MATHEMATICAL MODELING OF CONTINUOUS CASTING PROCESS OF THIN SLABS

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Abstract. *The continuous casting process has played important role on the steelmaking industry representing around 90% of the total steel production. The steel industry has focused on continuous optimization of the processes aiming at low energy consumption together with high productivity. In this context, the continuous casting of thin slab combined with continuous charge of the heating furnace for sequential hot rolling has became an attractive route. The phenomena that take place in the process are complex and involve mainly heat tranfer and phase transformations. Experimentalworks usually carried out in order to clarify these phenomena under reliable process conditions are very expensive and scarce for large range of steel products .On the other hand, progresses in computational simulation do allowed better knowledge of the process and provided several investigation guidances for process parameters under safety operations. The purpose of this work is to develop a mathematical model able to simulate this process and investigate optimized operational conditions. The model is based on transport equations of energy coupled with the continuous solidification of the steel within the caster machine. The model formulation involves the momentum equations of liquid and solidified materials in addition to the temperature evolution. The differential equations and boundary conditions are solved numerically based on the finite volume technique. Boundary conditions are specified as cooling heat flux for each region, in addition to heat flow resistance due to fluxing layer at the oscillating mold region. The model predictions were compared with industrial data for conventional continuous casting and extended to thin slabs of steel. Technological parameters such as water cooling flow rates and casting velocity were simulated in order to determine smooth operational conditions that minimize energy consumption and promotes high productivity.*

Keywords*: Continuous Casting, Thin slabs, Mathematical Modeling.*

1. INTRODUCTION

The development of mathematical models makes possible large technological advances in several metallurgical sectors. The progresses in computational simulation have provided better knowledge of the continuous casting process and driven several investigations of the effects of process parameters under safety operation conditions. The caster machine is designed to promotes continuously solidification of liquid hot metal fed by tundish though a submerse valve. In the mold region, a strong heat flux is imposed and a thick solid shell is formed while water cooling is intermittently applied until the slab is cut and discharged on the rolled table. Fig. 1 shows a schematic view of the caster machine and facilities.

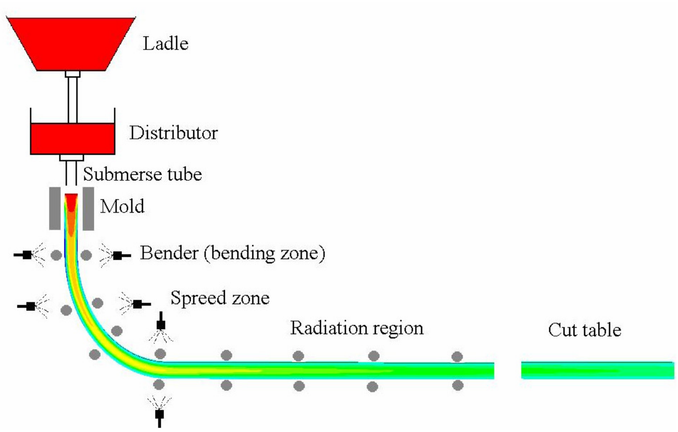

Figure 1 – Schematic view of continuous casting process and facilities

Due to the complexity of the process, which involves heat transfer coupled with phase transformation, the prediction of technological parameters and process optimization is usually performed by using empirical correlations. However, with the development of efficient numerical methods and computers the modeling task has become possible and contributed to increase the understandings and new operational techniques can be developed. To date, it is possible to investigate virtually the production of several kinds of steels with low cost and high material efficiency.

Several works have been focused on the study of metal behavior within the oscillating mold of the continuous caster machine due to its importance on the productivity and final quality of the sheets produced. The oscillating mold is an important component of the machine and has strong influence on the observed surface defeats and the temperature distribution inside the mold, defining its useful life(Lan, 2001; Wang, 2001; Ha, 2003; Janik, 2004 and Peng, 2005).

The heat transfer analysis during the solidification is traditionally performed by two methods: analytical and numerical ones. Although analytical methods are more elegant, it requires a series of considerations that usually leads to considerable simplifications on the physical phenomena and unrealistic results may arise. Therefore, the numerical methods are largely used. Four numerical methods are commonly used: finite differences (Mizicar, 1967; Lerardi, 1986 Choudhary, 1993; Shi, 2004 and Spinelli, 2004), finite elements, (Thomas, 1990; Chan, 1989; Brian, 1991 and Janik, 2004), finite volumes (Husepe, 2000) and boundary elements (Fic, 2000). These methods are able to solve the heat transfer equation, but seldom the velocity field is neglected or imposed.

