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# 3D THERMOMECHANICAL SIMULATION OF THE SECONDARY COOLING ZONE OF STEEL CONTINUOUS CASTING

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## Abstract

This paper addresses the simulation of steel continuous casting (CC) using two non steady-state approaches: a slice method and a global method. Both methods can take into account the curvature of the CC machine. We describe the implementation of the two methods. We present the resolution of the thermo mechanical problem of the process. The two methods are compared in the case of CC of thick products.

## Introduction

The continuous casting (CC) of slabs or billets is a widespread process in steel industry. Starting from liquid steel, a primary cooling zone constituted of a water-cooled vertical copper mould achieves the solidification of a solid shell. This shell is thick enough to permit downwards extraction of steel by supporting rolls which convey it throughout the secondary cooling zone, in which the product is submitted to intense water cooling. Hence the solidification proceeds from surface towards the centre of the product.

Simulating CC process is challenging, at least for two main reasons. On one hand, it is difficult to model steel behavior in a very large temperature interval. This is a real problem insofar as researchers have not proposed yet any model to fit correctly with the three different states encountered. On the other hand, it is necessary to calculate on very large domains: because of the low diffusivity of steel, the solidification depth ranges from 15 to 20 m for classical thick slabs (2000*200mm). The simulation then requires a huge computation power or the parallel computation techniques.

The final objective of the study is to model the thermo mechanical state of the product at the bottom of the mushy pool, where solidification ends. Improvement of internal quality of continuously cast products (segregated internal cracks and segregations) is essentially tied to mastering the thermo mechanical deformations induced in this critical region. In the long term, a thermo mechanical model would be very useful to optimize the techniques that are used to prevent from these defects like the control of process parameters (speed, solidified thickness, temperature, ferrostatic pressure, water jet spraying) or still the evolution of support system geometry during casting (control of the product bulging...).

This paper presents a three-dimensional thermo mechanical model under industrial continuous caster conditions. In a fist part, we present hereafter the two different approaches that have been developed: a non steady-state slice method and a non steady-state global method. In a second part, the constitutive equations that have to be considered in thermo mechanical computations are presented. This point is central because the steel is simultaneously present in liquid, mushy (mix of liquid and solid) and solid state**.** Finally, results issued from the different formulations are compared in the case of CC of thick products.

## Resolution strategies for steel CC

In the literature, two different strategies are usually used: the non steady-state slice method, and the steady-state approach.

Non steady-state slice method:[1] [2]

In order to limit the number of unknowns, the slice method is often used (fig. 1). It consists in conveying throughout the machine a transverse section of the product (either a plane section or a small volumic domain having a small length in the casting direction). Adiabaticity and no axial deformation are generally used as boundary conditions. As the thermal gradients are very low along the casting direction, this method provides good thermal results. However, the mechanical bc's are not correct, yielding poor mechanical results. In addition, the slice concept cannot lead to bulging prediction, if the volumic domain is too small, and then cannot be used for precise thermomechanical calculations.

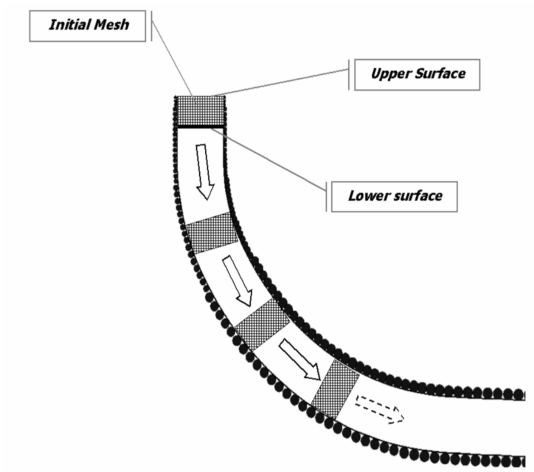

Figure 1: the non steady-state slice method

Global non steady-state method:

This method is illustrated in fig. 2. Starting from an initial small mesh representing a small volume of steel at a given location in the machine, the advancing of the material in the machine is simulated by imposing at the lower surface of the mesh a bilateral contact with a rigid tool which serves as an extraction tool. However, the upper surface is fixed and consequently the mesh volume enlarges continuously at the casting speed. Actually the lower rigid tool acts as the real bottom block which is used to initiate the real casting, but the prescribed boundary conditions must be consistent with the steady-state regime. Therefore, adiabaticity and perfectly sliding contact conditions are imposed. That method thus requires solving a transient thermomechanical problem and also to define the values used as initial values and as imposed values on the upper entry surface.

