Multiphysics modeling of glass melting in cold crucible

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Abstract: The vitrification of high-level nuclear waste ensures their long-term confinement through atomic integration of radioisotopes within a vitreous matrix. Among the various vitrification processes, the one based on the use of a cold crucible with direct electromagnetic induction shows many advantages. Thus it has been in operation since 2010 at the French reprocessing plant at La Hague. Refining the understanding and the modeling of the phenomena involved during glass melting inside a cold crucible constitutes a decisive stake for industrial support and process optimization. In this context, our work presents a multiphysics model as well as a predictive numerical simulation taking into account all the coupled phenomena governing the behavior of the glass melt, in terms of convection, heat fluxes and electromagnetic interactions. The working hypotheses are first formulated, allowing the mathematical modeling of the magneto-thermo-hydraulic system with a controlled degree of approximation. In particular, we design a multi-scale approach to take into account the diphasic nature of nuclear glass, consisting of a homogeneous matrix seeded with micrometric particles mostly made of platinum-group metals. The numerical resolution of the coupled model is then assured by the development and use of precise, stable and optimized simulation codes, by proposing numerical schemes and adapted coupling methods. A large part of our work is dedicated to the analysis of the physical phenomena characteristic of glass melting, generally related to the variable physicochemical properties of the material (viscosity, density, electrical conductivity...). In particular, two main axes are studied here with important applications: transport, response to the induction and settling of the platinum-group metal particles and heat transfers between the molten glass and the cooled walls of the crucible. Scaling laws for the evaluation of the respective intensity of these phenomena are derived from the coupled model analysis. Finally, precise experimental comparisons, both on a small scale and on an industrial scale, make it possible to validate the chosen approach and the outcoming results.

Keywords: fluid mechanics, glass, heat transfer, cold crucible, suspension, electromagnetic induction