A Heat Transfer Model for Ugitech's Continuous Casting Machine

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Abstract: Ugitech S.A., stainless steel long products producer, uses a continuous casting machine to solidify square blooms. More than 150 different steel grades are produced; and each one requires specific casting conditions in terms of casting speed, mould powder properties, secondary cooling flow rate, etc. Considering the temperatures involved and the intrinsic difficulties of a continuous casting machine driving, models are required to help defining the appropriate casting process. Such a model is presented in this article, starting from its necessary simplifications (many phenomena are intricately coupled together). Then the equations and couplings are explained, with some emphasize on their implementation within Comsol Multiphysics. In a third part, we are showing some results : adjustment of the heat transfer model compared to the real situation and first thermo-mechanical coupling trials. Finally, some new opportunities opened by such a tool are displayed, together with its current developments.

Keywords: continuous casting, heat transfer, thermo-mechanical coupling, solidification.

1. Introduction

1.1 The continuous Casting Machine

Ugitech's continuous casting machine is a three-strand vertical bloom caster. The section of the product is square with rounded corners. The model we have built is free to take advantage of this symmetry (thus reducing the problem size by a factor 8), or to maintain the square geometry, and study eventual asymmetrical boundary conditions. The machine layout is shown on figure 1: one can see in color, the strand surface temperature superimposed to a mould and secondary cooling drawing.

The total metallurgical length — 19 m — is enough to fully solidify the steel section. After complete solidification, each strand is torch-cut at the appropriate length, to make around 15 blooms *per* heat. One of the questions we have to answer, is the position of the liquid well: if we would increase the casting speed too much, we may torch-cut on the liquid well: this would be a major accident since 5 tons of liquid steel could flood the bottom parts of the machine!

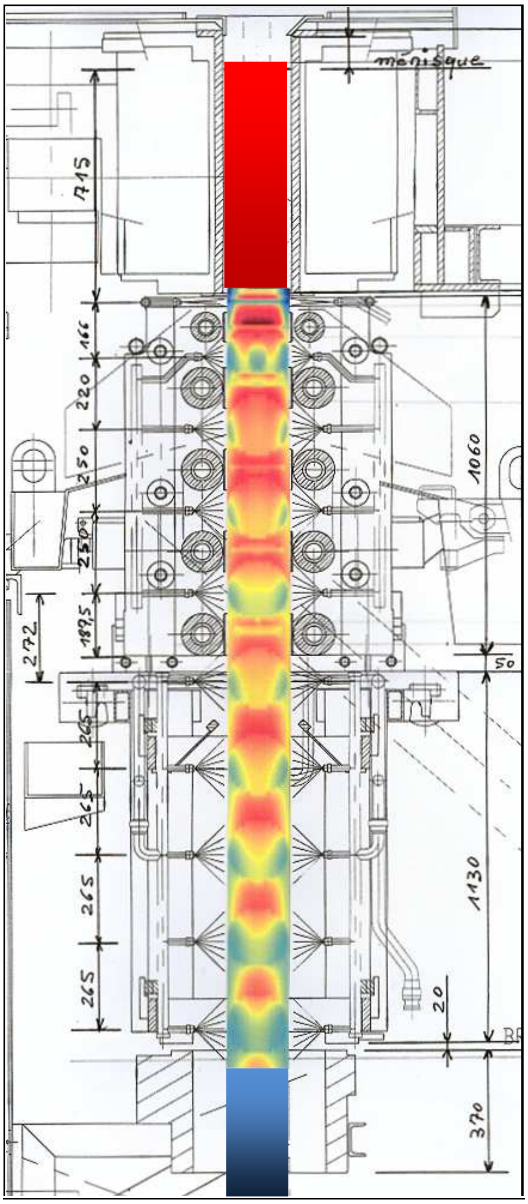

Figure 1. Ugitech's concast machine drawing, showing the upper 4 m : mould and secondary cooling

The mould is a copper tube with an intense water cooling. This tube presents a double taper in order to follow the steel shell shrinkage, as it is cooled and extracted. The machine automatons measure the heat flux through the mould thanks to a heat balance on the cooling water.

