UNIVERSITAT POLITECNICA DE CATALUNYA
INTERNATIONAL CENTER FOR NUMERICAL METHODS IN ENGINEERING
MASTER IN NUMERICAL METHODS IN ENGINEERING

Industrial Training

Simulation of casting process

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Introduction

Over the last decades, simulations in engineering have become an important tool used in industrial design, since it enables to check strength, predicts possible manufacturing problems and properties before producing the final product. Thus, the product's cost can be significantly reduced considering that several models can be simulated before prototyping and testing. However, in many fields there are still a lot of challenges and investigation must be done to make results more accurate and reliable. One of these fields is Die Casting Manufacturing, which is an ancient technique that consists in pouring molten metal in a sand cavity with the desired shape (mold), cooling the piece down.

In the Industrial Forming Processes Group of CIMNE, the challenges regarding to Die Casting Simulations are being addressed, taking into account some of the complexities of the physical problem. Previous works in the department were performed on simpler geometries and considering simplified models, but with the limitation that results were not accurate enough. In this sense, it was recognized that additional parameters were needed to obtain a better approach to the physical behavior.

This report is part of the internship work which main task is to simulate the cooling of a cast iron addressing the mentioned limitation. In this sense, more physical parameters are included such as: a second change of phase in the casting, evaporation of water contained in the mold, and change of the conductivity in the mold. Sensibility analysis is done to each parameter to evaluate their influence in the results. Finally, experimental data is given in order to compare the obtained results and evaluate how close the numerical solution is from the experiments (validation).

Methodology

The setup of the model consists on defining the geometry, material data and others parameters. In this sense, the geometry to be used is created in a CAD model, matching the dimension of the part from which experimental data were extracted. The material properties of the cast and the mold are extracted from previous works done in the department and from online resources [1], [2]. Extended information of the material and the definition of the parameters is given in the following section "Settings of the model".

GiD preprocessor is used to assign mesh size, material's properties, boundary conditions and initial values. The problem to solve is the transient heat transfer equation [Equation 1] and considering heat source coming from the change of phase.

$$\nabla \cdot [k(T)\nabla T(\boldsymbol{x},t)] + \dot{Q} = \rho C_p(T)\frac{\partial T(\boldsymbol{x},t)}{\partial t} \quad in \quad \Omega$$

Equation 1

$$\dot{Q} = \rho L \frac{\partial f_s(\boldsymbol{x},t)}{\partial t}$$

Equation 2

Where T is the temperature that depends on the spatial coordinates ($\boldsymbol{x}$) and time (t); ρ, C_p and k are the density, specific heat and conductivity, respectively and $\dot{Q}$ is the source term. When change of phase occurs, the source term activates within the Liquidus and Solidus temperature and takes the form of the Equation 2, outside this interval it is zero. In this equation, ρL is the volumetric latent heat and f_s the solid fraction. The Boundary Conditions and Initial Values are expressed in Equation 3.

$$BC(Neuman): q_{air}\,(flux) = q_{conv} + q_{rad} \quad at \quad \Gamma_{air}$$
$$BC: q_{mold} = q_{cast} = HTC * (T_{cast} - T_{mold}) \quad at \quad \Gamma_{mold-cast}$$
$$IV \ : \ T(\boldsymbol{x},0) = T_0 \quad in \quad \Omega$$

Equation 3

Where q_{conv} and q_{rad} are the heat fluxes due to convection and radiation respectively at the boundary in contact with air, q_{mold} and q_{cast} are the heat fluxes in the mold-cast contact interface and T_0 is the initial temperature distribution which it assumed to be homogenous in the whole body. Equation 1 is solved separately for each material and computations were done using a code developed by Professor Michelle Chiumenti in the Industrial Forming Processes Group of CIMNE. Once the results are obtained, they are analyzed using the GiD postprocessor.

Another step performed in this work was to analyze the given experimental data with the idea of understand the cooling curves in the cast and the heating curves in the mold, and see the behavior to be able to detect which phenomena is taking place. The section "Experimental Data" is dedicated to this specific subject.

For the sake of this work several assumptions and idealizations were considered in order to simplify the model due to its high complexity. The considerations are listed following:

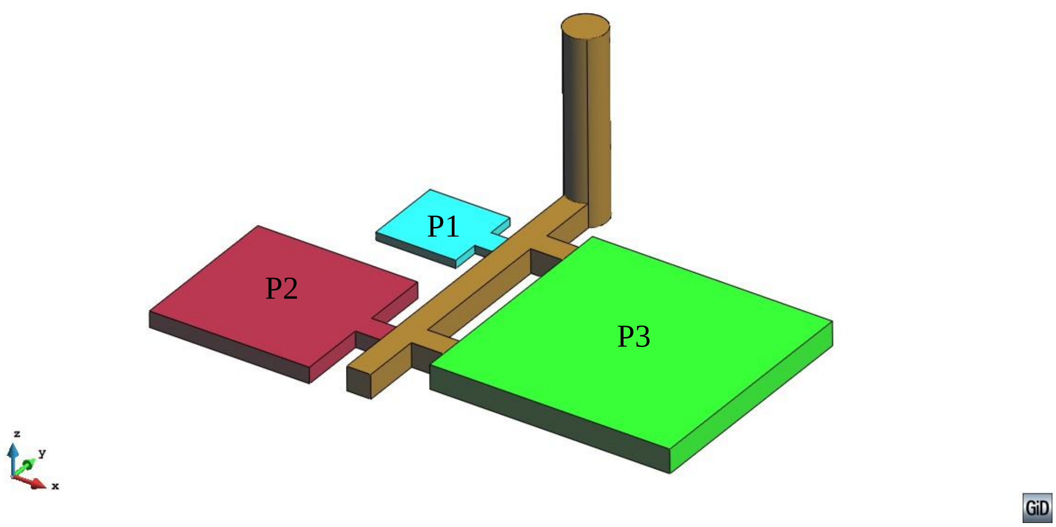
- Thermal analysis (mechanical effects not considered).
- Explicit expression of solid fraction in terms of the temperature.
- Homogeneous distribution of initial temperature.
- Effect of radiation and convection are merged into a single and constant heat transfer coefficient.
- Constant Heat Transfer Coefficients considered.
- Eutectic changes of phase.

Once the model is prepared, sensibility analysis was performed to firstly establish the mesh to be used and then to see the influence of: Latent heat of the water in the mold, Mold's conductivity and Heat Transfer Coefficient between mold-cast interface. The Section "Sensibility Analysis" explains in detail this step. Then, the tested values were combined to find the result that adjusts better the experimental data and it is discussed in the section "Final Results".

Settings of the model

Geometry

The geometry of the casting consists in 3 plates with thickness of 10mm, 20mm and 30mm, called from now on P1, P2 and P3 respectively; which are connected through feed channels as it can be seen in Picture 1. The geometry is confined within a wet-sand mold with external dimensions of 870mm of width, 820mm of depth and 400mm of height.



Picture 1: Geometry of the casting

Properties of the Casting (Gray Cast Iron) and Mold (wet-sand)

The intention of this section is to show the values of the material's properties and other parameters used in the simulations. Recalling that the material of the cast is a Gray Cast Iron and the mold is made of green-sand, the parameters are extracted from previous work done in the group [1] and from internet resources [2]. In Table 1 and in Table 2, properties of the casting and mold are displayed respectively. For the cast, some of the properties like heat conduction coefficient, specific heat and density are given in tabular data as function of temperature. As for the mold, since the sand has a certain percentage of water (wet sand), the conductivity change considerable during the vaporization of water and hence two values are considered. Other parameters like mold's specific heat and density are considered constant. It must be remarked that the properties founded for the sand are used as reference since no specific information about the sand was available.

In Table 3, the Heat Transfer Coefficients (HTC) for the different interfaces are specified. Since variation of temperature is small at the boundaries of the mold, the HTC between the mold and the environment do not have mayor influence in the result. It should be noticed that the values of Latent heat of water in sand, Heat Conduction in Dry/Wet Sand and the HTC between cast-mold interfaces are defined after the tests.

