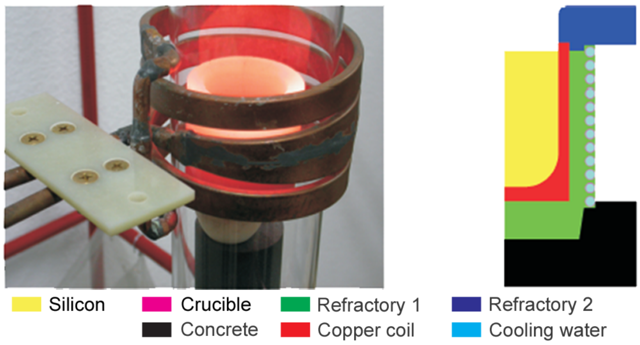
Thermo-magneto-hydrodynamic simulation of an induction heating furnace

The Spanish Network for Mathematics and industry, the math-in network, has proposed the researchers Pilar Salgado from the University of Santiago de Compostela (Spain) and Rafael Vázquez, from IMATI- CNR in Pavia (Italy), as candidates for the Felix Klein Prize 2012.

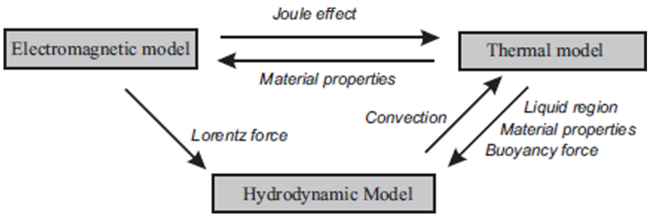
That nomination was motivated by their fruitful trajectory in the numerical simulation and mathematical analysis of Industrial problems. The work considered for this prize concerns the numerical simulation of induction furnaces for the production of photovoltaic silicon. It was developed at the University of Santiago de Compostela and in collaboration with the company FerroAtlántica I+D, the research subdivision of FerroAtlántica Group, which is a world leader in the production of silicon. According to staments of Javier Bullón Camarasa, R+D CEO of FerroAtlántica I+D: "Both candidates joined the project at its very beginning, and they have partipated in all the contracts signed with the university group to simulate the different furnaces acquired by us. We are more than satisfied with the competence for interacting with the engineers of our company. The candidates have always replied to our demands of new simulations with high quality reports explaining the results given by their complex model, and they have always adhered to our requested deadlines. They have also co-operated with us in meetings with our customers, where the performance of the furnace has been explained with the help of the numerical simulations". FerroAtlántica Group is one of the most competitive industrial groups on an international level in the ferroalloy sector. FerroAtlántica I+D coordinates the research activities of the group and has co-operates with the University of Santiago de Compostela research group in Mathematical Engineering since 1996, with the objective of improving the technology for silicon production. This research activity has been mainly funded by FerroAtlántica S.L. with the financial support of the Galician and Spanish administrations.

One of the most outstanding benefits of this co-operation is the ELSA electrode, patented by FerroAlantica. Since 1999, Pilar Salgado devoted part of her research to the simulation of this electrode. The scientific support given by the simulations has helped FerroAtlántica selling its technology worldwide. Today, 35% of the world production of metallurgical silicon is made with technology developed by Ferroatlántica, but with the support of the Mathematical Engineering group.

In the last years, FerroAtlántica I+D started new research on the production of photovoltaic silicon using new technologies. After the good experience with the ELSA electrode, they asked the university group to carry out the simulation of the new technologies under research, and in particular the induction furnaces for silicon melting. That has been a project intended to give results in the long run, and the collaboration with the university group started, at a first stage, with the simulation of experimental furnaces to run some test in their plant. Induction heating is a physical process extensively used in metallurgy for several purposes such as melting or stirring. An induction heating system consists of one or several inductors supplied with alternating electrical current and a conductive workpiece to be heated. The alternating current traversing the inductor generates eddy currents in the workpiece, and through the Ohmic losses the workpiece is heated. Different furnaces can be designed depending on its application. In particular, FerroAtlántica I+D was interested in modeling the behavior of a cylindrical induction furnace used for melting and stirring silicon. Solid chunks of silicon are initially introduced in the furnace and melted during the processes. An important advantage of induction heating is that the melt is very well stirred, since the Lorentz forces generated by the induced fields cause a movement in the liquid material; thus, the inductive system can be designed to maintain the silicon in a liquid state, to control the shape of its free surface and to provide a strong electromagnetic stirring, ensuring a rapid transfer of pollutants from the bulk liquid to its surface. This stirring also aids in melting the charge since the moving fluid transfers heat from the crucible wall to the solid.