In this work a three dimensional mathematical modeling to simulate the continuous casting process of steel is used to investigate the necessary casting conditions suitable to produce thin slab of steel. In this simulation the cooling rates for each machine sector is taking into account compatible with smooth operation practice. The temperature distribution and velocity field were calculated using the heat transfer and momentum equations under the assumption of stationary condition. The finite volume method was selected to discretise the partial differential equations and specified boundary conditions. The mathematical model is used to predict the slab temperature field from the mold feeder up to runout table. The model uses the process information to setup realistic cooling boundary conditions and casting velocities.

2. MATERIALS AND METHODS

2.1. Mathematical modeling

The model is based on the transport equations of momentum and energy coupled with solidification rate. The domain is restricted to the continuous casting vein from the hot metal inlet through the submerse valve bottom to the runout table where the sheet is cut. The motion of liquid metal and solidified regions are modeled as non-newtonian fluid and an apparent viscosity is selected. Eq. 1 - 2 represents the model description. Additional equation for the solidification phenomenon is adopted to determine the solidified fraction as in Eq. 4. The boundary conditions for the momentum equations are considered as constant inlet velocity field and integral outlet fully developed mass flow is assumed. In addition, at the mold and roll surfaces perfect slipping conditions are imposed. As for the heat transfer boundary conditions, the vein was divided into several sectors and cooling rates were specified by an effective heat transfer coefficient taking into account the combined effects of radiation, forced convection and conduction in the cooling film. The effective heat transfer coefficient was modeled as function of water flow rates and film temperature. At the runout table region, only natural convective and radiative heat fluxes are imposed.

The numerical simulations were carried out dividing the computational domain into eight sectors: mold, foot roll, four secondary cooling zones and the runout table. The length of each zone is presented in Tab. 1.

Table 1 – cooling zones dimensions

Mold	0,9 m
Foot Roll	0,422 m
Bender	2,416 m
Region 1	1,257 m
Region 2	3,828 m
Region 3	3,828 m
Region 4	4,492 m
Runout table	9,315 m

Equation 1 represents the momentum balance, as follows:

$$\rho \frac{\partial u_i}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu_{eff}\left(\frac{\partial u_i}{\partial x_j}\right)\right] \tag{1}$$

where u is the velocity field, p the pressure and μ_{eff} effective viscosity according (Moreira and Castro, 2008), Eq. 7.

The temperature distribution in the slab during the continuous casting process can be described by three-dimensional heat equation. Considering the stationary regime:

$$\frac{\partial\left(\rho u_j c_P T\right)}{\partial x_j} = \left[\frac{\partial}{\partial x_j}\left(k\frac{\partial T}{\partial x_j}\right)\right] + S \tag{2}$$

where T is the temperature, k the thermal conductivity, c_p the specific heat, ρ the density and S the energy changes associated with solidification given by Eq. 5:

For the solid phase the thermal conductivity and the specific heat were assumed as temperature functions, as shown in Eq. 3-4, respectively found in Holman (Holman, 1982) and Colin et al (Colin, 1976) .

$$k = x - y \times 10^{-2} T \tag{3}$$

$$c_P = a + bT + cT^{-1/2} \tag{4}$$

$$S = \rho L \frac{\partial f_S}{\partial t} \tag{5}$$

where L is the latent heat of fusion, f_s is a solid fraction and can be calculated using eq.4:

$$f_S = 1 - \left(\frac{T_f - T}{T_f - T_l}\right) \tag{6}$$

where T_f is the melting temperature and T_l the liquidus temperature extracted from the equilibrium diagram.

$$\mu_{eff} = \frac{\bar{\sigma}}{3\dot{\bar{\varepsilon}}} \tag{7}$$

where $\bar{\sigma}$ is the material mean stress and $\dot{\bar{\varepsilon}}$ is the effective deformation rate presented by (Zienkiewicz 1978)

2.2. Temperature boundary Conditions

Figure 2 summarizes the different sectors considered to impose boundary heat fluxes. In the mold and in foot roll is specified the cooling water flow at the four faces (internal and external large faces and right and left narrow faces) while at the other zones the heat fluxes were imposed only for two faces (internal and external large faces)