The secondary cooling is made of three series of water nozzles. A first ring of 4 flat nozzles is situated just below the mould, then two series of round nozzles — one with rolls to maintain the thin solid steel skin, one without — increase the solidified shell thickness further, until it can withstand the ferrostatic pressure in the liquid well.

The rest of the strand is cooled down mainly through radiative heat transfer, and marginally through convection (natural convection). The temperatures of the steel are varying from 1500°C to 800°C.

2. Modeling hypotheses

The phenomena involved in a solidification process are numerous. Regarding the bulk of the material, one can quote : heat transfer through conduction and convection, liquid metal flow, solidification with segregations, mechanical stresses and strains. Regarding the boundary conditions, we have radiative and convective heat transfers, phase changes (cooling water), varying contact conditions (air gap), through non-linear conductive layers (mould flux), etc.

Obviously, some simplifications are to be done the get an industrially relevant model. This means that:

- The result should be calculated in a reasonable laps of time. This strongly depends on the computer speed, and on the operator patience. But it definitely forbids full 3D models, especially when they involve fluid flow, phase changes and thermo-mechanical strains together. The more physics we want in the model, the less ambitious should be the mesh! *We have chosen a 2D transient model with a mesh, fine enough to track the solidification front with accuracy.*
- The fluid flow is thus neglected. An annex model was used to define a correction of the heat transfer parameters in the regions influenced by an important liquid metal flow. The correction involves a *locally increased thermal conductivity in the submerged entry nozzle jets region*.
- The solidification phenomena are treated in two uncoupled steps: a thermo-dynamical model (outside of Comsol) calculates, depending on the steel composition and temperature, the phases and enthalpy variations of the grade. We are assuming an equilibrium situation. Then these results are input within the Comsol model which handles the solidification as a strong non-linearity in the material properties around its melting temperature. *Segregation phenomena are thus neglected for the time being*.
- The contact between steel and mould is simplified in two different ways, depending on the model version: a pure heat transfer model considers only a heat balance, and spreads the extracted heat flux along the mould length, assuring only the overall amount of heat extracted. On the other hand, the coupled model, which involves also thermo-mechanical calculations, deals with a thin interface layer, made of molten or re-solidified mould power, with eventually an additional air gap.

All these elements are implemented using Comsol Multiphysics 3.4. As mentioned above, two versions of the model have been built:

- a pure heat transfer model, which runs in about a quarter of an hour, is currently used for industrial purposes (new grades studies, process optimization, machine modifications testing, etc.).
- a heat-transfer / thermo-mechanics coupled model, whose purpose is to calculate the local heat flux density through the mould. This model requires a more extensive computational effort (around 5 hours *per* run). This model's building is still going on, since its main difficulty remains the constitutive law for the steel near its melting point.

3. Implementation of the model

3.1 Physical domain

The physical domain is restricted to a fraction of the bloom section. In most cases, we take advantage from the symmetries, while considering a transient 2D problem. The time t variable is transformed into a space variable z using the casting speed as a scale. This allows us to use the very fine mesh, necessary to handle the solidification non-linearities.

Two meshes are used. A complete one, with regular cell size is used for the heat transfer problem (figure 2), and a partial one for the mechanical calculations (figure 3). The former is used for both models, while the latter is only designed for the mould boundary condition calculation in the thermo-mechanical version.

