"This is an Accepted Manuscript of an article published by Taylor & Francis in INTERNATIONAL JOURNAL OF CAST METALS RESEARCH on Vol. 30 (4), July 2017, available at http://www.tandfonline.com/doi/10.1080/13640461.2017.1286557"

Rapid simulation models for aluminium furnaces design

Eva Anglada [(1,*)]; Iban Vicario [(1)]; Leonor de Landia [(2)]; Gorka Mendizabal [(3)]; Nagore Toledo [(2)]

[(1)] TECNALIA. Industry and Transport Division, Mikeletegi Pasealekua 2, Donostia – San Sebastián E-20009, Spain.

[(2)] REFRACTARIOS KELSEN S.A. Belen Industrialgunea 1, Aduna E-20150, Spain.

[(3)] CALCINOR S.A. Egileor auzoa, 1010, Altzo E-20268, Spain.

ABSTRACT

The minimization of energy consumption in aluminium metal casting industries requires an appropriate design of the furnaces to reduce as possible the heat losses through the walls. Detailed simulation models have been developed that allow the in-depth study of furnace behaviour, but these models are too complex and slow for some industrial necessities. To make possible a fast evaluation during preliminary phases more agile models are needed.

This agility may be achieved by simplified models, but the results could be affected by a lack of accuracy. The work presented hereafter shows how the steady state analysis of the furnace walls with simplified models of finite elements may give sufficiently accurate and fast results.

The simulation models have been validated against experimental results, thus confirming their ability to adequately reproduce the thermal behaviour of the walls of several furnaces regardless of their composition or heating system.

Keywords: metal casting; furnace; aluminium; energy; heat transfer; numerical simulation; finite elements.

1 INTRODUCTION

The metal casting industry is an energy consumer intensive industry. The manufacturing processes in the aluminium industry require heating the alloys to reach their melting point. This is done at melting furnaces. In addition, it is usually required to maintain molten alloys at high temperatures for different periods of time, a process that takes place at the holding furnaces. The necessity to minimize energy consumption requires an appropriate design of these two types of furnaces in order to reduce heat losses through their walls as much as possible.

However, the design of walls of this type of furnaces is not based solely on the thermal behaviour. The refractory materials in contact with molten aluminium must also

[*] Corresponding author: Eva Anglada
Email address: eva.anglada@tecnalia.com
Postal address: TECNALIA. Industry and Transport Division, Mikeletegi Pasealekua 2, Donostia – San Sebastián E-20009, Spain.

withstand chemical wear, which increases the difficulty of furnace design. These aspects should be considered not only by furnace designers but also by the developers of other materials and systems involved, such as refractories designers.

Different studies have been published about the development of detailed simulation models that allow the in-depth study of the thermal behaviour of the furnaces (see Ref. 1-4). But these types of models are often too complex and too slow to be used during the preliminary phases of furnace design or refractory development. During these preliminary phases, the industrial necessities require the use of faster models that allow a rapid evaluation of the influence of the properties of the refractory in combination with the different materials that form the walls of the furnace. This agility may be achieved using simplified models, but it can be thought that this can lead a lack of accuracy in the obtained results.

The work presented hereafter shows how the steady state analysis of furnace walls by means of finite element simplified models is sufficiently accurate and fast to be used during the preliminary phases of furnace design at industrial level. The simulation models have been validated experimentally with different furnace prototypes to confirm their level of precision.

2 METHODOLOGY

2.1 SIMULATION MODELS

The heat transfer through the furnace walls has been simplified assuming that it is one-dimensional. Thus, although the elements that have been used to model the furnace wall are three-dimensional, they represent only one slice of the wall (Fig. 1).