Table 1: Properties of the Cast

Parameter	Value [Units]
Latent heat 1st change of phase (L-S)	258097 [J/kg]
Liquidus Temperature	1232.5 [°C]
Solidus Temperature	1119 [°C]
Latent heat 2nd change of phase (γ -> α austenite to pearlite)	100000 [J/kg]
Start Temperature	715 [°C]
End Temperature	705 [°C]
Heat Conduction	See Table 4 in Annex
Specific Heat	See Table 4 in Annex
Density	See Table 5 in Annex
Solid Fraction (1st change of phase)	See Table 6 in Annex
Solid Fraction (2st change of phase)	linear

Table 2: Properties of the mold

Parameter	Value [Units]
Latent heat of water in sand*	110000 [J/kg]
Vaporization Temperature	102 [°C]
Liquidus Temperature	98 [°C]
Density (constant)	1540 [kg/m^3]
Specific heat (constant)	800 [J/kg-°C]
Heat Conduction in Dry/Wet Sand*	0.5 [W/m-°C] - Dry 1.6 [W/m-°C] – Wet
Solid Fraction	Linear

* Defined after test

Table 3: Heat Transfer Coefficients

Parameter	Value [Units]
HTC between cast-mold interface*	2000 [J/kg-°C]
HTC between parts-environment interface	50 [J/kg-°C]

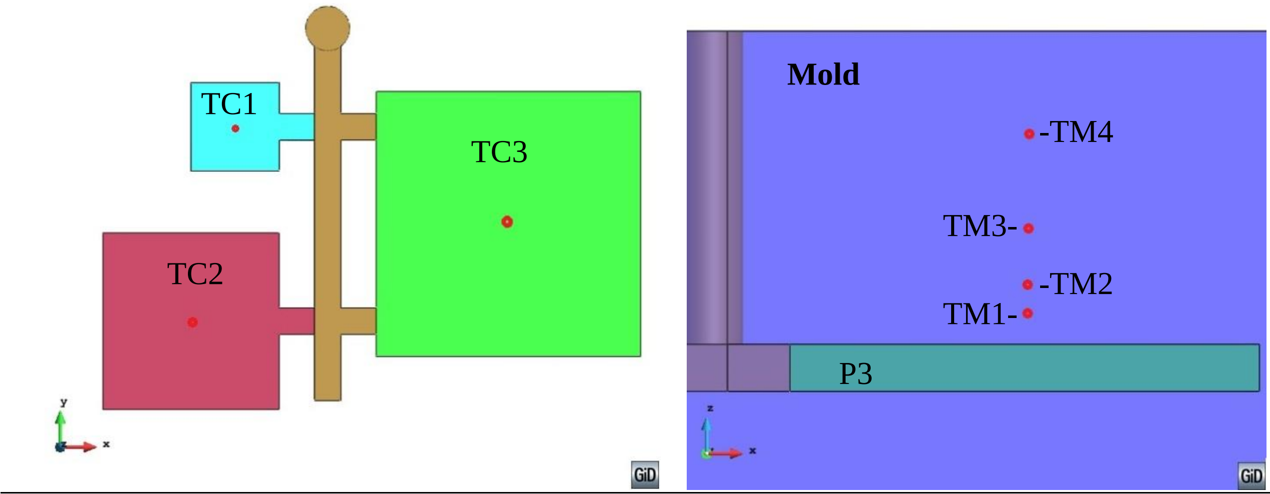
* Defined after test

Rest of parameters

Initial temperature for simulation is set to 1300°C for the cast and 20°C for the mold. The time increment was set to 5 second to be able to run simulation in a reasonable period of time and since it was seen that smaller time increments do not offer improvements in the results. The end time was set to 2000 since it enough to simulate the cooling process.

Experimental Data

As mentioned before, experimental data is provided in order to compare the obtained result and perform the validation. The experiment was conducted outsourced using the mentioned geometry and placing 7 thermocouples to register the evolution of the temperature during casting process. Three were located at the center of each plate and the rest were located at a distance of 6mm, 15mm, 35mm and 75mm from the upper face of the plate P3, aligned to the axis that passes tough the center of P3 and is perpendicular to this face. In this sense, these points are of interest in the simulation, whose positions are represented in Picture 2 and are going to be called from now on TC1, TC2, TC3 and TM1, TM2, TM3 and TM4. Then, the evolution of temperature given by the numerical results at these points, are going to be evaluated and compared to the experimental results to validate results.



Picture 2: Position of the thermocouples

The data obtained from experiments are showed in the following figures. In Figure 1, the information for the temperature evolution at the center of each plate is showed and in Figure 2 the experimental data for the thermocouples located at the mold is showed.

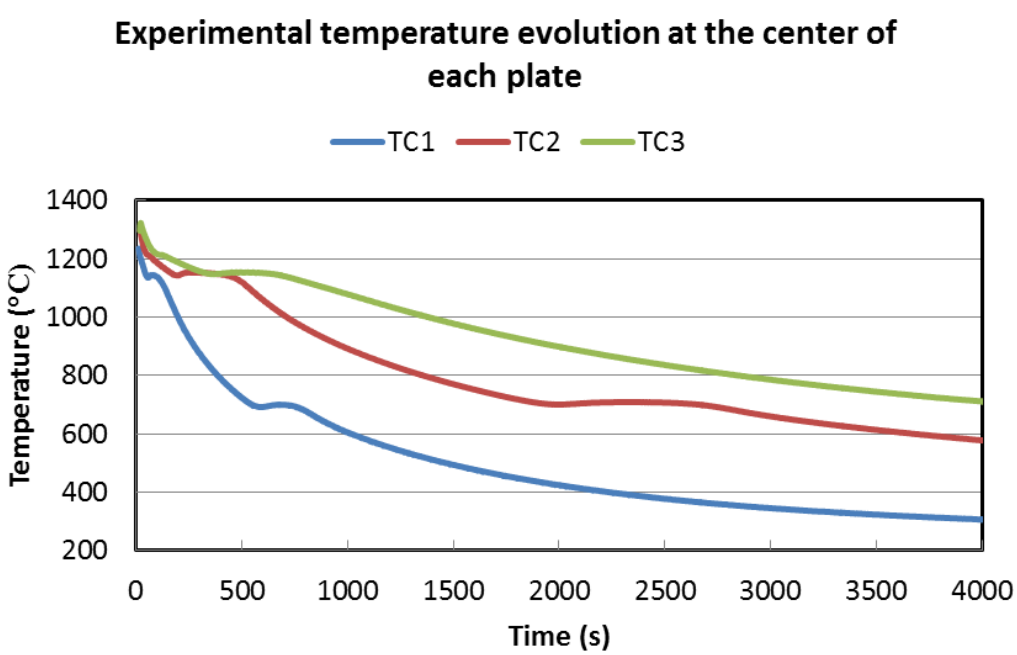


Figure 1: Experimental Temperature evolution at the center of each plate (TC1, TC2 and TC3)

One of the conclusions from data retrieved in the cast, is that there exists flat zones in all curves, where the temperature remains almost constant in certain period of time. This happens at the same temperature in all curves: one at around 1150 °C and the other at around 700 °C. These temperatures coincide with equilibrium points of change of phase. The first correspond to a change of phase from *liquid* to *Austenite* + *Graphite* (Eutectic) and the second correspond to the change from *Austenite* to *Pearlite* (Eutectoid). Another conclusion is that as it can be seen the curves are very similar in behavior but with different cooling rates. As is expected the smaller plate cools down faster (TC1).

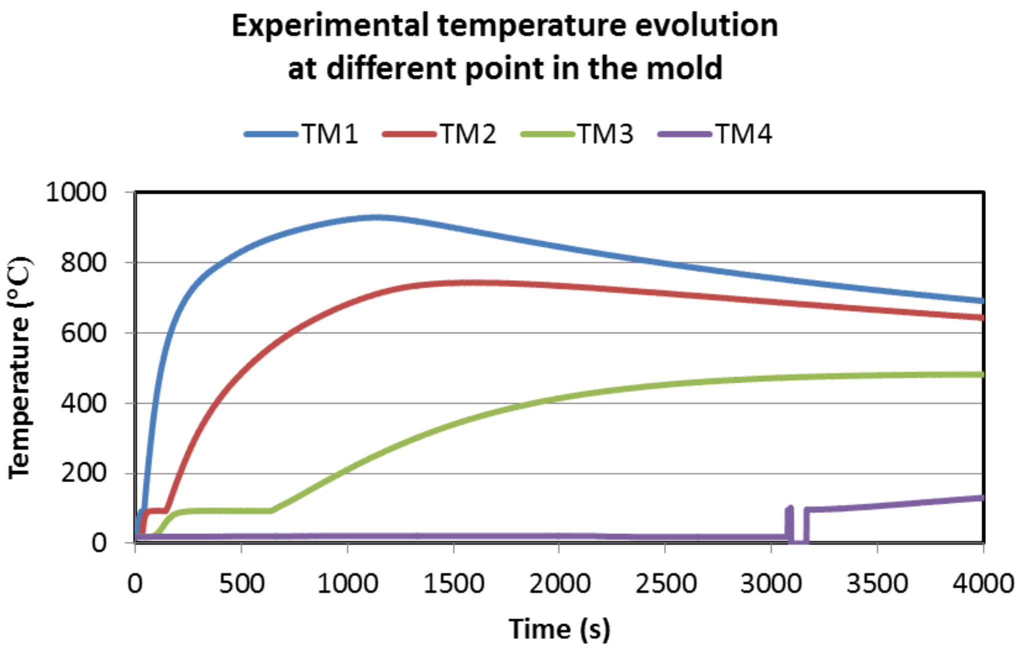


Figure 2: Experimental temperature evolution at TM1, TM2, TM3 and TM4.

In the case of the data collected in the mold, it can be seen that similarly to the casting, around 100°C the temperature remains constant, suggesting that the water within the sand mold is evaporating and absorbing heat. Also it is noticed that this change of phase take longer as it is farther from P3. It is seen that the measure of the thermocouple TM4 is not reliable since it register an abrupt gradient of temperature around 3000s as it can be seen in Figure 2. Despite this fact, the result in this point is still analyzed, but not compared.

In general, it was seen that flat zones suggest change of phase, heating that is being absorbed from the control volume. However, regarding to the experimental data, there is no enough information to estimate the dispersion of measure and to know the order of the measure errors. In this sense it is going to be assumed that measure errors are small enough (less than 10%).