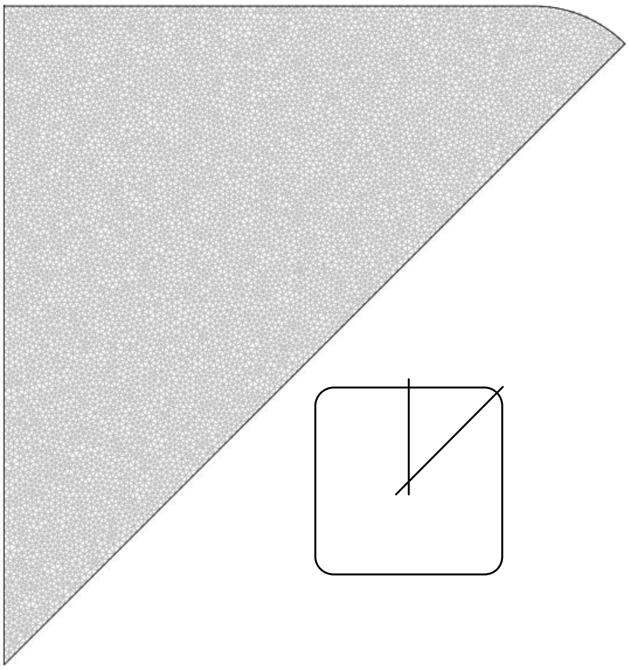

Figure 2. Heat transfer mesh compared to the bloom section.

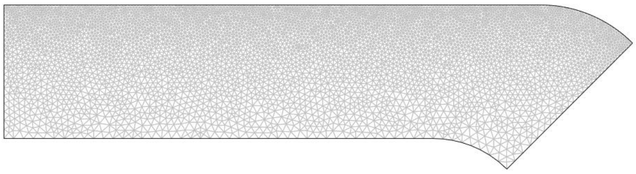

Figure 3. Mechanical partial mesh.

Both meshes are very fine, due to the very strong non-linearities that cross the whole mesh during the simulation. While the material is in a single phase state, its properties consist mainly in analytical laws extracted from bibliographical or experimental data. Between the *solidus* and *liquidus* temperatures, a phase fraction, calculated outside Comsol Multiphysics, is input as a curve. The heat transfer data, such as k, ρ and Cp, are calculated using the solid and liquid fractions as weighting coefficients.

In the thermo-mechanical model, the constitutive law, for the time being, is composite : in the liquid phase the material is represented by a purely elastic medium, with a very low Young modulus, so as to accommodate any deformation without strain accumulations; while in the solid state, the medium is purely elastoplastic, with a temperature dependant elastic limit.

3.2 Boundary conditions

The main difficulty in such a model is the boundary conditions. Two difficulties arise:

The first one is our choice for a 2D transient model, supposed to represent a 3D stationary situation: the boundary conditions depend on the *z* axis, hence on time... For example, the nozzle spray geometry has to be described as a time dependant data, since any section of the bloom circulates in front of each nozzle or roll section...

The second one is the values of these boundary conditions: as a matter of fact, the data for the material itself are fairly well documented (at least, for conventional grades). On the other hand, the emissivity against T of a high temperature oxidized steel surface, or the convection coefficients for a specific nozzle (including its geometry, its water flow rate, and the surface temperature) are very poorly documented.

After an extensive bibliography, we have used the unsurpassed ability of Comsol Multiphysics to handle large equations (including their formal derivation!) to feed complicated expressions as boundary conditions. For example, the convection coefficient h of a specific nozzle has been described as a function of x and z like this:

```
h = f(x,z,...
      Number of nozzles along x,...
      Inter axis between nozzles,…
      Distance to the bloom surface,…
      Vertical angle,…
      Horizontal angle,…
      Water flow,…
      Water temperature)
```

This function is a 523 characters expression, just for one nozzle ! The 3D graph on figure 4 shows the value of the convection coefficient, as a function of x and z. The same function handles flat (i.e. elliptic) and round nozzles. The final convection boundary condition cumulates the influences of all the nozzles in one single formula: it contains 16 calls to the convection function!