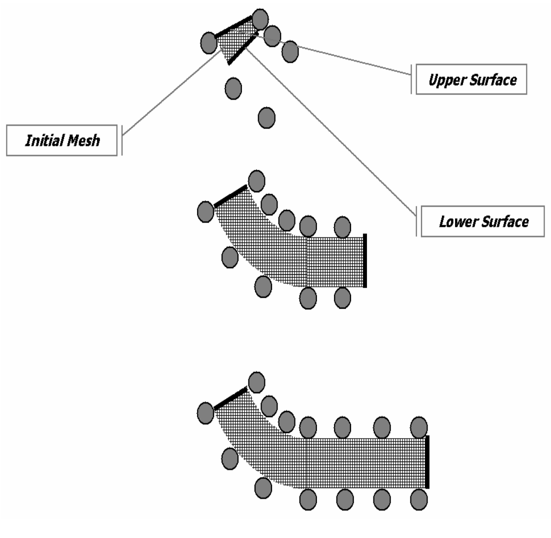

Figure 2: schematic view of the global non steady-state approach

In addition, we could use a steady state method that is of Eulerian type and considers a static computational domain. This supposes integration of the highly non-linear constitutive equations along streamlines (elastic-viscoplasticity). This formulation has been often used in the primary cooling zone or the beginning of the secondary cooling. Regarding application to the end of secondary cooling, as the shape of the free surface is unknown (bulging), specific algorithms have to be used in order to force the velocity field to be tangent to the surface [3]. Due to the high number of supporting rolls, this can lead to convergence difficulties. Some authors have supposed that the surface of the computational mesh does not depart from its nominal shape [4] [5]. This supposes then that the bulging computation is simply post-processed, which can give rise to imprecision and presents from any further coupling with the modeling of segregation phenomena for instance.

It is thought that the global non steady-state method, although computationally intensive, is well adapted to the above mentioned objectives, provided that a rapid convergence to the steady-state regime can be observed. This approach has been implemented in the tree-dimensional finite element software: THERCAST®, developed at Cemef laboratory and Transvalor.

## Thermo mechanical model

The earlier works dealing with the modelling of thermomechanical phenomena in casting processes (stress-strain computations) generally have been based on elastic-viscoplastic constitutive equations for the material behavior. The material parameters are then temperature dependent in order to model the evolution of the material behavior over a very large temperature interval, including the liquid-solid phase change. However, it has become clear that such a formulation fails to predict accurately those phenomena [7]. For instance, several drawbacks of this approach can be mentioned.

First, the change of specific volume associated with the liquid-solid phase change cannot be modeled adequately using a single elastic-viscoplastic constitutive equation because it causes artificial elastic stresses. A direct consequence is the poor quality of the prediction of the amount of volumetric shrinkage.

Second, regarding the modelling of the liquid phase, this approach is unable to provide a simple and acceptable representation of liquid or mushy states. The use of such a single model supposes the fluid to be at rest. This excludes the modelling of fluid motion associated with thermal or solutal convection, and so the relevant computation of the distribution of temperature and alloying elements in the liquid pool.

To overcome those difficulties, it has been suggested [7,8] to make a clear distinction between the constitutive equations used for the liquid or mushy state, and for the solid state of the alloys. The liquid or mushy state is modeled using a pure thermo-viscoplastic law, without any elastic contribution. Depending on the temperature (or the solid fraction), the model is either purely Newtonian (pure liquid state) or non-linear viscoplastic (mushy state). Below a critical temperature $T_C$, the alloy behavior is modeled by a thermo-elastic-viscoplastic constitutive law, which is more representative of solid-like behavior.

Without entering into mathematical details (see [7] [8]) we can see how those models can be used simultaneously in a single finite element resolution in the case of CC.