Sensibility Analysis

In order to study the influence of the properties that are going to be estimated, sensitivity analysis is performed applying the One At a Time technique (OAT, OFAT). This means that one variable is going to be changed while the others remain constant during the analysis and study its influence in the results. The first step was to define the proper mesh, consequently a convergence analysis is performed changing the mesh size and distribution, then evaluate the result in one point in the cast and one point in the mold where high gradients are expected.

After selecting a suitable mesh, a sensibility analysis is performed to see not only the influence of each parameter but also to select a set of values that best adjust to the experimental results. The first parameter that is tested is the Latent Heat of the water in the mold and the value that best fits is the one used in further simulations.

Then, the influence of mold's conductivity is analyzed and as initial test the conductivity is assumed constant. After testing several values, the one with the best approximation is selected as the dry-mold conductivity. Then, dry/wet conductivity is considered and several values of wet-mold conductivity are tested. The one that best approximates the experimental results was selected and used for the rest of the simulations. After this test it is possible to obtain dry-mold and wet-mold conductivity.

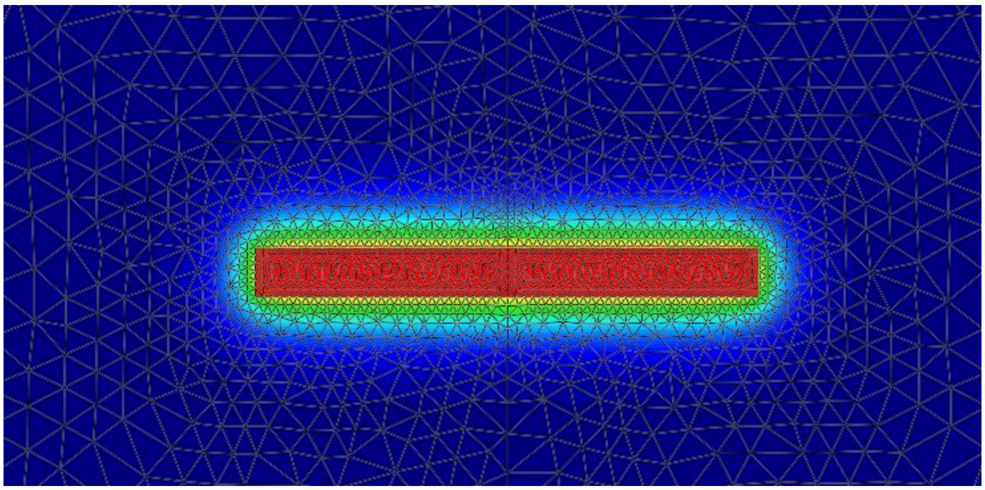
And finally the Heat Transfer Coefficient (HTC) between the cast-mold interface is estimated in the same way. All the values extracted from sensibility analysis that best approximates to the experimental solution are reported in Table 2 and Table 3 and results are analyzed in the section "Final Results".

Mesh Size

It was observed in initial simulations that in the zone close to the cast, mold's temperature gradients are significantly higher (See Picture 3), in this sense the mesh needed to be smaller in this zone. To perform the convergence analysis the size of the elements in the cast and the transition parameter were changed. This last one adjusts the smoothness of elements between the boundary of the cast and the external boundary of the mold. Four different meshes were evaluated and for each one, the evolution of the temperature was obtained in one point in the cast (TC1) and in one point in the mold (TM2).

To analyze the convergence tendency the temperature evolution were plotted for each mesh but considering the number of the elements in the cast for TC1 (See Figure 3) and the number of elements in the mold for TM2 (See Figure 4). In this sense, it must be remarked that curves with the same color correspond to the same mesh; for example, the green curve corresponds to a mesh that has total number of elements 88398, 18257 elements in the cast and 70141 elements in the mold.

It must be remarked that in order to reduce computation time in this stage, only one change of phase in the casting was considered, i.e. no change of phase in the mold and no variation in the mold's conductivity. It is assumed that the behavior of this mesh will be equal if more phases are added and the variation of mold's conductivity is considered. Taking into account this aspect, the smallest mesh was selected.



Picture 3: Temperature distribution in the cast and the mold and mesh

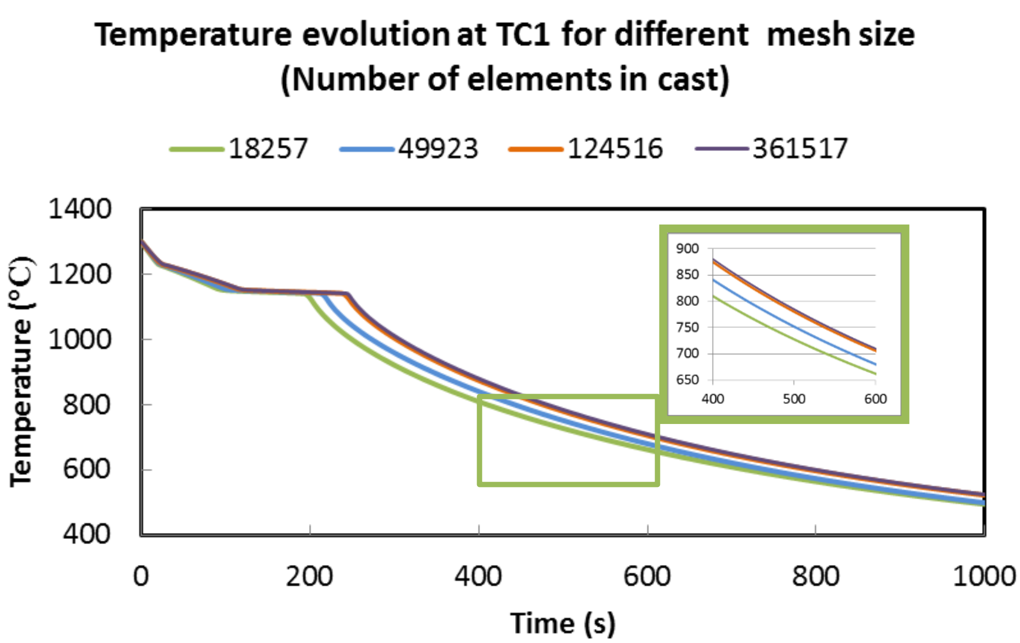


Figure 3: Temperature evolution in the cast for different mesh sizes

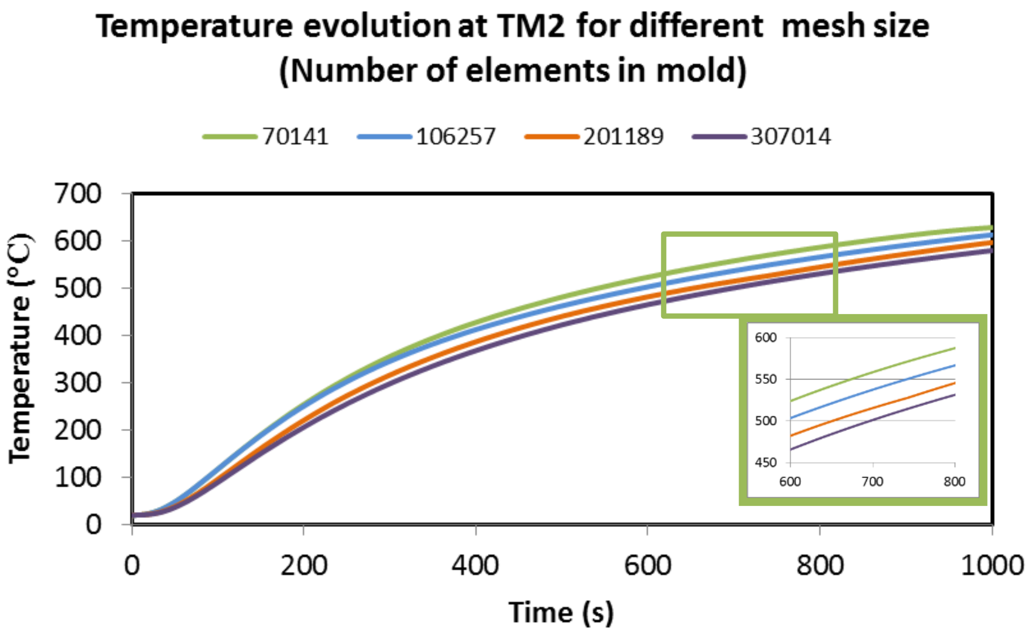
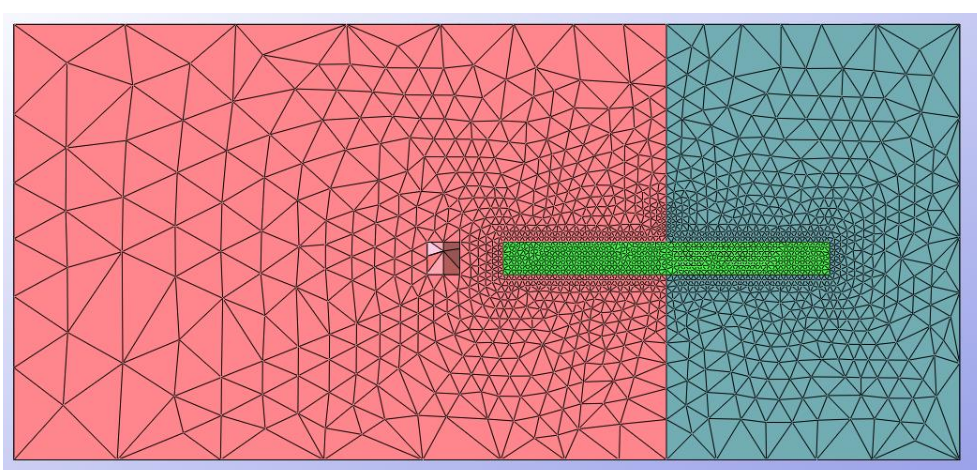


Figure 4: Temperature evolution in the mold for different mesh sizes

It can be noticed that for the last two meshes, the influence of the result in the cast is negligible; however considering the assumption mentioned before, the smallest mesh is selected. In both cases when the number of elements increases, the curves get closer to the one that has the finer mesh, suggesting convergence of results. The final mesh can be seen in Picture 4.