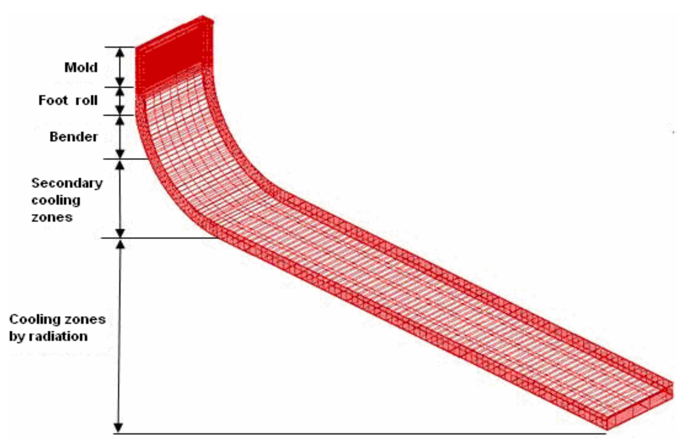

Figure 2 – schematic view of continuous casting with selected grid and boundary conditions

The slab heat flux to the surface in the water cooling areas and in the radiation zone is considered as shown by Eq. 8

$$-k\frac{\partial T}{\partial x_j} = h_{eff}\left(T_{sur} - T_e\right) + \sigma\varepsilon\left(T_{sur}^4 - T_e^4\right) \tag{8}$$

where h_{eff} is heat transfer coefficient, Eq. 9, T_{sur} the slab temperature, T_e the environment temperature, σ is the Stefan Boltzmann constant and ε the emissivity.

The heat exchange coefficient in the sprays zones (foot roll, bender and secondary cooling zone) was obtained by the water cooling enthalpy balance.

$$h_{eff} = \frac{m_w \times c_p \times \Delta T}{A\left(T_{sur} - T_e\right)} \tag{9}$$

where m_w is the water flow, c_p the water specific heat, A is the area and ΔT is water temperature difference introduced as set up of the cooling system.

The mold region was modeled using the steel residence time to calculate the effective heat transfer coefficient. This coefficient includes the effect of thermal resistance due to air gap formation (Silva, 1996).

$$h_{mold} = 1004{,}6.\exp\left(-0{,}02 t_m\right) \quad , \mathrm{W/m^2K} \tag{10}$$

where t_m is the steel residence time in the mold and calculated using the cast velocity (V_c) and the mold height (Y).

$$t_m = \frac{Y}{V_c} \tag{11}$$

2.4. Numerical Methodology

The equations for motion and heat transfer were discretizated using the Finite Volume Method (FVM) applied for general coordinates system recommended by (Melaaen, 1992), where the integration is taken over a control volume as shown in Fig. 3 and Eq. 12. The final product of this operation is an algebraic equation resumed in Eq. 13 and the coefficients obtained by the so-called power law scheme, according Patankar (Patankar,1992).

$$\int_{\delta t}\int_{\delta V} \frac{\partial(\rho\varepsilon\phi)}{\partial t} dvdt + \int_{\delta t}\int_{\delta V}\left[div\left(\rho\varepsilon\vec{U}\phi - \varepsilon\Gamma_\phi grad(\phi)\right)\right]dvdt = \int_{\delta t}\int_{\delta V} S_\phi dvdt \tag{12}$$

where ϕ represent the dependent variable, $\vec{U}$ the convective flux, ε the volumetric fraction and Γ the transport coefficient.

$$a_P\phi_P = a_W\phi_W + a_E\phi_E + a_B\phi_B + a_T\phi_T + a_S\phi_S + a_N\phi_N + b \tag{13}$$

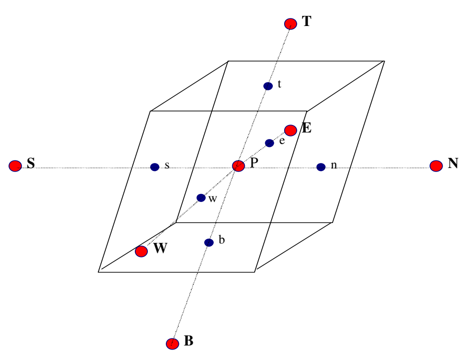

Figure 3 – Control volume

The motion of liquid and solidified material was obtained by using the SIMPLE algorithm where the velocities components and pressure are iteratively determined. The enthalpy method was used to model the temperature field coupled with the solidification process. The numerical solution of the algebraic equations resulted from the discretization method demands large computational effort. This code uses the line-by-line method based on the tri-diagonal matrix solution (TDMA). The ADI iterative procedure is used within a common solver for all equations. The convergence criteria for all calculated fields were adopted 10^{-6} and the computational grid was 6x10x150 = 9000 control volumes.

