MODELING THE NEAR NET SHAPE CONTINUOUS CASTING PROCESS OF IF STEELS [1]

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Abstract
The steel industry has continuously optimizing the process aiming at low energy consumption. In this context, the continuous casting of low carbon steels of thin slabs together with continuous charge of heating furnace for sequential hot rolling has become an attractive route. This work aims to develop a mathematical model able to simulate and investigate optimized operational conditions. The model is based on the transport equation of energy coupled with the continuous solidification. The differential equations and boundary conditions are solved numerically based on the finite volume discretization technique. The cooling and conditions are specified for each region, in addition to heat flow resistance due to fluxing layer and oscillating in the mold region. The model predictions were confronted with industrial data for conventional continuous casting conditions and extended to thin slab operation. Technological parameters such as water cooling flow rates and casting velocity were investigated in order to determine smooth operational conditions that minimize energy consumption and allows high productivity.
Key words: Continuous casting; Thin slabs; Mathematical modeling.

MODELAMENTO DO PROCESSO DE LINGOTAMENTO CONTINUO PARA CHAPAS FINAS DE AÇO IF

Resumo
A indústria do aço vem continuamente otimizando os processos objetivando redução do consumo de energia. Neste contexto o lingotamento continuo de chapas finas de aços baixo carbono juntamente com continua alimentação dos fornos de reaquecimento para laminação a quente seqüencial tem se tornado uma rota atrativa. O propósito deste trabalho é desenvolver um modelo matemático capaz de simular este processo e analisar condições operacionais otimizadas. O modelo é baseado na equação de transporte de energia juntamente com a solidificação do aço dentro da maquina de lingotar. A formulação do modelo envolve as equações de momentum e energia acoplada à taxa de solidificação. As equações diferenciais são resolvidas numericamente baseadas na técnica de discretização volumes finitos. As condições de resfriamento são especificadas para cada região, além da resitência ao fluxo de calor devido ao fluxante e oscilação na região do molde. Os resultados foram confrontados com dados industriais para condições de lingotamento continuo convencional e estendido para chapas finas.
Palavras-chave: Lingotamento continuo; Chapas finas; Modelamento matemático.

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1 INTRODUCTION

The data processing development makes possible a large technological advance in several metallurgical sectors. The progress in computational simulation has provided a better knowledge of the continuous casting process and has driven several investigation of the effect of process parameters for safety operation. The caster machine consist of continuous solidification of liquid hot metal fed by tundish though a submerse valve, a strong heat flux is imposed in the mold with a solid shell formed being pulled out while water cooling is applied until the slab is cut and discharged in the rolled table. Figure 1 shows a schematic view of the caster machine and facilities. Due to the complexity of the process involving heat transfer coupled with phase transformation, the prediction of technological parameters and process optimization is usually done by 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 have been developed. To date, it is possible to investigate virtually the production of several kinds of steels with low cost and high material efficiency.