Picture 4: Mesh used for simulations

Latent Heat of water in the mold

In this analysis, the mold's conductivity was considered constant and with value of 0,8 W/m-°C as initial guess and for the HTC between cast-mold interface the value of 200 was used as first guess. Three values of Latent Heat were tested (10000, 110000, 200000) and the temperature's evolution in a point in the cast and in the mold are analyzed. Values of Latent Heat more than 200000 will suggest that there is a lot of water in the mold, which will have no sense, since it is known than humidity in mold do not reach more than 10%. In Figure 5 the result for the most representative point in the cast is showed and similarly with the mold in Figure 6. Results in the other points are very similar; hence only significant curves of each material are showed.

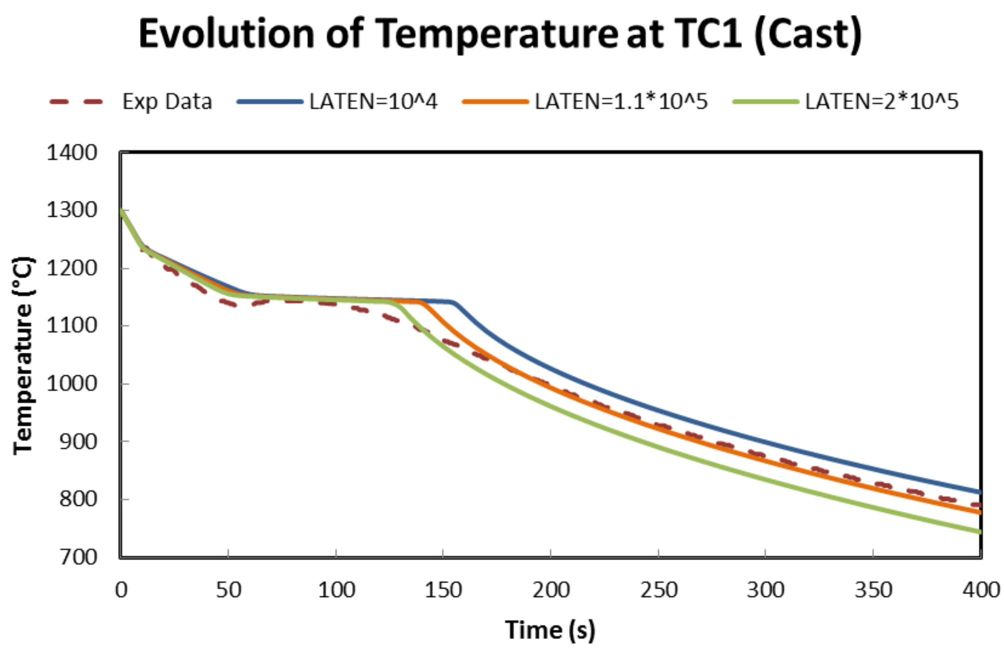


Figure 5: Temperature evolution in cast for different values of Latent Heat of water in the mold

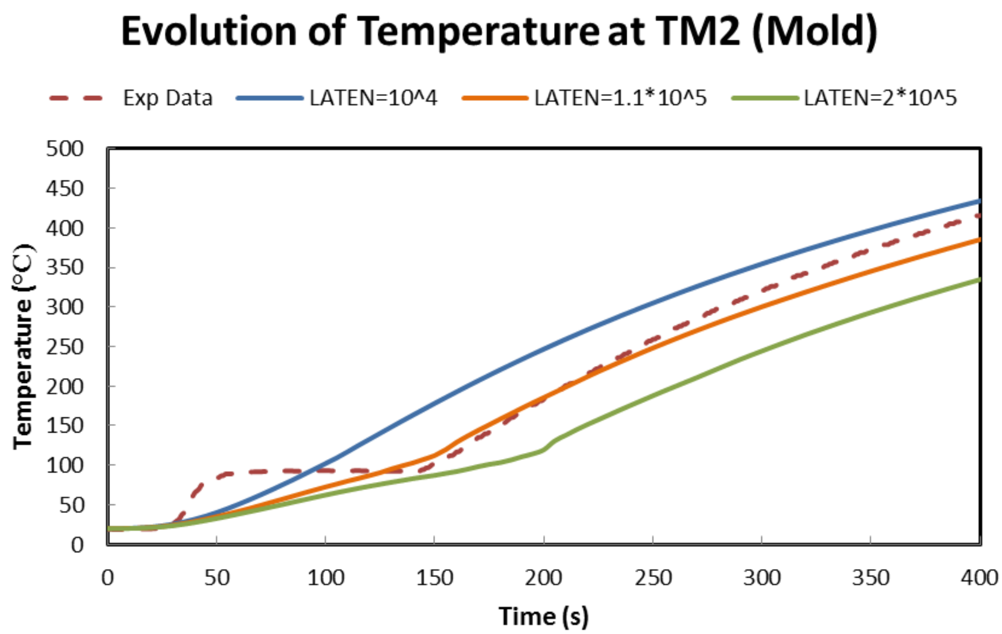


Figure 6: Temperature evolution in mold for different values of Latent Heat of water in the mold

It can be seen that the Latent heat has influence in the formation of the plateau in cast and the mold. In the cast, the plateau is larger for smaller values of Latent Heat (LH). In the case of the mold, despite there is no clear formation of the plateau, it can be seen that for higher values of LH, the heating rate decreases in the range of temperature less than 100 °C. After this range the heating rate seems to be equal and independent of the LH. Finally, the value selected for further tests was 110000 J/kg, since is the one that fits best to the experimental results.

Conductivity in the mold

Wet Sand and Dry Sand can be considerable different, which is why is important to evaluate the consequences of this difference. It was noticed that the dry conductivity has more influence in the results than the wet conductivity. In this sense, first tests were performed using a constant value of conductivity and the value that best fits to the experimental data, was the one used as dry-sand conductivity. After setting the dry-sand conductivity, other tests were performed considering the jump in mold's conductivity and testing different values of the wet-sand conductivity.

The results in this first test were analyzed particularly in the cast since in the mold the fitting is not good, because constant conductivity is considered. It is known from literature that the dry-sand conductivity can take values within a range of 0.3-0.8 W/m-°C, hence three values were tested (0.3, 0.5, 0.8). In Figures 7-9, the evolution of temperature in the center of each plate, are plotted.

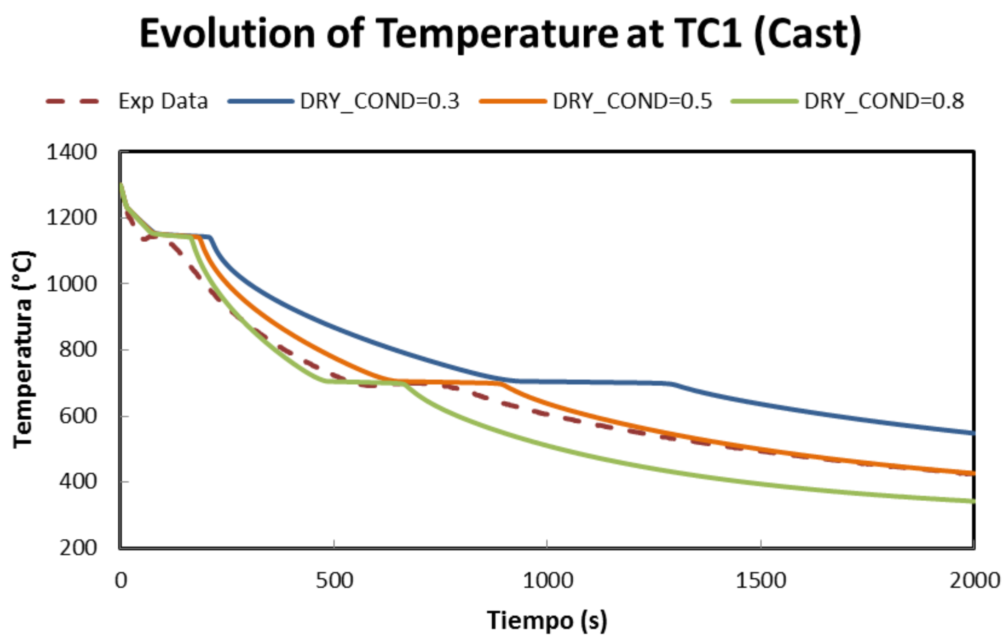


Figure 7: Temperature evolution in TC1 for different values of dry-sand conductivity