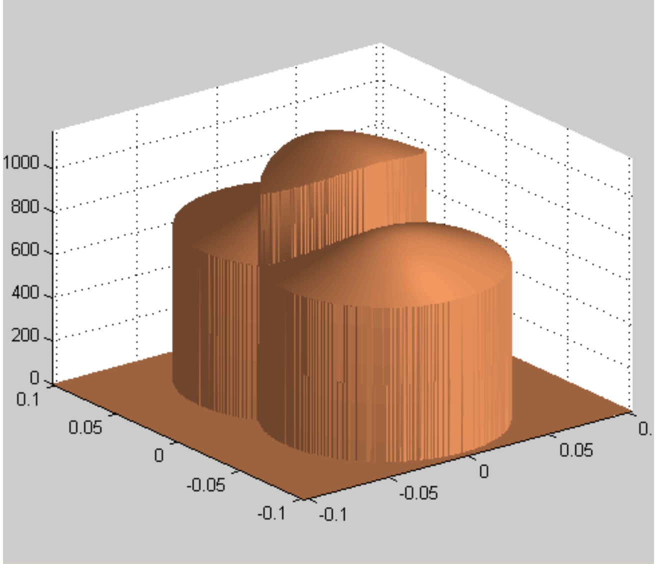

Figure 4. Convection coefficient in W.m^2.K^{-1} for two partly overlapping nozzles, against *x* and *y*

The radiative heat transfer is handled in the same manner, with an analytical formula input in Comsol Multiphysics, depending on *T*.

3.3 Coupling

The main purpose of having two coupled models here, is to calculate the local heat flux within the mould. As a matter of fact, the overall heat extraction is known from industrial data, and the heat transfer model gives results, good enough to forecast the liquid well closure position, with a good accuracy. But, if one considers for example, the steel shell thickness at the mould exit, one has to consider the way this heat flux is spread over the metal/mould interface.

The solution for this problem involves a series of very tightly coupled phenomena:

- Some heat is extracted by the mould, through the mould flux interface. This interface properties are temperature dependant, with liquid, solid, translucent or opaque phases.
- This heat comes from the solidification front progression within the bulk of the metal.
- This solidification, and the temperature gradients associated, bring up some stresses in the solid shell.
- The thermal stresses, due to solidification and cooling, induce strains in the shell. These strains may — or may not — open gaps inside the metal/mould interface, depending on the ferrostatic pressure within the shell compared with the shell mechanical resistance.
- The eventual gap opened at the interface modifies the heat extraction...

Within Comsol, two meshes handle the two parts of the problem. The mechanical mesh receives an internal pressure proportional to *z* (ferrostatic pressure), and a manually implemented frictionless contact condition at the outside. The position of the mould depends also on *z*, to take its taper into account.

Finally, the distance between the mould position, and the shell surface (when positive) is used within yet another analytical formula, for the interface heat resistance between mould and shell. See figure 5.

In the other direction, the temperature field is transported as a data for the mechanical model, using projection variables.

4. Some results

Two cases are presented here. The first one deals with the comparison between the heat transfer model and real measurements on the continuous casting machine. This validates the boundary condition laws we have used.

The second case is the local heat flux calculation explained in the last paragraph. This calculation is to be considered as a feasibility trial, more than as a real forecast. Nevertheless, it gives fairly good results compared with literature data. Today, the average heat flux *per* section is used as a repartition key for the overall heat flux, along the mould, in the first model.