<u>Mechanical equilibrium equations:</u>
At any time, the mechanical equilibrium is governed by the momentum equation:

$$\nabla.\sigma + \rho g - \rho\gamma = \nabla.s - \nabla p + \rho g - \rho\gamma = 0 \qquad (1)$$

where $g$ denotes the gravity vector and $\gamma$ the acceleration vector. The acceleration is in fact noticeable only in the liquid pools, when they are affected by fluid convection. The Cauchy stress tensor $\sigma$ is in turn defined by: $\sigma = s - pI$ with $p = -\frac{1}{3} tr\, \sigma$ ($s$ the stress deviator and $p$ the associated hydrostatic pressure).

Concerning boundary conditions we have to distinguish between different cases:

- Lower surface: the kinetics of the extraction plane being known (the machine curvature and the extraction speed are known), the nodes in contact with this plane obey a bilateral condition with perfect sliding in the tangential plane.
- Upper surface: in the slice method, the upper surface is a free surface. For a global non-steady strategy, the upper surface is fixed (see further section).
- Free lateral surface: it is submitted to the contact with supporting rolls which are assumed non-deformable. This unilateral contact is modeled by a penalty method with respect to the analytical circular shape of each roll. For any boundary point M of the product and for any roll of centre C and radius R, we must have: $CM \geq R$, which is the non-penetration condition.

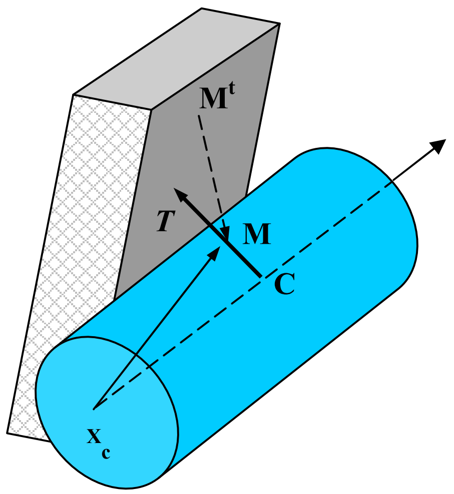


Figure 3: contact between rolls and product

Referring to Figure 3 and using a penalty constant $\chi_p$, we express that a possible penetration of $M$ into the roll gives rise to the application of a normal stress vector $T$ whose expression is:

$$T = -\chi_p \left[ R - \left\| \overrightarrow{CM} \right\| \right]^+ \frac{\overrightarrow{CM}}{\left\| \overrightarrow{CM} \right\|} \qquad (2)$$

with $M$ the updated position of the point at the end of the time increment, $C$ its projection onto the roll axis.

Mesh generation in a global approach

Before giving the weak formulation, we detail here the principle of the implementation of a global non-steady strategy. Indeed, our Lagrangian approach to the problem involves a deformation of the mesh and more particularly from the elements close to the upper surface. In order to avoid a global remeshing of the product and the heavy associated operations (transport of all the variables), a local remeshing is performed thanks to an extraction of topology. It is only on the remeshed part that the transport procedures are carried out. This limits considerably the computation time dedicated to the remeshing. A final merge of the two grids is performed, yielding the new mesh that is used for another series of times increments. When the deformation of the first row element near the upper surface is too important, a new mesh regeneration procedure is triggered (Figure 4).