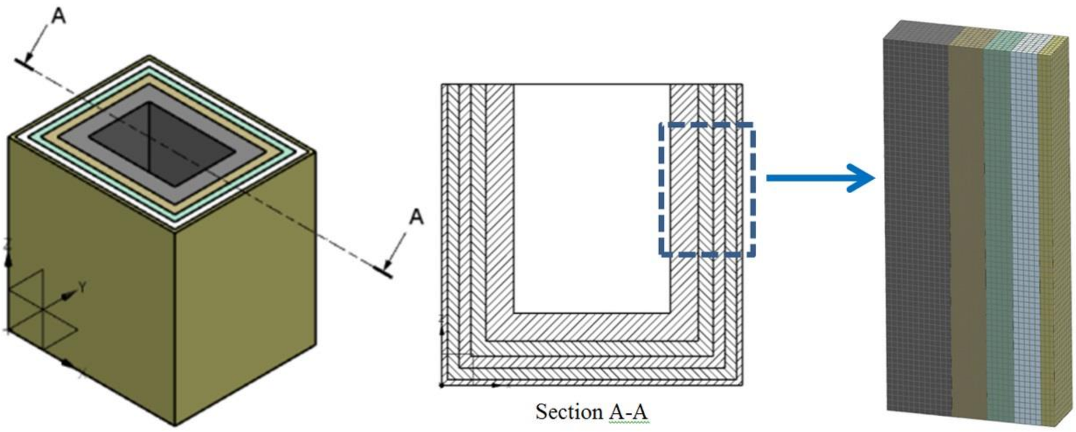

Fig. 1. Sketch of one of the furnace prototypes and the finite element model

The different layers of diverse materials that form the walls have been modelled as independent bodies to be able to define the heat transfer coefficients between them (Fig. 2). However, finally all the values used for the heat transfer coefficients between them have been large enough to be almost equivalent to a perfect contact. The thermal conductivities of the materials have been defined as function of temperature.

The boundary conditions have been applied only on the surface of the internal wall in contact with the molten alloy and on the surface of the outer wall exposed to ambient temperature. The boundary condition applied to the surface in contact with the molten aluminium is a fixed temperature equal to the alloy temperature. In the case of the outer wall surface, a convection coefficient and an ambient temperature have been defined. Radiation has not been included in the models.

In all models, the same properties have been used for the same materials and the same modelling guidelines have been followed during the set-up of the simulations.

The numerical simulations have been performed assuming steady state behaviour. The simulation software used is NX Thermal/Flow, which is the heat transfer solver included in NX software from Siemens Company (Ref 5).

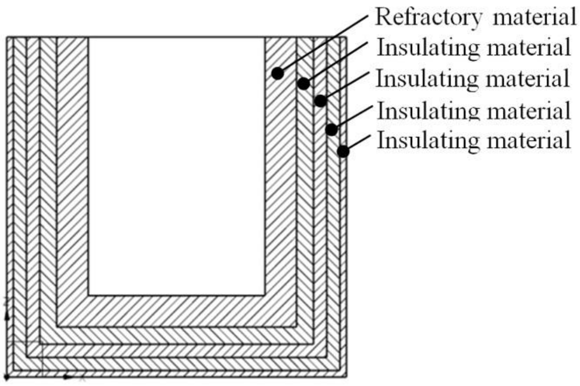

Fig. 2. Example of a furnace wall composition.

2.2 EXPERIMENTAL TESTS

Three different prototypes have been used for the experimental validation of the simulation models: A semi-industrial prototype, a holding chamber prototype and a melting chamber prototype.

- **The semi-industrial prototype** basically consists of an iron vessel, with a square cross section, with a total capacity of 60 kg of aluminium alloy. The walls are not formed by layers of different materials as is usual in industrial furnaces. In this case each wall is formed by only one layer of refractory material. The geometry is very similar to that shown in Fig. 1 and Fig. 2, except for the number of layers forming the wall. Two of these walls have been manufactured in a conventional refractory material and the other two in a newly developed refractory. The reason for this unusual configuration is that the main objective of this prototype is to test the behaviour and properties of the refractories. For clarity, the data included in this article have been restricted only to the walls made with the newly developed refractory. More detailed information about this prototype and the tested refractories can be found in Ref. 6. The heating system consists of electrical resistances located on the top cover.

- **The holding chamber prototype** is also an iron vessel which corresponding to Fig. 1 and Fig. 2. In this case the walls of the furnace are formed by 5 layers of insulating materials. The layer in contact with the molten alloy is made of refractory material. Next to it there are 3 different materials distributed in 4 different layers. The heating system is also made by electrical resistances, but in this case they are located in the lower base of the furnace.
- **The melting chamber prototype** is also a container whose walls are formed by 5 layers of insulating materials. The refractory layer is in contact with the molten alloy and it is followed by 4 more layers made of 2 different materials. Also in this case, there are several walls with different configurations but for clarity only the results of one of them are included in this work. In this case the heating system consists on a plasma torch.