3. RESULTS

3.1 Materials properties and process input data

In the continuous casting of steel simulations the data presented in table 2 were used.

Table 2 – Simulation data

Parâmetros	C-Mn steel	IF steel
Slab width	1,6 m	1,6 m
Slab depth	0,255 m and 0,010 m	0,010 m
casting temperature	1.574 ºC	1.574 ºC
Casting speed	0,81m/min and 22 m/min	20,5 m/min
Cooling water temperature	30 ºC	30 ºC
Environment Temperature	40 º C	40 º C
Solidify begin temperature	1.539 ºC	1.533 ºC
Solidify final temperature	1.534 ºC	1.528 ºC
Slab material	C-Mn steel (0,15 % C)	IF steel (0,003 % C)
Emissivity	0,6	0,6
Thermal conductivity in liquid phase	41,0 W/m K	12,0 W/m K
Specific heat in liquid phase	749,5 J/kg K	448,5 J/kg K
Density	7.830 kg/m^3	7.640 kg/m^3
Latent heat of solidification, L	2,07x10^8 J/m^3	2,07x10^8 J/m^3

The model developed was validated with industrial data for conventional (255 mm) continuous casting of C-Mn steel. The model input was selected the water flow rates of each cooling zones and the surface temperature of the slab measured. In addition, the model was used to investigate cooling and casting speed conditions necessary for producing thin slab. As reference, it was iteratively determined the cooling and speed conditions which gives similar temperature profiles of the solidified shell, which, in turn, indicate smooth caster operation without break out. Fig. 4 – 6 shows the comparison of temperature profiles for the shell region and the center of the slab. As can be observed, the shell temperature could be kept nearly constant for all the casting conditions simulated while the center temperature is strongly modified, especially for the thin slab case. Under the conditions of thin slab continuous casting, the center temperature reached around 1200 ^{o}C at the foot roll zone where strong deformation is need for bending and final cooling, however break outs may occurs for high speed operation.

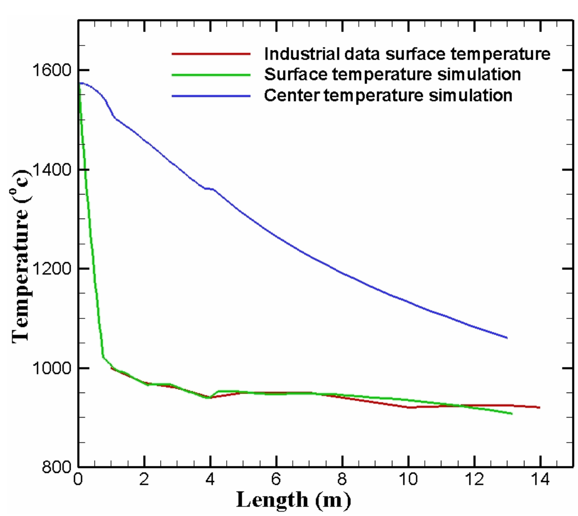

Figure 4 – C-Mn Steel conventional continuous casting (255mm)

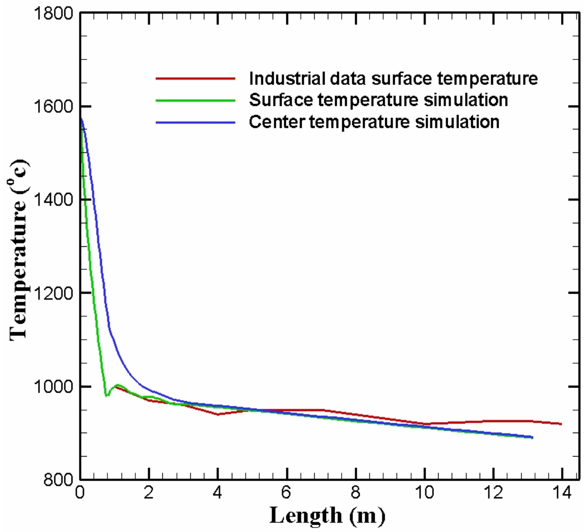

Figure 5 – C-Mn Steel near net shape slab (10mm)