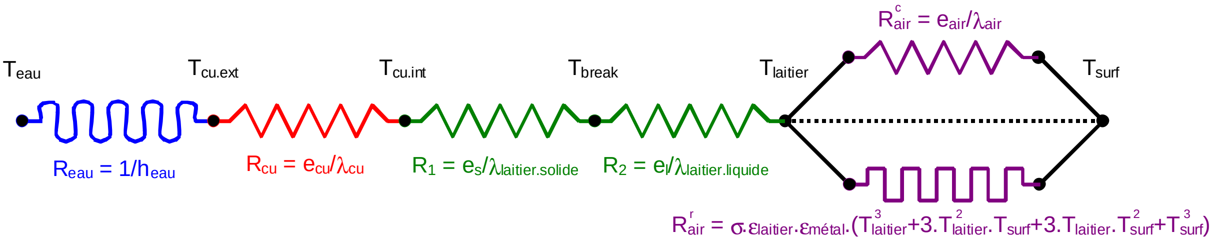

Figure 5. The analytical interface model between mold and shell

4.1 Heat transfer simulation, comparison with real measurements...

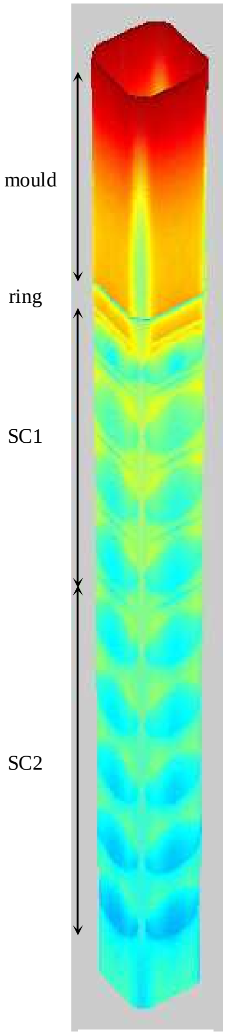

Figure 6

Figure 6 shows the surface temperature of the strand, inside the upper part of the machine. One can see the influence of each cooling device on the surface temperature. Each roll is also taken into account.

Figure 7 shows three curves giving the temperatures along the strand. The length of the liquid well can be read when the center temperature crosses the solidus value.

Figure 8 shows an image of the mushy zone, using a modified scale to accommodate the shape of the strand: the horizontal axis represents 205 mm, while the vertical axis represents 19 m! The meniscus being at the bottom of the picture, one sees that this grade has a fairly large solidification interval, which gives 5 meters of mushy zone at the axis.

During our experiments on the real process, we have compared the measured values with the calculated temperatures, and adjusted a variable remaining unclear, regarding the radiative heat transfer inside the secondary cooling. After this adjustment, the model remains within a good precision range of ± 10°C, all along the strand.

Finally, we had an occasion to torch-cut a bloom, in the machine, very near the liquid well closure, confirming the forecast at less than 12 cm.

This heat transfer model is now used to explore different possibilities regarding the secondary cooling. The main problem remaining is the data collection for poorly documented grades. Everybody knows 304 or 316 stainless, but the literature is sparse for more exotic grades such as 904L, 321, 431, UR45N, etc...

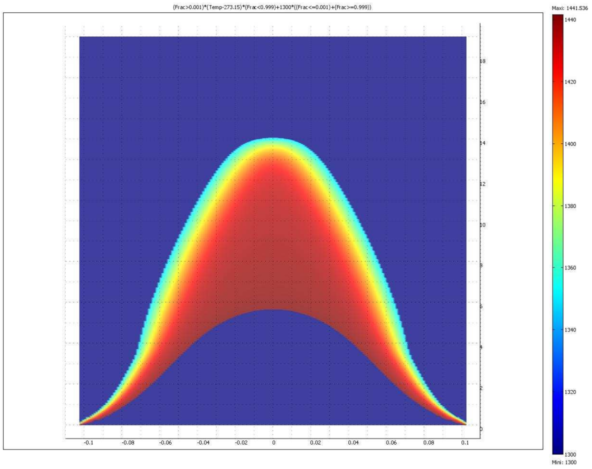

Figure 8. Liquid well shape (vertical scale contracted)

4.2 Thermo-mechanical calculation within the mould, using a simplified constitutive law.

The results, presented in section 4.1, are calculated using a specified heat flux within the mould. Since the overall flux is measured on the machine, the temperatures are correct below the mould and after. In the mould, the simulation does not take into account the complex interface phenomena.

