process was developed at the Marcoule Vitrification Unit starting in 1978. Over the past 20 years, the French Atomic Energy Commission (CEA, France) has been developing a new vitrification process to meet requirements including the vitrification of other types of waste and a reduction in waste volumes. The technology is under investigation at Marcoule and is intended to replace metal pots on one of the six vitrification lines of the reprocessing plant at La Hague. Features of the process include an inductor supplied by a sinusoidal current and cooling of all the walls (Fig. 1). For a cold crucible with a diameter of 650 mm, the inductor surrounding the crucible is connected to a high-frequency current generator with output of 400 kW at a frequency of 300 kHz. The process is based on direct induction of electric currents in the glass. Energy dissipated by the induced currents due to the Joule effect keeps the glass molten. To allow the induction of electric currents, the crucible is divided into segments. The advantage of cooling the walls is mainly related to the formation of a thin layer of solidified glass, which forms a skull melter that insulates the walls from the molten glass. Thus, the walls are not corroded by the molten glass and in turn the molten glass is not contaminated. A cooled mechanical stirrer is added to thermally and chemically homogenize the molten glass. Large

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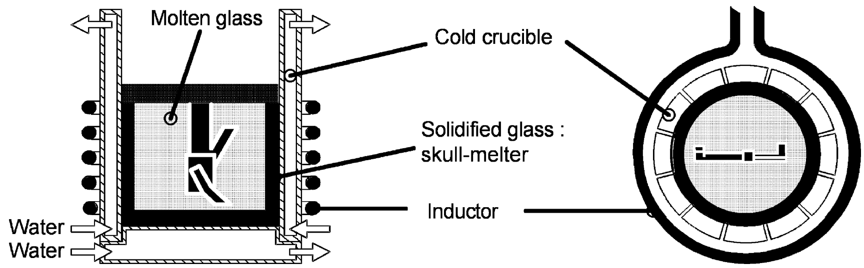

Fig. 1. Cold crucible vitrification process with the stirrer studied.

efforts are being made to identify the optimal process settings, which involves many fields, including electrical engineering, electromagnetism, hydrodynamics, heat transfer and chemical science. Hence, modeling is very useful in understanding and predicting phenomena that occur within the glass bath. In the present study, we consider electromagnetic, thermal and hydrodynamic phenomena within the molten-glass bath. The main difficulties encountered are related to two complications: (1) large thermal variations in the physical properties of the glass, which requires coupling of the electromagnetic, hydrodynamic and thermal phenomena; and (2) asymmetry created by the stirring systems, which requires 3D calculations. To date, only a few studies have been devoted to identifying numerical solutions for this process. To the best of our knowledge, there are no reports of 3D calculations to study mechanical stirring within a molten-glass bath heated by induction.

Some 2D studies have concentrated on the modeling of natural convection in an unstirred molten-glass bath heated by induction. In their studies, Servant et al. (1992) and Saumabere (1994) did not take fluid flow into account, and only thermal and electromagnetic phenomena were coupled. Schiff et al. (2000) studied all three aspects, but their electromagnetic model neglected border effects. Lopukh et al. (2004) did not consider coupling between the different phenomena: the maximum Joule power density was injected close to the crucible walls. Similar results will be obtained if the electrical conductivity is assumed to be constant.

A considerable number of studies have considered mechanical stirring. In fact, stirred tanks are widely used to carry out a variety of operations in chemical engineering. Background information and references are provided by Brucato et al. (1998). Many experimental investigations of hydrodynamics in vessels of different geometrical configurations agitated by various types of impeller have been carried out. These studies have been complemented by the application of advanced numerical modeling techniques to provide more detailed insight into such processes in a cost-effective way. Investigations to quantify stirred tank performance and heat transfer on the walls have also been carried out. The power number N_p and the Nusselt number Nu are commonly used as macroscopic indicators to characterize stirred systems. To date, most reports have regarded fluids with constant physical properties or non-Newtonian fluids (see, for instance, reviews by Nagata, 1975; Mohan et al., 1992). No studies on macroscopic indicators within a glass bath or fluids with large thermal variations in viscosity seem to have been performed. The difficulty is in choosing a viscosity value to compute the dimensionless numbers. In addition, few studies have been devoted to simulation of mechanical stirring within a molten-glass bath. The TNO Glass Group (Op den Camp and Aume, 1998; Op den Camp et al., 2002; Hegen et al., 2002; Novak and Kasa, 2005) has developed software for 3D simulation of a TV panel production line. In these studies, the refining zone and spout are equipped with non-cooled stirrers. However, the glass bath is not heated by direct induction. Experimental temperature distributions or profiles calculated by an external program are used as thermal boundary condition. Thus, coupling was not developed.

The aim of the present study was to simulate electromagnetic, hydrodynamic and thermal phenomena during cold crucible vitrification. The goal is to take into account the mechanical stirrer and to develop coupling between these aspects. The coupling and the high amount of elements in the 3D mesh result in high calculation time. Thus, this present study shows how to couple the programs with highest degree of accuracy and with smallest calculation time possible. Secondly, classical correlations commonly used for fluids with constant physical properties to characterize stirrer efficiency and heat transfer have been adapted to the glass.

2. Mathematical models

2.1. Thermohydrodynamic model

Thermohydrodynamic calculations are based on the following assumptions:

- Only the glass bath is modeled. The flow is assumed to be laminar, 3D and unsteady.
- The fluid is assumed to be Newtonian.
- 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 as $\rho = \rho_0(1 - \beta(T - T_0))$, ρ_0 is the constant density of the flow ($\rho = 2800\,\mathrm{kg\,m^{-3}}$), T_0 is the reference temperature ($T_0 = 293\,\mathrm{K}$) and β is the thermal expansion coefficient ($\beta = 3 \times 10^{-5}\,\mathrm{K^{-1}}$). This approximation is accurate because changes in actual density are small; specifically, the Boussinesq approximation is valid because $\beta(T - T_0) \ll 1$.