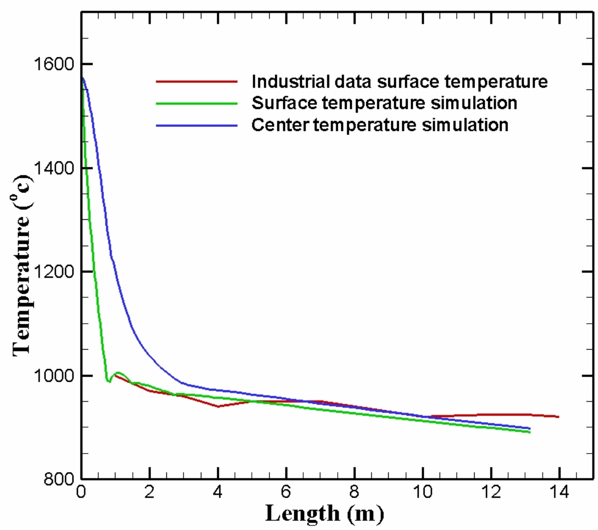

Figure 6 – IF Steel near net shape slab (10mm)

As shown in Fig. 5 and 6 small recalescence after mold region is observed. It is justified by the fact that in the mold region when the process executed is thin slab there is low recirculation of liquid metal reducing the thermal conductivity. In addition, the IF steel presents low thermal conductivity and specific heat increasing this phenomenon.

A Specific heat transfer coefficient is placed in each region for the steel slab cooling as shown in Fig. 7 and 8. Where can be observed the high heat transfer coefficient imposed in the mold region for the thin slab, particularly on the IF steel, and consequent low coefficient to the other regions. Contrarily to the conventional continuous casting, the thin slab operation demanded smaller coefficient in the mold region and higher coefficient to the other regions. It was observed mainly due to the heat coefficients and the different velocities setting to the continuous casting machine operating in both conditions. For the thin slab case the velocities were 22 m/min and 20,5 m/min to the IF and C-Mn steel respectively while 0.81 m/min was considered to conventional continuous casting of C-Mn steel.

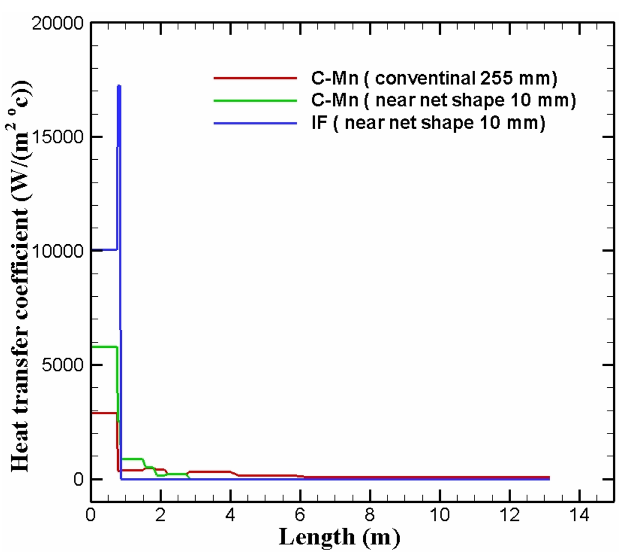

Figure 7 – Effective heat transfer coefficient (top and bottom faces)

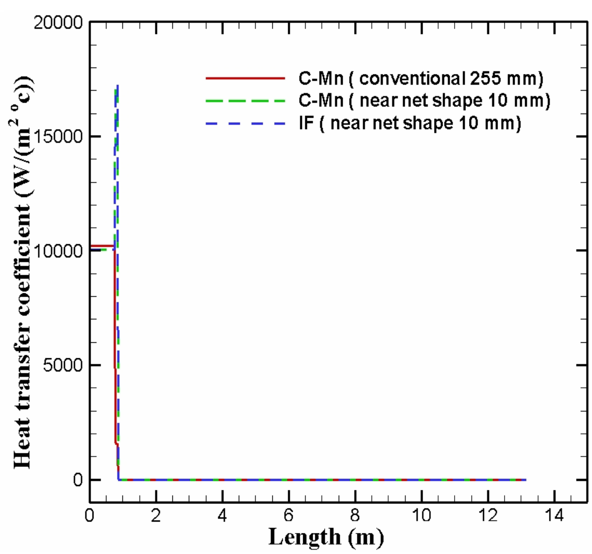

Figure 8 – Effective heat transfer coefficient (lateral faces)