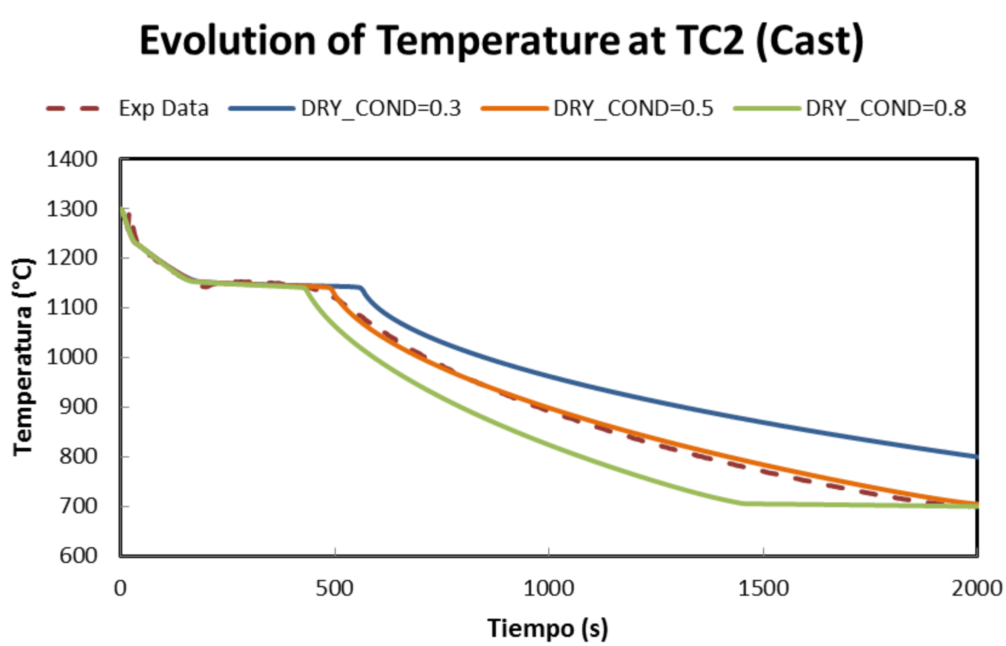


Figure 8: Temperature evolution in TC2 for different values of dry-sand conductivity

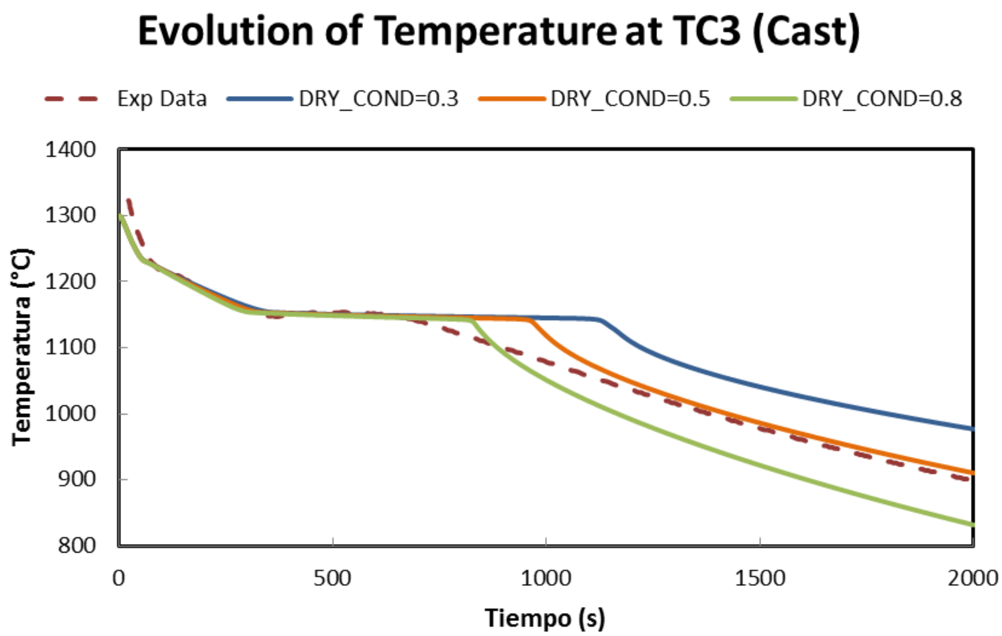


Figure 9: Temperature evolution in TC3 for different values of dry-sand conductivity

It is seen that the conductivity in the mold have a lot of influence in the cooling rate of the cast, high conductivity gives higher cooling rate and vice versa. Also it is seen that has influence in the change of phase, for lower conductivity the plateau gets larger and vice versa. In this analysis it can be clearly seen that the value of conductivity that best fits the experimental results is 0.5 W/m-°C, which is the value selected for the dry-mold conductivity, used in further tests.

Next step is to consider the variation of the mold's conductivity. In this case the conductivity is defined as a function of temperature, considering wet-sand conductivity when the temperature is less than 100 °C and taking dry-sand conductivity otherwise. Dry-sand conductivity is fixed and different values of wet-sand conductivity are tested. It is known from literature that the wet-sand conductivity is within a range of 0.8-1.7 W/m-°C, hence three values were tested (0.8, 1.1, 1.6). In this test it was noticed that change of conductivity has more influence in the formation of the mold's plateau and results in the cast are almost the same comparing to the previous case. In this sense, the results are analyzed in the mold, in the most representative point (TM2), considering that the results are very similar in the other points and finally plotted in Figure 10.

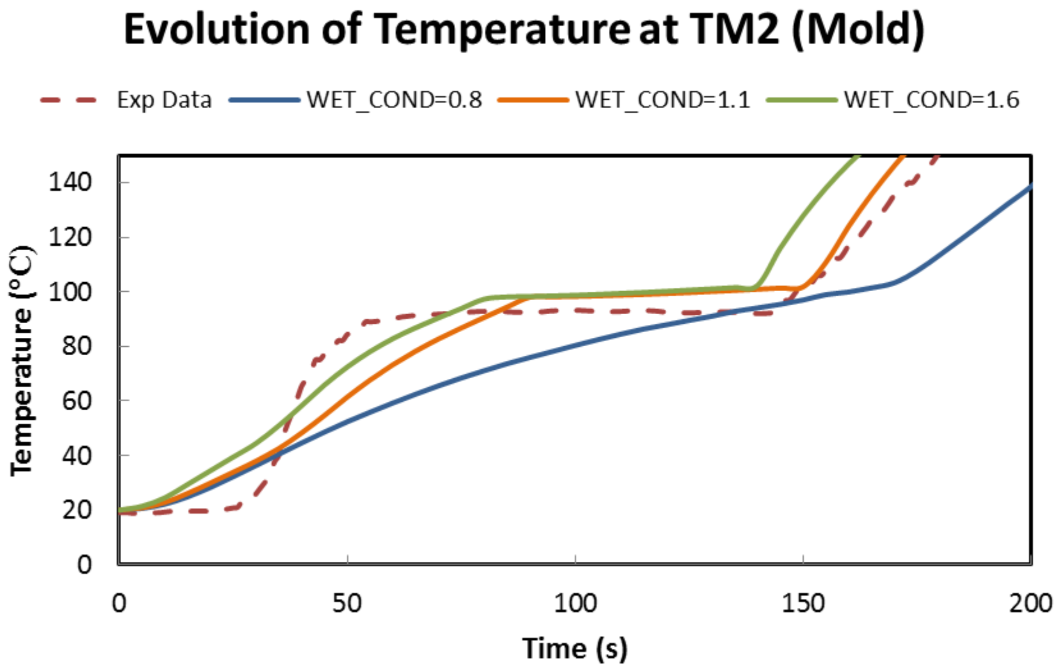


Figure 10: Temperature evolution in mold for different values of wet-sand conductivity

It can be seen that wet conductivity influences the formation of the mold's plateau, despite the two last values are almost equal, the higher values was selected in order to try to represent the fast initial increment of the temperature, which indicates that the conductivity is high at the beginning. Finally the value selected as wet-sand conductivity is 1.6 W/m-°C and is the value used for the further tests.

After this test the conductivity in the mold is defined as follows:

$$k_{mold}(T) = \begin{cases} 0.5 & if\ T \leq 100\ ℃ \\ 1.6 & otherwise \end{cases}$$

Equation 4

Heat Transfer Coefficient in cast/mold interface

As last step the influence of the HTC in the cast/mold interface was studied to see which value fits better to the experimental results. Like in previous cases three values of HTC were tested to see the influence in the results. Several articles were investigated to have an idea of the estimation of the initial values and the paper of Santos et al. [6] gives good values to start. Despite in reality the HTC is variable due to material contraction, it is considered constant in this study for simplicity. In Figure 11 the temperature evolution is shown for a representative point in the cast and analogously for the mold in Figure 12.