At the initial step the company proposed to simulate the behavior of a small furnace which would allow them to learn about the induction process, to analyze the most relevant phenomena affecting the melting process and also to validate the mathematical model. In a second phase, the company was interested in using the numerical results for improving the design of industrial furnaces before being purchased, and also for adjusting their operating parameters after the furnaces were installed. The main questions requested by the company concerning the behavior of these furnaces were: Choice of electrical parameters of the alternating current supplied to the furnace: frequency and intensity current. Choice of geometrical parameters and materials composing the furnace. Questions related to operating conditions. To answer these questions, it was necessary to develop a mathematical model allowing to take into account the most important physical phenomena involved in the furnace: thermal, electromagnetic and hydrodynamic ones. This model was built progressively, starting with the thermoelectrical model and then including the hydrodynamical one. Notice that the questions require to know the distribution of temperature and power density in the furnace but also the velocity in the molten load in order to know the velocity patterns. Moreover, the set of questions have been increasing in parallel with the model: the answers given by the simulation led to a modification in the furnace design and more sophisticated models were demanded by the company. The simulation of the furnace was a very complex multiphysics problem and, since there was no available commercial software to deal with it, it was developed its own software code to carry out the numerical simulation. From the mathematical point of view, there were three main steps before the actual development of the software: first, the choice of the mathematical models that represent the physical processes taking part in the furnace; second, the mathematical analysis of the physical models, either separately or coupled, for a better understanding of the problem; and third, the choice of suitable discretization techniques and computational algorithms to perform the numerical simulation of the industrial process. The most complicated problem implemented for the numerical simulation consists of a transient coupled nonlinear thermo-electromagneto-hydrodynamic model, with turbulent flow, and considering phase change and nonlocal radiation conditions in the heat equation. In order to solve the problem in a reasonable computational time, cylindrical symmetry is assumed in all the models, which reduces the problem to a two-dimensional domain.



In order to develop the software code for the numerical simulation it was necessary, for each of the submodels considered, to choose a suitable discretization technique. It was also necessary to decide which algorithms should be used to deal with the couplings among the models, and the nonlinearities appearing in them.

For the discretization of the electromagnetic problem, a finite element code was first developed, for which a fictitious boundary was added to bound the air domain surrounding the furnace. Later, a mixed finite element/boundary element method was also implemented.

The solution of the thermal and the hydrodynamic models was computed by using a Lagrange/Galerkin scheme, with a finite element method for spatial discretization, and the characteristicsmethod for time discretization involving the convective terms.

Concerning the way to treat the coupling of the three models, the thermoelectrical coupling, due to Joule effect and temperature dependent properties, was solved with a simple fixed point algorithm. The hydrodynamic model, instead, was decoupled from the two others, because the velocity terms can be neglected in the electromagnetic model, and the convective term in the heat equation can be treated using the velocity at the previous time step. An important issue for the numerical simulation was the need of reproducing the operating conditions of the real induction furnaces, for which the adjustable parameters are mainly theelectromagnetic frequency and the power supplied to the furnace. The research group has not found any commercial software on computational magnetics allowing to set the supplied power as a datum. They included in the model the nonlinear equation relating the power to the intensity and the voltage, in such a way that, by solving the nonlinearity with a Newton's algorithm, the power can also be given as a source. Another capability of the model that is not usually found in commercial packages is the possibility to include several inductors, each working at different power and also at different phase. Finally, another important feature of the model is the inclusion of the coil in the thermal domain.

The results, obtained in terms of publications and software, are:

- It was developed a doctoral thesis on this subject which received an outstood award from the Faculty of Mathematics (University of Santiago de Compostela) in 2008/2009. The thesis also received an award for PhD Theses in Industrial Mathematics established by the RSME (Real Sociedad Matemática Espa?ola) in 2011.
- 10 papers were published in international journals appearing in the Journal Citation Reports and developed during the collaboration with the company. We can distinguish two sets of publications: those related with the development and numerical solution of the models and those related with the mathematical and numerical analysis.
- Besides the cited papers, three chapters of books also contain results concerning the simulation of the induction heating furnace. The advances in the solution of the problem have also been progressively presented at several international conferences that cover engineering and numerical analysis areas.
- Finally, the software code containing the models and the discretization schemes explained above was included in a software package, THESIF, that was made available to other researchers under an open source license.

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