The temperature field distribution for conventional and thin slab continuous casting of steel is shown, Fig. 9 – 11, where the vein of caster machine as well mold regions details is presented.

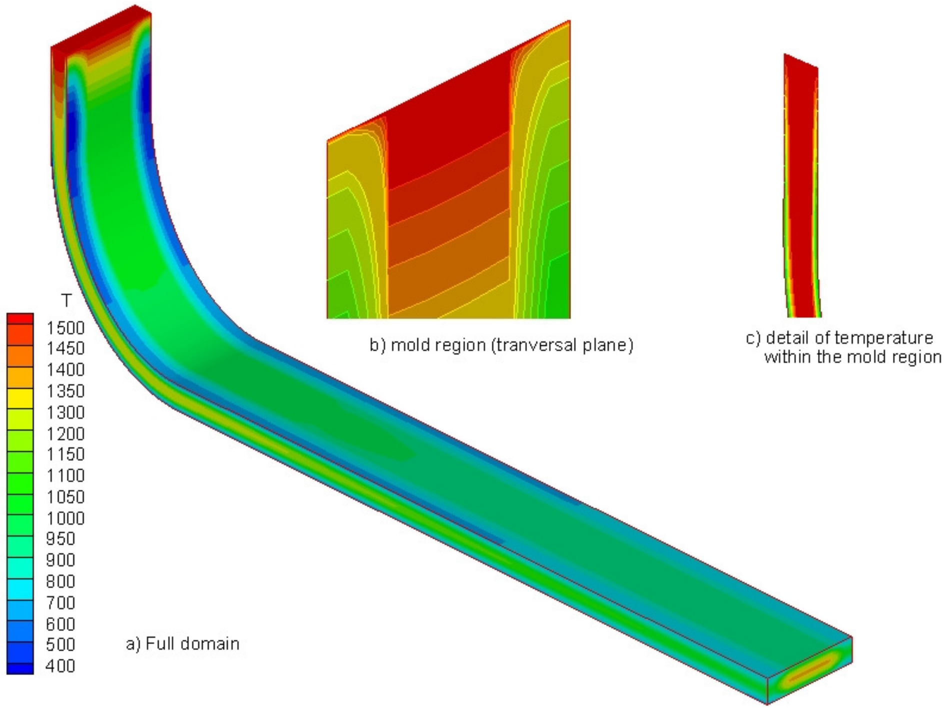

Figure 9 -Temperature pattern for conventional continuous casting process of C-Mn steel (255 mm)