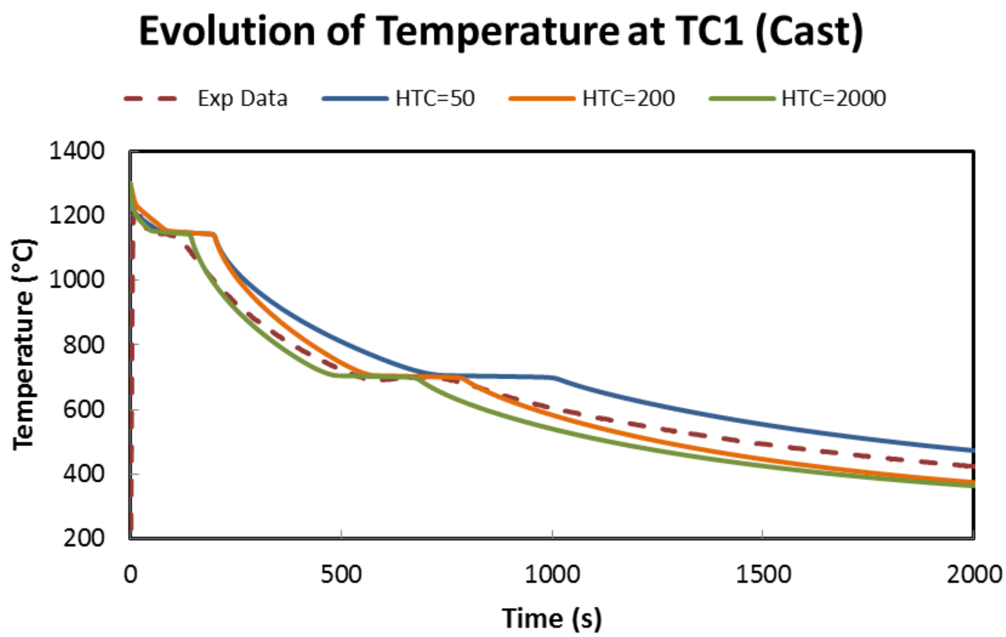


Figure 11: Temperature evolution in cast for different values of HTC in cast/mold interface

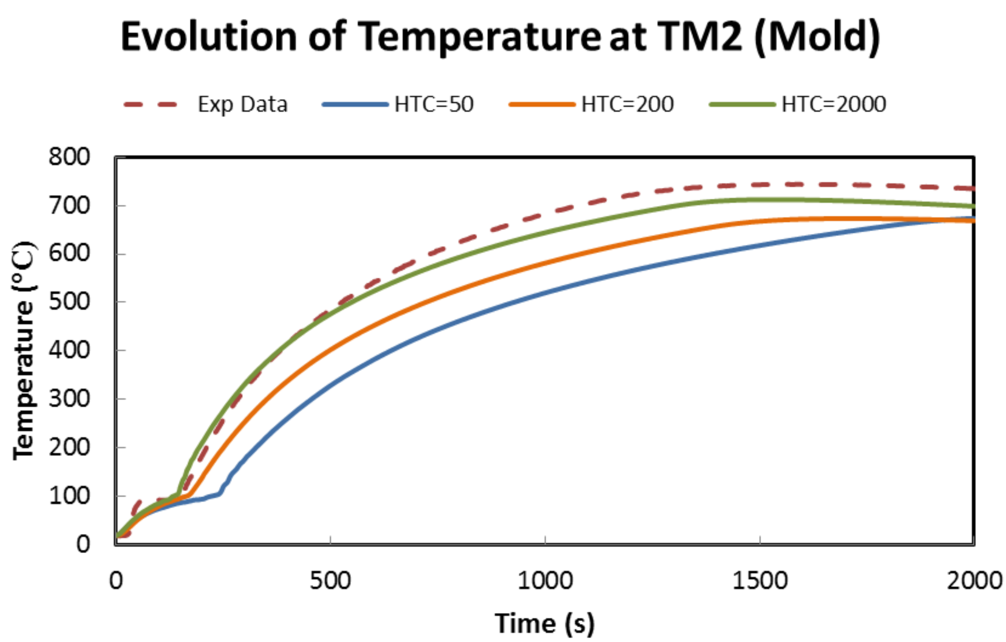


Figure 12: Temperature evolution in mold for different values of HTC in cast/mold interface

As it is seen, the influence in the mold's heating curve is bigger comparing to the cast's cooling curve. Also, the influence of the HTC has similar effects comparing to the mold's conductivity. But in general higher HTC will heat faster the mold and cool down faster the cast. In the mold's curve, a lot of variation occurs in the range of 200s-1500s, after this range the variation is reduced. It can be seen that the best fit for the curve in the mold is achieve with a HTC of 2000 J/kg-°C and therefore this is the value chosen for further analysis. However, as it was mentioned before and as articles of Sun et al. [3], Santos et al. [6] and Palumbo et al.[7] suggest, the Heat transfer Coefficient is not constant and this should be taken into account in further analysis.

Final Results

In the following section, the results for each location of the sensors; are presented using the final parameters estimated in the sensibility analysis and specified in Tables 1-3. Also, it should be recalled that the measure of TM4 is not reliable as it was mentioned in the section "Experimental Data". The first three curves correspond to the evolution of the temperature in the cast and the last four correspond to the temperature's evolution in the mold. The experimental data is showed in dash-red and the simulated data in blue. A final plot shows the relative error calculated for each curve.

In the cast

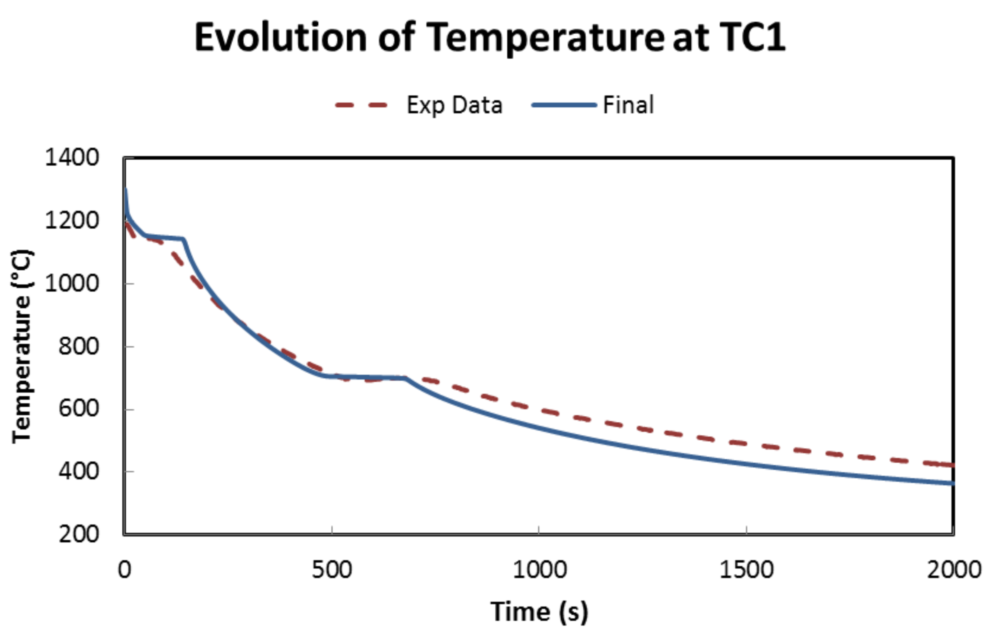


Figure 13: Temperature evolution in TC1 (best fit)

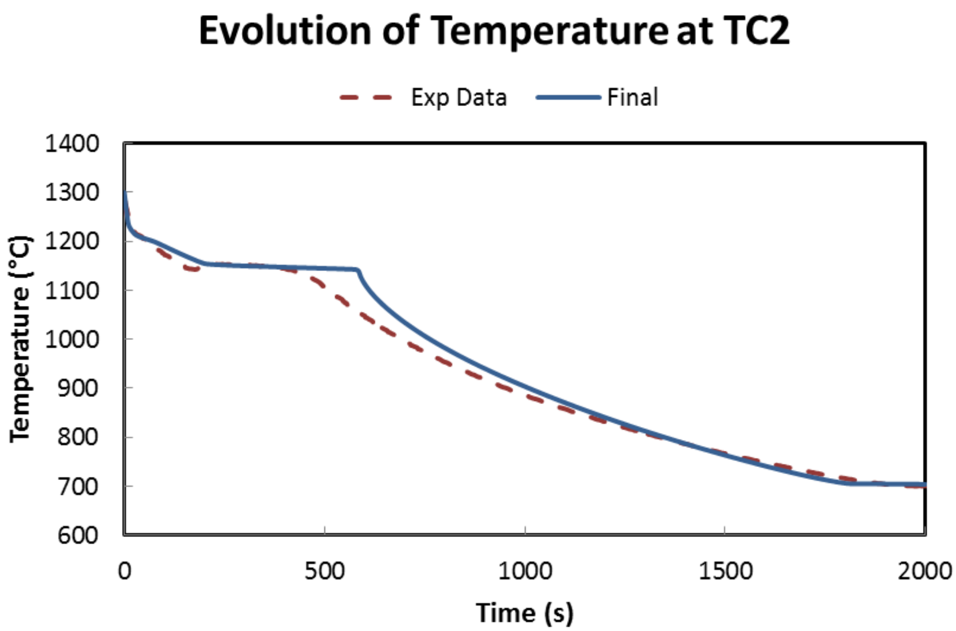


Figure 14: Temperature evolution in TC2 (best fit)