The three prototypes have been subjected to similar operating conditions, analogous to those expected on an industrial scale. The main temperatures recorded during tests are collected in Table 1. The measurements have been made by a thermography camera in the semi-industrial prototype and by thermocouples in the other two cases. In addition, in the holding and melting chamber prototypes, temperatures have been recorded at different control points inside the walls (Fig. 3). The indicated values correspond to the temperature values recorded once the furnaces have reached thermal stabilization.

Table 1. Experimental data recorded during test campaign

PROTOTYPE	Aluminium alloy	Alloy temperature (ºC)	Temperature at external surface (ºC)
Semi-industrial	$AlSi_9Cu_3$	750	385
Holding chamber	$AlSi_9Cu_3$	680	70
Melting chamber	$AlSi_9Cu_3$	815	38

Fig. 3. Measurements performed by means of thermocouples

"This is an Accepted Manuscript of an article published by Taylor & Francis in INTERNATIONAL JOURNAL OF CAST METALS RESEARCH on Vol. 30 (4), July 2017, available at http://www.tandfonline.com/doi/10.1080/13640461.2017.1286557"

3 RESULTS AND DISCUSSION

Semi-industrial prototype

Several walls of the prototypes studied include a new innovative refractory that was developed during the project where the work presented here has been performed (see acknowledgments section). This fact is an additional difficulty for the validation of the simulation models, since it is a new material and therefore has not been modelled or studied before. But thanks to the configuration of the semi-industrial prototype furnace, where one of the walls was manufactured with this new material, it was possible to confirm their expected values of thermal conductivity (see Ref. 7 for more details).

The Fig. 4 shows the comparison between temperature results provided by the simulation (blue line in the graph) and the temperature measurements performed during the experimental tests (green points in the graph). As can be observed, the model is able to correctly predict the external temperature of the furnace surface, confirming the utility of this type of simplified models.

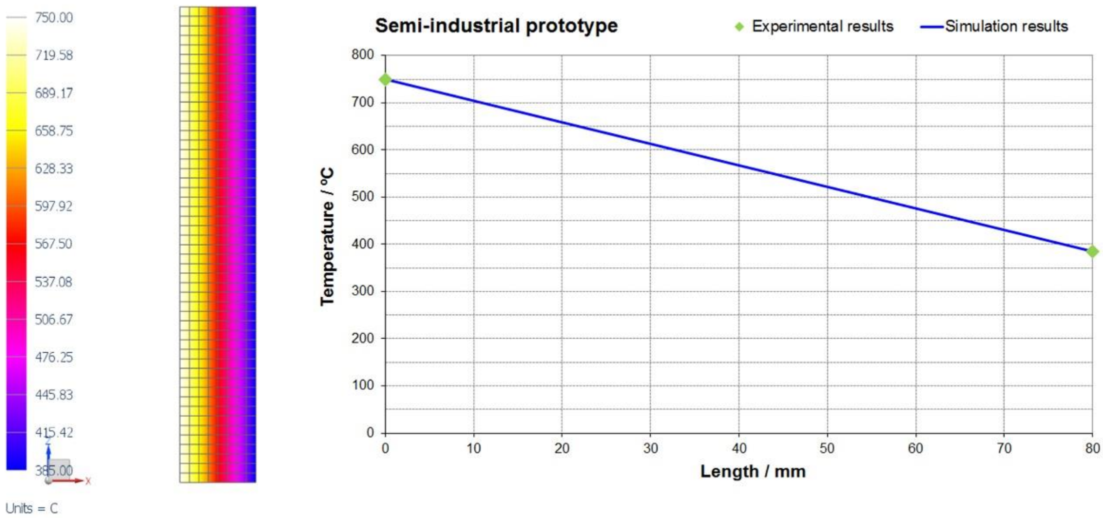

Fig. 4. Temperature results obtained from simulation. Semi-industrial prototype

Holding chamber prototype

During the experimental testing campaign of the holding chamber prototype, temperatures have been collected at 5 different points. One corresponds to the molten alloy, one to the outer surface of the furnace and three more to the interior of the furnace wall.