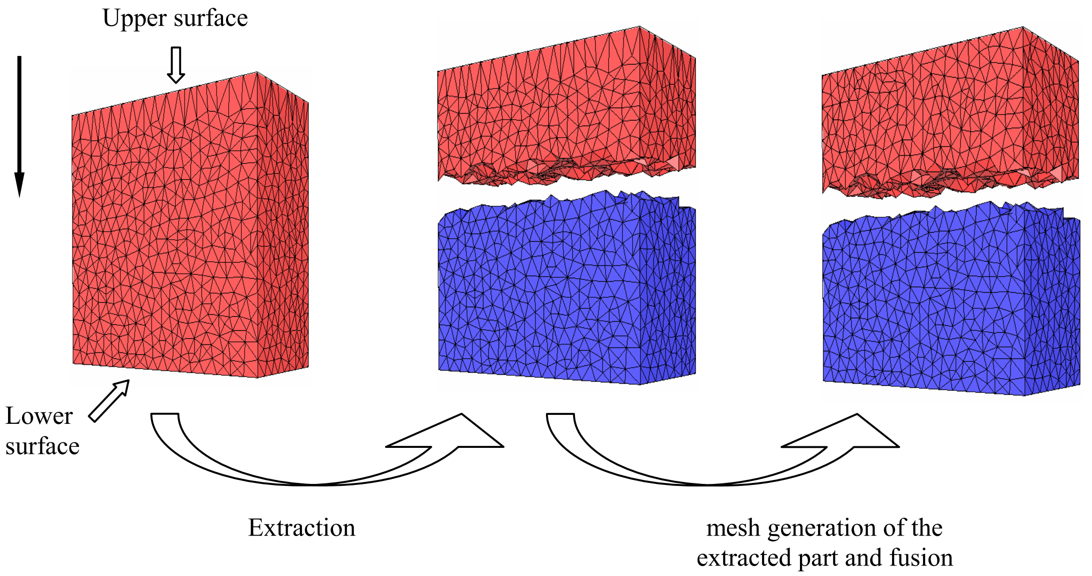


Figure 4: Periodic mesh regeneration procedure used in the global non steady-state approach

Weak form of mechanical equations:

The primitive variables are velocity and pressure. The problem to be solved is then composed of two equations. The first one is the weak form of the momentum equation, also known as the principle of virtual power. Since $p$ is kept as a primitive variable, only the deviatoric part of constitutive equations is accounted for and has to be solved locally in order to determine the deviatoric stress tensor $s$. Therefore the second equation consists of a weak form of the volumetric part of the constitutive equations. It expresses the incompressibility of the plastic deformation and governs the pressure evolution. This leads to:

$$\begin{cases} \forall v^* & \int_\Omega s:\dot{\varepsilon}^* dV - \int_\Omega p\nabla.v^* dV - \int_{\partial\Omega} T.v^* dS - \int_\Omega \rho g.v^* dV + \int_\Omega \rho\gamma.v^* dV = 0 \\ \forall p^* & \int_\Omega p^* \, tr\,\dot{\varepsilon}^{vp} dV = 0 \end{cases} \quad (3)$$

The pressure variable appears as a Lagrange multiplier of the plastic incompressibility constraint. The form of the term integrated in the second equation will change according to the local state of the alloy (*i.e.* according to the local temperature). Accordingly, the stress deviator $s$ will result either from an elastic-viscoplastic constitutive equation, or from a viscoplastic or Newtonian law.

After spatial discretization with the triangular mini-element (P1+/P1) [6] [8], the problem is solved for $(v, p)$ by a Newton-Raphson method.

Thermal problem

The thermal problem is based on the resolution of the heat transfer equation:

$$\rho c \frac{dH}{dT} = \nabla.[k\nabla T] \quad (4)$$

where $k$ is the thermal conductivity, $\rho$ the specific mass and $H$ the enthalpy per unit of mass which is defined as :

$$H = \int_0^T c_p(\tau) d\tau + L(1 - f_s) \quad (5)$$

where $c_p$ is the specific mass, $L$ the latent haet per unit of mass and $f_s$ the solid volume fraction. We assume that the solidification path $f_s(T)$ is given, which permits a resolution of (4) for the temperature [8]. The parameters $k$, $c$ and $\rho$ may depend on the temperature $T$. The initial temperature of the product is taken equal to the nominal casting temperature. The boundary conditions resulting from the interactions with outside are:

- Condition of imposed flux: $-k\nabla T.n = \Phi_{imp}$ (6)
- Condition of convection type: $-k\nabla T.n = h(T - T_{ext})$ (7)

These two conditions simulate the parietal cooling by water jet, the thermal contact with the cylinders and the radiation. They are averaged by zone: we don't calculate heat exchange in contact with each roll.

For the lower surface, as the thermal gradient is usually low in the casting direction, the lower surface is adiabatic. For the upper surface, in the global non steady-state strategy, the temperature is imposed in order to simulate the injection. In the slice strategy, both the upper and lower surface are supposed to be adiabatic.