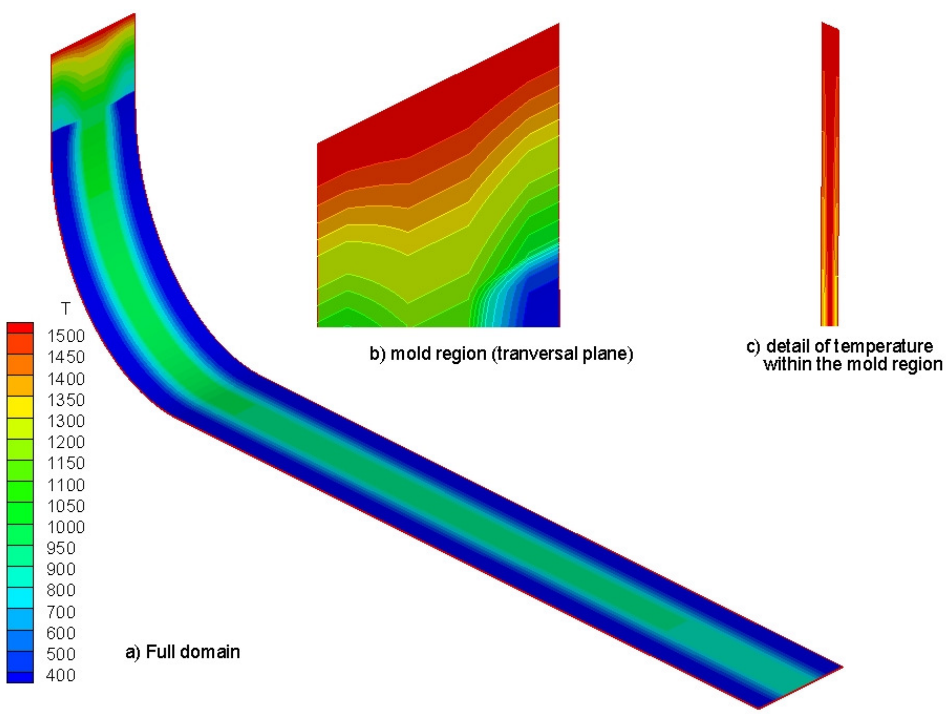

Figure 10 - Temperature pattern for thin slab of C-Mn steel (10 mm)

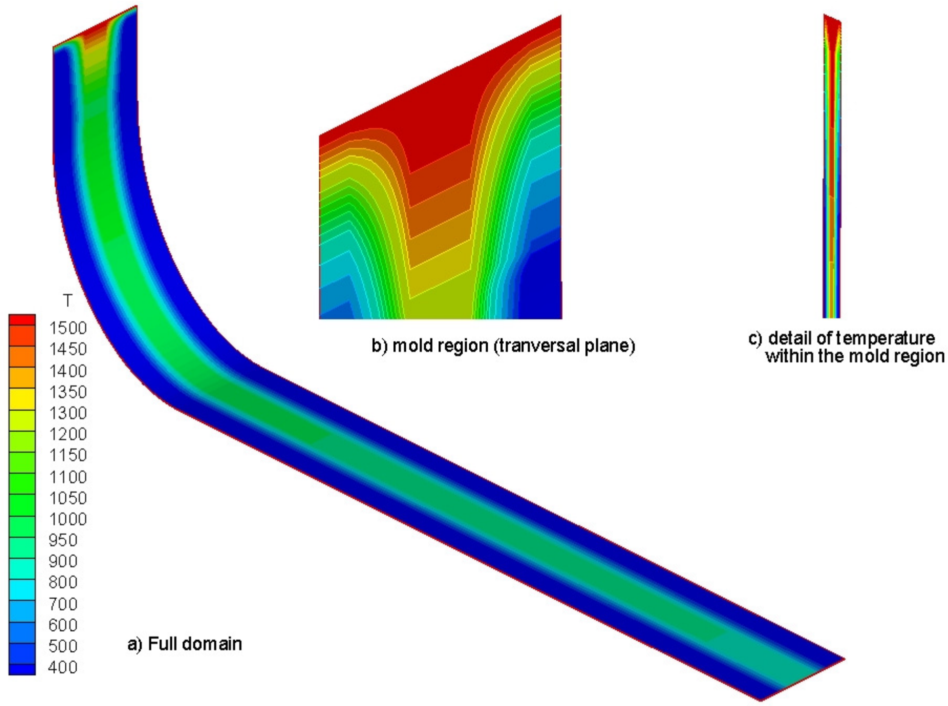

Figure 11 - Temperature pattern thin slab of IF steel (10 mm)

4. CONCLUSIONS

In this work the development of a computational code for simulating the thin slab continuous casting process of steel was presented. The model is able to simulate casting and cooling conditions. The model has been applied to predict near net shape process of steel production. The model was validated comparing numerical predictions with industrial data of the surface temperature evolution for conventional slab production. Model results indicated that is possible to produce thin slab under severe cooling conditions and casting speed of 20,5 m/min and 22 m/min for IF and C-Mn steel respectively, which corresponds to high productivity of the process. Comparing the distribution of temperature was possible to indicate the simulated cases that hypothetically would permit smooth casting operation for thin slab continuous casting production and consequent reduction of energy consumption avoiding additional hot rolling. However, this model was not designed to predict the mechanical proprieties, which is usually attained in the conventional continuous casting process. Nevertheless, the simulation results were carried out aiming at similar temperature profile, therefore it is assumed that the final mechanical properties are attained. In fact, experimental works have supported these assumptions for moderated casting velocities.

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