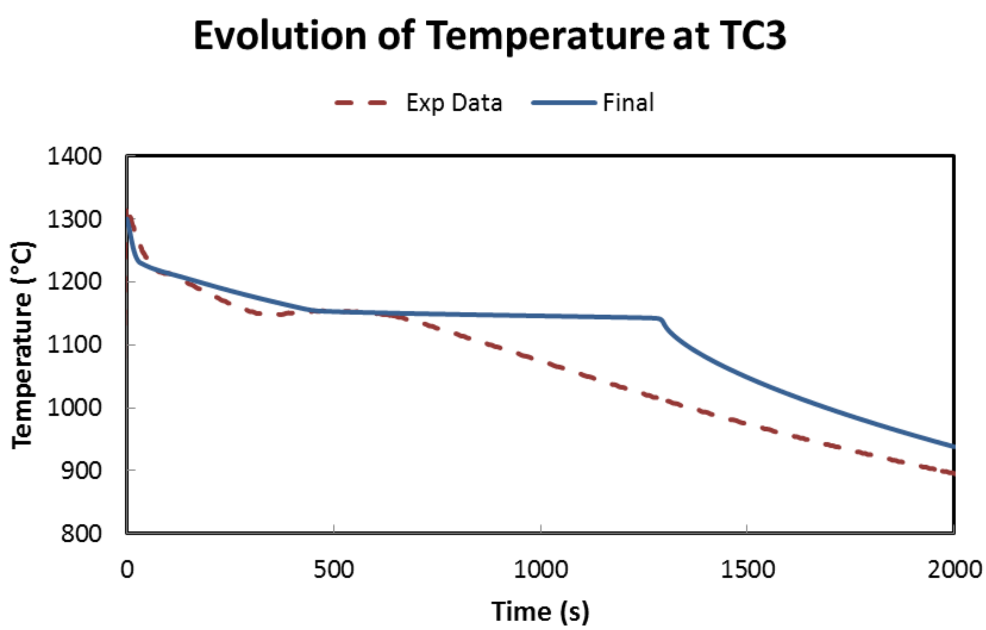


Figure 15: Temperature evolution in TC3 (best fit)

In the mold

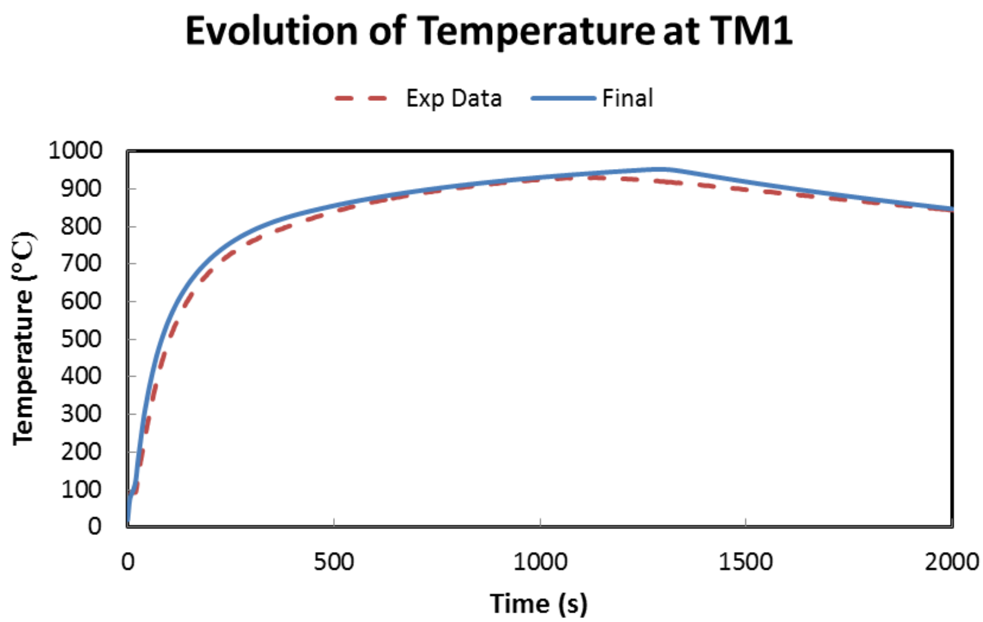


Figure 16: Temperature evolution in TM1 (best fit)

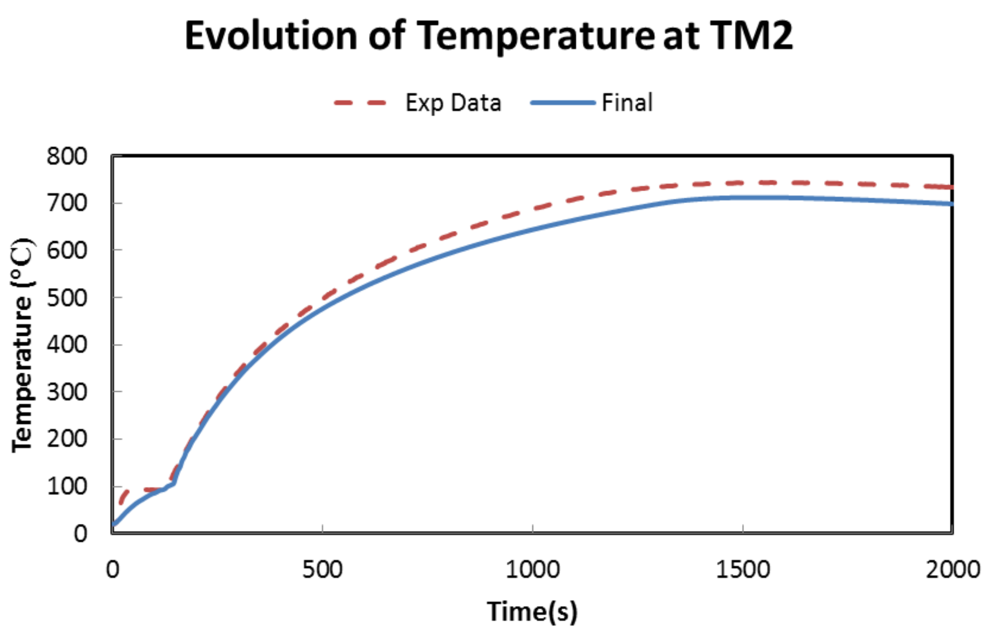


Figure 17: Temperature evolution in TM2 (best fit)

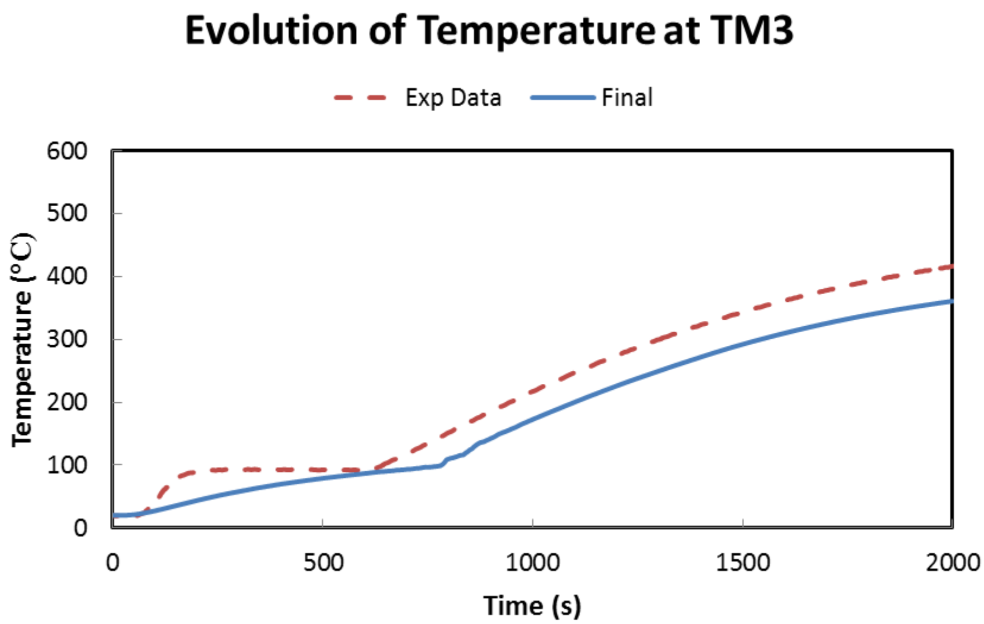


Figure 18: Temperature evolution in TM3 (best fit)