The Fig. 5 shows the adjustment obtained between the results of the simulation (blue line) and the actual experimental data (green points). As can be seen, also in this case the model has been able to adequately predict the thermal distribution through the furnace wall.

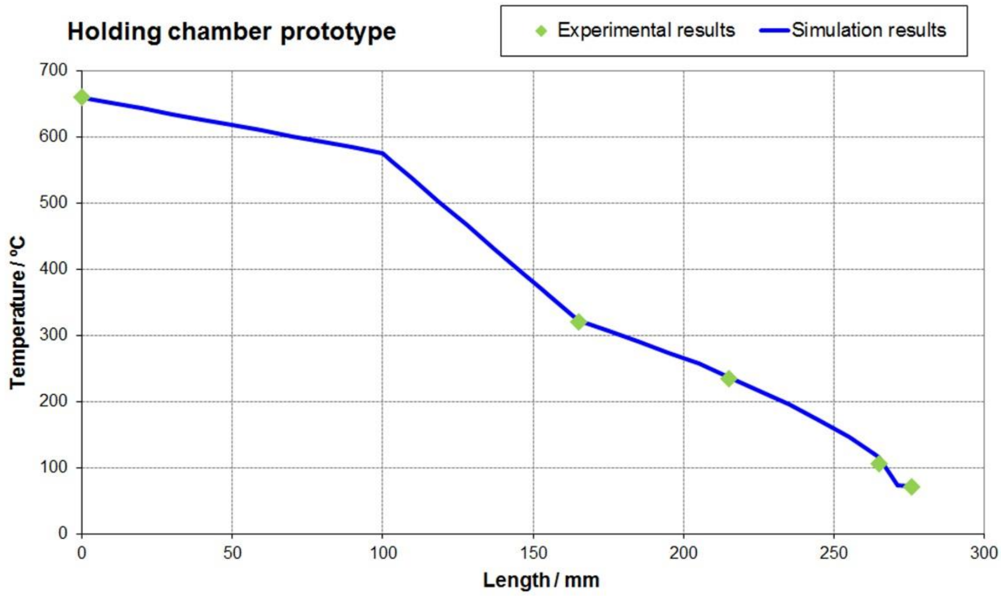

Fig. 5. Temperatures recorded during tests and simulation results. Holding chamber prototype

Melting chamber prototype

In the case of the melting chamber prototype, temperatures have been recorded at three different points. In addition to alloy and external wall temperatures, one measurement has been made inside the furnace wall.

The comparison between the temperatures predicted by simulation (blue line) and the values measured during the experimental test (green points) are shown in Fig. 6. Once again, the adjustment between them is good, validating the capacity of this type of simulation model to reproduce the thermal behaviour of the furnace walls.