The second version of the model brings the

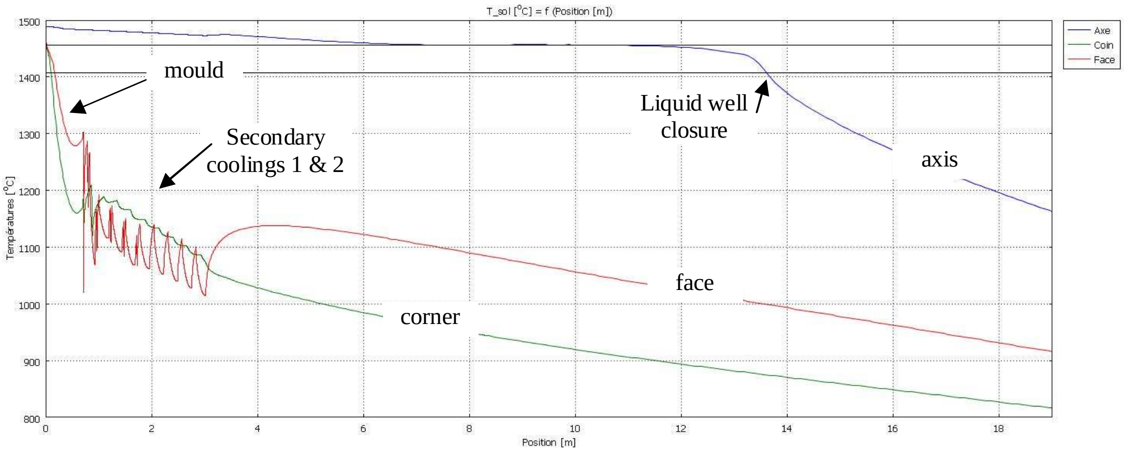

Figure 7. Temperatures at the corner, face and axis of the bloom

thermo-mechanical behavior of the solidified shell into action, and evaluates the presence of an air gap, which decreases drastically the local heat flux. Figure 8 and 9 give the average heat flux *per* section as a function of the distance to the meniscus, and a picture of the heat flux on one face of the mould.

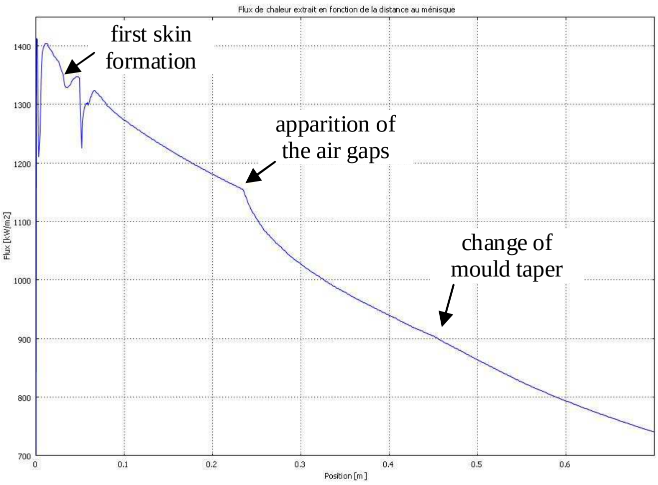

Figure 8. Average heat flux in the mould as a function of the distance to the meniscus