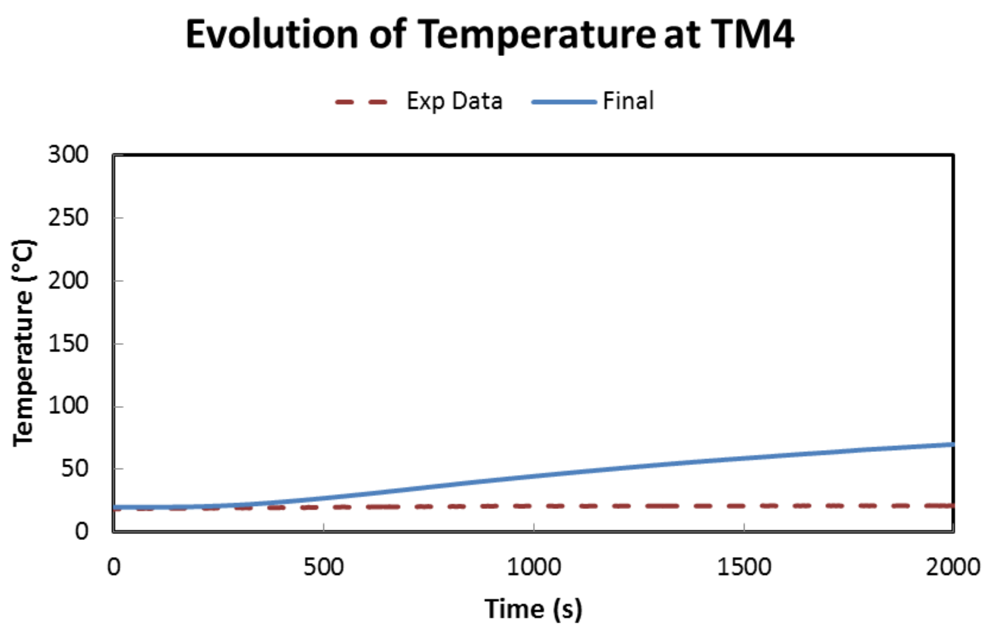


Figure 19: Temperature evolution in TM4

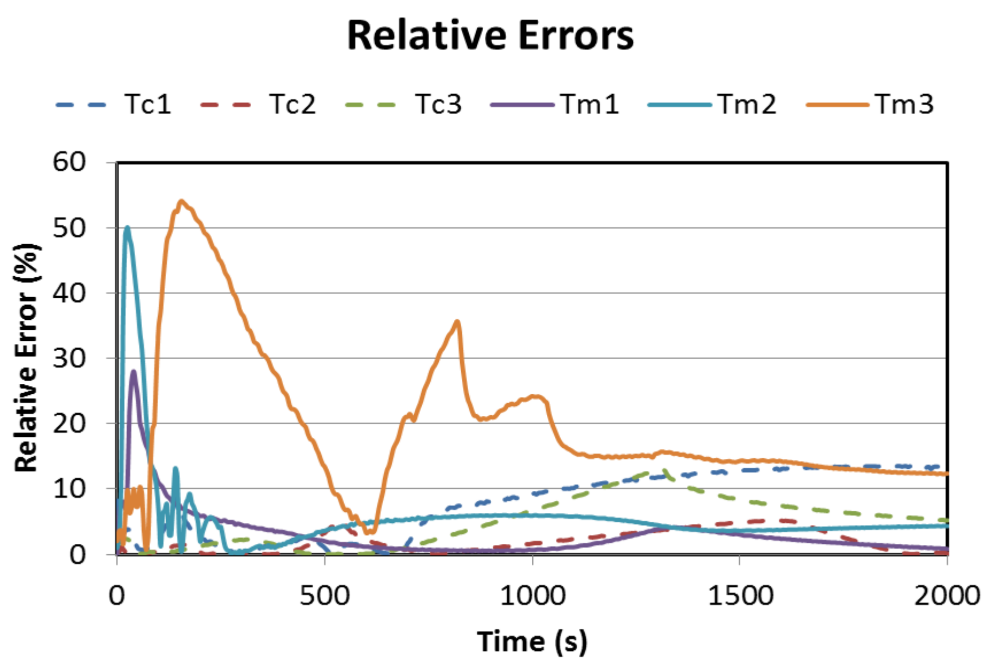


Figure 20: Relative Errors of final result

Conclusions and future work

In general, it was possible to obtain good results, considering that many parameters were unknowns and there is not a lot of information available of its values. As it is seen in Figure 20, the errors at initial steps are higher than 10% and after around 100s are reduced considerably. The only exception is TM3, which errors are more than 10% in the whole time interval.

It can be concluded that the increment of the mold's conductivity and the increment of the heat transfer coefficient (HTC) have similar effects on the results, high values of conductivity or HTC, gives a higher cooling rate (cast) and vice versa.

Despite, it was not possible to model accurately the plateau formed in the mold, it was found that the Latent Heat of water in the mold and the wet-sand conductivity influences its formation. It must be remarked that considering the change of mold's conductivity was a key point to see the change of the heating rate that happens around 100 °C in the mold.

As mentioned at the beginning, the HTC from the material boundaries to the environment do not have influence in the results since for the defined time intervals, the temperature at the boundaries do not change considerably. On the other hand, the HTC between cast-mold interfaces plays a key role in the cooling/heating process. It was observed that for values of HTC higher than 2000 the results are very close to each other. However, it must me recalled that an idealization is made considering that the HTC is not constant. In a more realistic scenario, variation of the HTC in the cast/mold interface takes place during cooling process when the cast shrinks and an air gap appears between the cast/mold interfaces, reducing the heat transfer considerably. Some studies and methodologies can be used to estimate experimentally the variation of the HTC in time [3], [6], [7].

During the adjustment of the parameters, it was hard to fit all curves at the same time, probably because of the assumption of homogeneous initial temperature distribution. In reality, the pouring of the molten metal gives a non-homogeneous initial temperature distribution and this fact should be considered for further analysis. Also, it must be taken into account that only one measure was given, meaning that there is no information about the dispersion of the measures and experimental errors.

During the development of the work, it was seen that this is a very complex problem because of its thermo-mechanical nature and due to the difficulty to find experimental values of parameters like heat conduction in the interface, emissivity, heat transfer coefficient due convection, concentration of compounds in each material and others. A suggested step will be to perform more experiments that involve the characterization of the properties for the simulated material, and recreate a model that estimates the HTC between the cast-mold interfaces. Also perform more measurement to define the dispersion and the errors.

Summarizing, the following considerations can be included for future work, to adapt the model to a more realistic physical phenomenon:

- Consider non-homogeneous initial temperature, due to the pouring process.
- Include variation of the HTC due to iron contraction. Creation of a model that describe the variation.
- Estimate measure errors and dispersion of experiments.
- Perform additional experiment to characterize the material's properties:
    - Humidity of the sand. This will give an accurate estimation of the latent heat of the water in the sand.
    - Conductivity for dry and wet sand.
    - Variation of HTC in time. This can be used to create the model that describes the variation of HTC.

Furthermore, deeper and complex developments can be done to characterize the biphasic heating of the sand and also the change of phase in the casting: for example using nucleation and evolutions laws and. Also, a deep analysis must be performed in the sand during heating and see what happens with the vapor generated, how much is released to the atmosphere, how much goes to the gap created between the cast-mold interface or stays in the sand absorbing heat.

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Annex

Table 4: Heat Conduction and Specific heat of the Casting

Temperature (°C)	Heat conduction (W/m-°C)	Temperature (°C)	Specific heat (J/kg-°C)
0.000	44.913	0.000	543.469
100.000	44.812	100.000	548.556
200.000	43.563	200.000	562.374
400.000	41.100	400.000	585.191
500.000	39.900	500.000	595.797
600.000	39.576	600.000	627.681
800.000	38.955	800.000	691.092
1000.000	38.385	1000.000	752.183
1101.555	38.138	1101.555	783.204
1140.000	36.638	1140.000	856.667
1151.598	36.365	1151.598	870.749
1194.758	36.000	1194.758	898.771
1235.000	36.000	1205.000	900.000
1600.000	34.000	1280.000	909.000

Table 5: Density of the Casting

Temperature (°C)	Density (kg/m^3)
0.00	7214.53
100.00	7213.32
250.00	7194.60
500	7163.40
750.00	7124.59
1000.00	7085.49
1100.00	7069.84
1101.00	7069.60
1140.00	7065.53
1151.00	7065.58
1194.00	6980.00
1600.00	6900.00

Table 6: Solid Fraction of the Casting

Temperature (°C)	Solid Fraction	Temperature (°C)	Solid Fraction	Temperature (°C)	Solid Fraction
1149.84	0.492777	1148.71	0.546744	1146.61	0.659402
1149.78	0.495582	1148.61	0.551613	1146.39	0.672054
1149.71	0.498472	1148.51	0.556713	1146.14	0.685832
1149.65	0.501452	1148.41	0.562064	1145.87	0.700922
1149.58	0.504527	1148.3	0.567701	1145.58	0.717562
1149.51	0.507706	1148.18	0.573659	1145.25	0.736178
1149.44	0.510992	1148.06	0.579964	1144.87	0.756935
1149.37	0.514391	1147.94	0.586669	1144.45	0.779774
1149.29	0.517908	1147.81	0.593744	1143.97	0.805596
1149.22	0.521555	1147.67	0.601257	1143.4	0.834975
1149.14	0.52534	1147.52	0.609265	1142.71	0.868485
1149.06	0.529274	1147.36	0.617816	1141.85	0.906644
1148.98	0.533375	1147.2	0.627028	1140.68	0.950114
1148.89	0.537635	1147.02	0.636977	1138.37	0.997871
1148.8	0.542089	1146.82	0.647773	1119.06	1