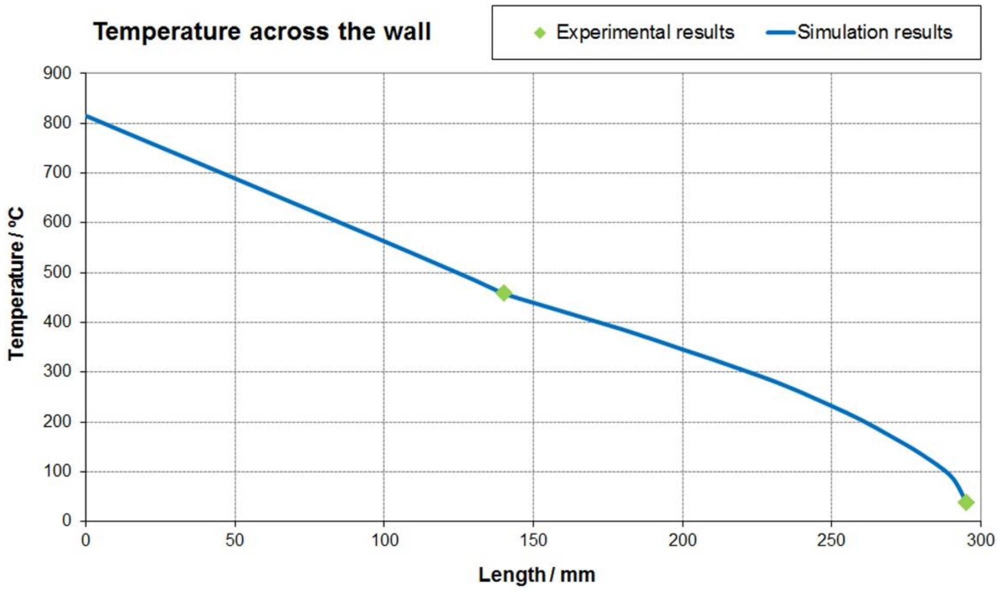

Fig. 6. Temperatures recorded during tests and simulation results. Melting chamber prototype

4 CONCLUSIONS

The models have been validated for different furnaces, a semi-industrial prototype, a holding chamber prototype and a melting chamber prototype. The validation of the model based on similar but different cases offers a greater confidence in the verification obtained.

The simulation models have been able to adequately reproduce the thermal behaviour of various furnace walls with different compositions and different heating systems. The use of a fixed value equal to the alloy temperature as boundary condition has proved to be valid for furnaces whose heating systems are based on electrical resistances, located at the top or bottom, and also with plasma torches.

The type of simulation model developed during this work has proved its usefulness for the preliminary design of the furnace according to industrial necessities. That is, the modelling is agile and fast, but also accurate enough. The simulation models are fast enough to allow the agile evaluation of different design alternatives, since the calculation time for each model is less than 1 minute. This type of model facilitates the study of the thermal influence that involves the inclusion of different materials in the furnace walls, the effect of their thickness, etc.

In addition, the modelling of the innovative refractory developed during the project in which this work has been carried out has also been validated. So it is ready to be used from now in the future design of new furnaces.

5 ACKNOWLEDGEMENTS

This work has been developed as part of the *EDEFU – New designs of Ecological Furnaces* project, funded by the European Commission under the FP7 Cooperation Programme for nanosciences, nanotechnologies, materials and new production technologies (FP7-NMP-2009-Large 3). Grant agreement: 246335.

The help of the personnel involved in experimental tests is kindly acknowledged, with special mention to Igotz Arocena from GIS and David Eguizabal from TECNALIA.

6 REFERENCES

1. M. Carmona and C. Cortés: ‘Numerical simulation of a secondary aluminum melting furnace heated by a plasma torch’, *J. Mater. Process. Technol.*, 2014, 214, 334–346.
2. A.R. Khoeia, I. Mastersb and D.T. Gethinb: ‘Numerical modelling of the rotary furnace in aluminium recycling processes’, *J. Mater. Process. Technol., 2003*, 139, 567–572.
3. N. Zhou, S. Zhou, J. Zhang and Q. Pan: ‘Numerical simulation of aluminum holding furnace with fluid-solid coupled heat transfer’, *J. Cent. South Univ. Technol.*, 2010, 17, 1389–1394.
4. R.T. Bui and J. Perron: ‘Performance analysis of the aluminum casting furnace’, *Metall. Trans. B*, 1988, 19, 171–180.

5. Siemens, NX, (n.d.). http://www.plm.automation.siemens.com/es_es/products/nx/for-simulation/thermal-analysis/index.shtml.
6. I. Vicario, L. de Landia, G. Mendizabal, N. Toledo, E. Anglada and P. Rodriguez: 'Development of a simulation procedure for the evaluation of new refractories for aluminium furnaces', in 'Proc. 71st World Foundry Cong. – Adv. Sustain. Foundry', 2014, Bilbao, SPAIN, Tabira Foundry Institute, WFO, IK4 Azterlan.
7. I. Vicario, L. de Landía, G. Mendizabal, N. Toledo, E. Anglada and P. Rodriguez, 'A novel procedure for the evaluation of new refractories for aluminium furnaces', Proc. 10th Eur. Conf. Ind. Furn. Boil., Gaia - Porto, Portugal, 2015, Cenertec – Centro de Energia e Tecnologia.