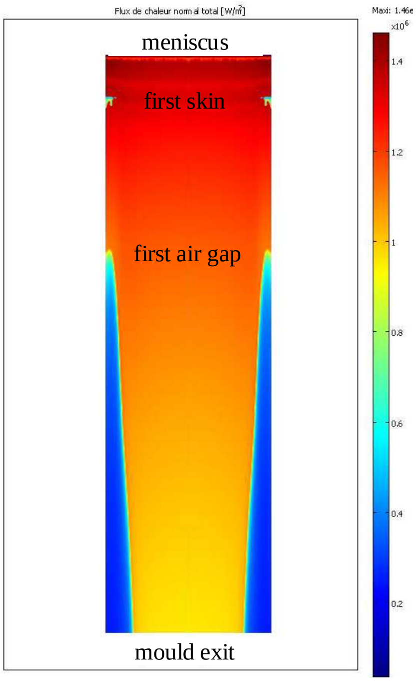

Figure 9. Heat flux between steel and mould on a face of the bloom

Finally, figure 10 presents the mould exit section of the product, with the temperatures, and iso-solid fractions on the left hand side, together with the internal stresses on the right hand side. The air gap built in the corners is clearly visible.

The current state of this model does not warranty an accurate prediction, since our current constitutive law is not yet correct. But we have proven the possibility to implement such a model within Comsol Multiphysics.

7. Current developments

Our current work on the model consists in:

- feeding it with new data regarding our steel grades. This work requires time and expensive experimental work, but is necessary to deal with undocumented grades,
- building a thermo-mechanical model (mainly a constitutive law) which is able to describe correctly the near solidification behavior of our steels. Some numerical aspects (convergence, stability) are at stake in this field.
- building a 3D stationary model of the mould content, in order to study the influence of the liquid metal flow on the first solidification.

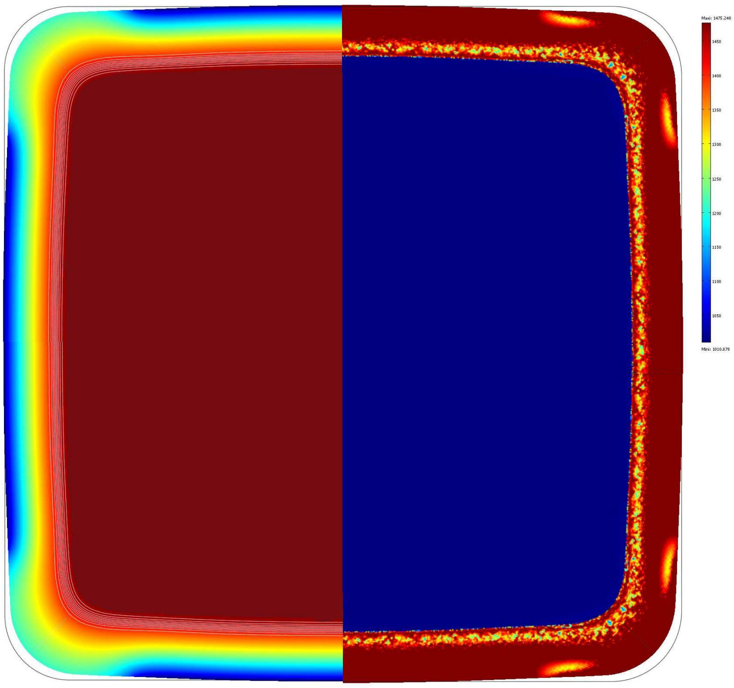

Figure 10. Mould exit composite section

8. Conclusions

With a reasonable investment in terms of software and engineering time, we have build a two stage model of Ugitech's continuous casting machine. This model was designed to deal with the heat transfers mainly. Due to coupled phenomena, we have also introduced a thermo-mechanical model to increase its accuracy within the mould.

This model is able to forecast the surface temperature along the strand, and the depth of the liquid well, with a good precision. It allows us to test new grades (modification of the solidification data), to test new secondary cooling adjustments (including eventually, new nozzles), and to test also new casting formats (other squares, rectangles, changes in the corner radiuses). The overall engineering effort put on this model represents around 2 to 3 man-months.

Since Comsol Multiphysics is very opened to the user's needs, our constant bibliographic survey can be easily transferred into the model, and used directly to drive an industrial process.

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Only the externally published references appear in this list. Our main collection of metallurgical data is not published.

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