## Results

In a first approach , the only role of the mechanical resolution is to convey the material throughout the CC machine, the study being then focused on heat transfer. As a consequence, the mechanical problem can be treated independently from the thermal one, using an arbitrary Newtonian behaviour.

A first test consists in using the non steady-state method. For comparison with 2D and 3D software, we restrict the analysis to the medium section of the slab. Using 3D software, we use a structured tetrahedral mesh (Figure 5) composed of 45 nodes in the thickness direction, 2 nodes in the width and in the casting direction. Initial temperature is taken equal to 1547°C at zero metallurgical length. Two sensors are used: in the center and the boundary of the section. Figure 6 shows the evolution of calculated temperature according to the metallurgical length and illustrates the good correspondance between the results of THERCAST® and those obtained with two other codes, which have been used in an effective 2D analysis with the same slice non steady-state approach: ABAQUS® and R2SOL (also developed in CEMEF)

A second test consists in modeling the cooling down with the global non steady-state method. As shown in Figure 7, the simulation is initiated with a small mesh whose growth is controlled by successive extraction-remeshing-merging procedures as described above. The advancement of the product in the machine is ensured by bilateral contact with the bottom plane which plays the role of the bottom block (except the associated adiabatic condition). The contact with the serves of supporting rolls is well managed by the penalty algorithm. It can also be noted that, despite the use of an arbitrary Newtonian behaviour, bulging effects can be seen, which shows the interest of this global approach.

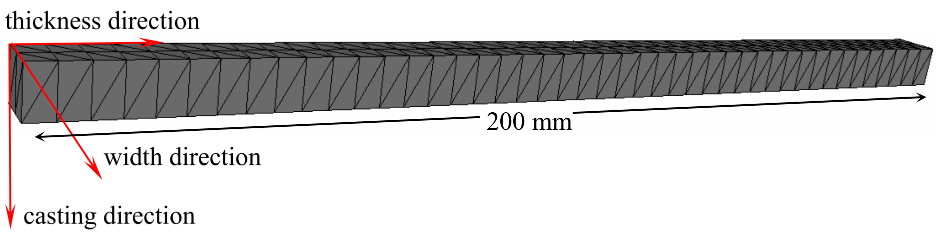


Figure 5: structured tetrahedral mesh

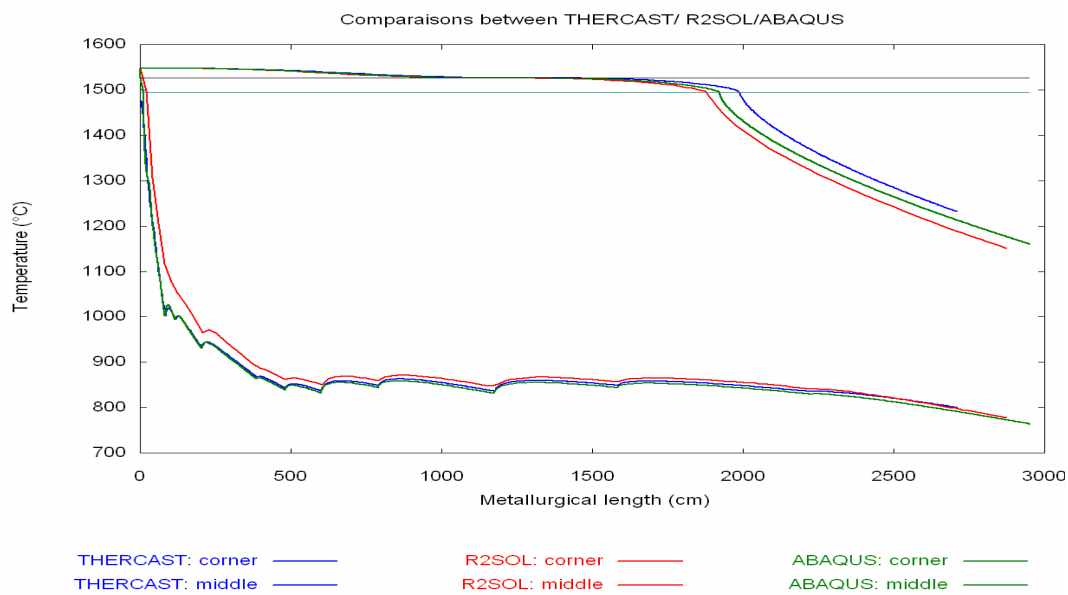


Figure 6: comparisons of temperatures

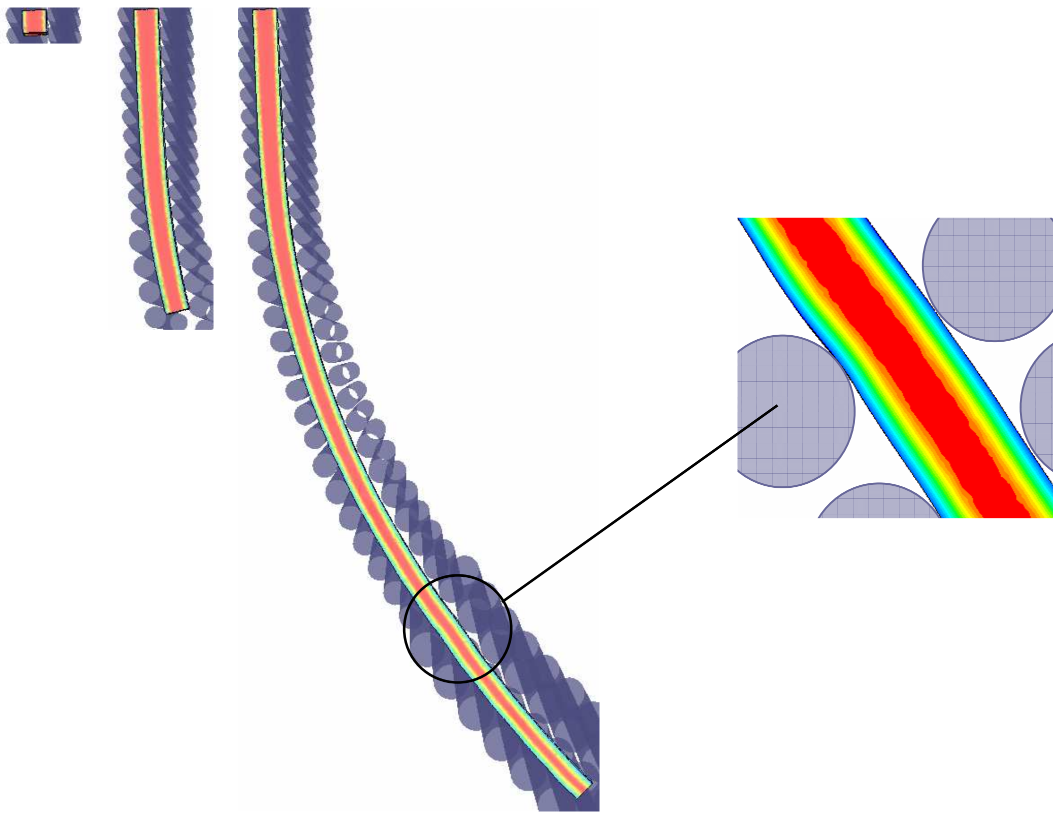

Figure 7: Global method results (evolution of temperature and bulging)

In addition, the confrontation of the temperatures in heart and on the skin shows coherence between the two types of methods used. The depth of the mushy pool is the depth at which the solidus isotherm curve intercepts the product axis. The predictions of the different formulations are 18.8m, 19.2m and 19.5m for R2SOL, Abaqus® and THERCAST® respectively with a slice non steady-state method. The results for the global non steady-state method are 18.5m and 19.2m for R2SOL® and THERCAST® respectively. The values are quite close, which proves that the global method is comparable to the slice method for heat transfer calculation. These results are also in agreement with what can be approximately measured on the real machine.

## Conclusion

In this study, different non steady-state slice formulations and a new global non steady-state method have been successfully compared for temperature calculation. Now, this formulation is being extended to the prediction of deformations (bulging) and stresses affecting the product. In this second approach, the elastic-viscoplastic model implemented in the software will be used, with parameters representative of steel behaviour at high and medium temperature. In addition, a complete three-dimensional calculation should be possible thanks to the use of the parallelized versionof THERCAST®.

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