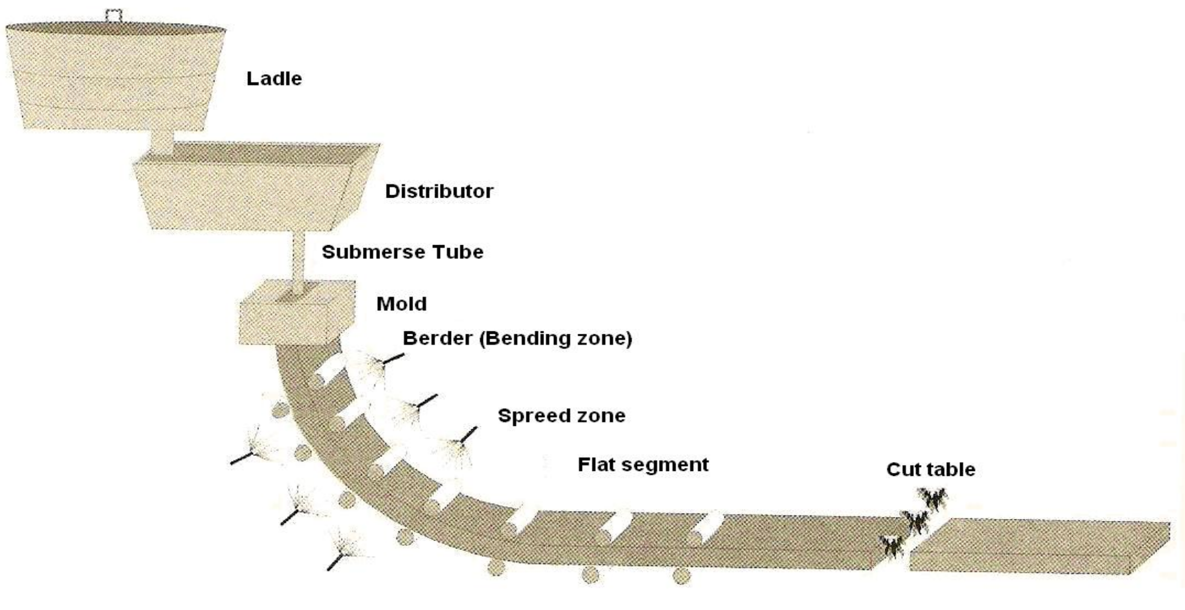

Figure 1 – Schematic view of continuous casting process and facilities.(1)

Several works have been focused on the study of metal behavior within the mold of continuous caster machine due to its importance on productivity and final quality of the slabs produced. The oscillating mold is an important component of the machine and has strong influence on the surface defeats and the temperature distribution inside the mold.(2-6)

The heat transfer analysis during the solidification is traditionally performed by two methods: analytical and numerical ones. Although analytical methods may be more elegant, its requires a series of considerations that usually leads to considerable simplifications and unrealistic results may arise. Therefore, the numerical method is largely used. Four numerical methods are commonly used: finite difference,(7-11) finite element,(12-15) finite volume(16) and boundary elements.(17) These methods are able to formulate and solve the heat transfer equation.

In this work a three dimensional mathematical modeling for simulating the continuous casting process of steel slabs is used to investigate the necessary casting conditions to produce near net shape steel slab and cooling rates for each machine sector in order to keep smooth operation. The temperature distribution was calculated using the heat transfer equation under the assumption of stationary condition and numerically solved using the finite volume method. The mathematical model is used to predict the slab temperature field from the mold feeder up to cut 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 energy coupled with solidification rate. The domain is restricted to the continuous casting vein from the hot metal inlet through the submerse valve up to the run out table where the slab is cut. The motion of liquid metal and solidified regions are modeled as non-newtonian fluid and an apparent viscosity is selected. Equation 1 - 2 represents the model description. Additional equation for the solidification phenomenon is considered to determine the solidified fraction as in equation 4. The boundary conditions for the momentum equations are considered as inlet and outlet while the mold and roll regions are considered as perfect slipping. As for heat transfer boundary conditions the vein was divided into several regions and cooling rates were specified through an effective heat transfer coefficient, which, in turn, is function of water flow rates and temperature. At the final region, radiation condition is included.

The numerical simulation was done dividing the computational domain in eight regions basically: mold, foot roll, four secondary cooling zones and the cooling zone by radiation. The length of each zone is presented in Table 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
Cooling region by radiation	9,315 m

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

$$\frac{\partial(\rho u_j c_P T)}{\partial x_j} = \left[\frac{\partial}{\partial x_j}\left(k\frac{\partial T}{\partial x_j}\right)\right] + S \qquad (1)$$

where T is the temperature, k the thermal conductivity, cp the specific heat, ρ the density and S the energy changes associated with solidification given by equation 3:

$$\rho \frac{\partial u_i}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j}\right)\right] \quad (2)$$

where $\vec{u}$ is the velocity field, p the pressure and μ apparent viscosity

$$S = \rho L \frac{\partial f_S}{\partial t} \quad (3)$$

where L is the latent heat of fusion, f_s is a solid fraction and can be calculated in the following way:

$$f_S = 1 - \left(\frac{T_f - T}{T_f - T_l}\right) \quad (4)$$

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

2.2 Boundary Conditions

The different zones characterizations were made imposing the boundaries conditions characteristic in each one. In the mold and in foot roll there are cooling water flow in the four faces (internal and external large faces and right and left narrow faces) while in the other zones there are only in two faces (internal and external large faces)

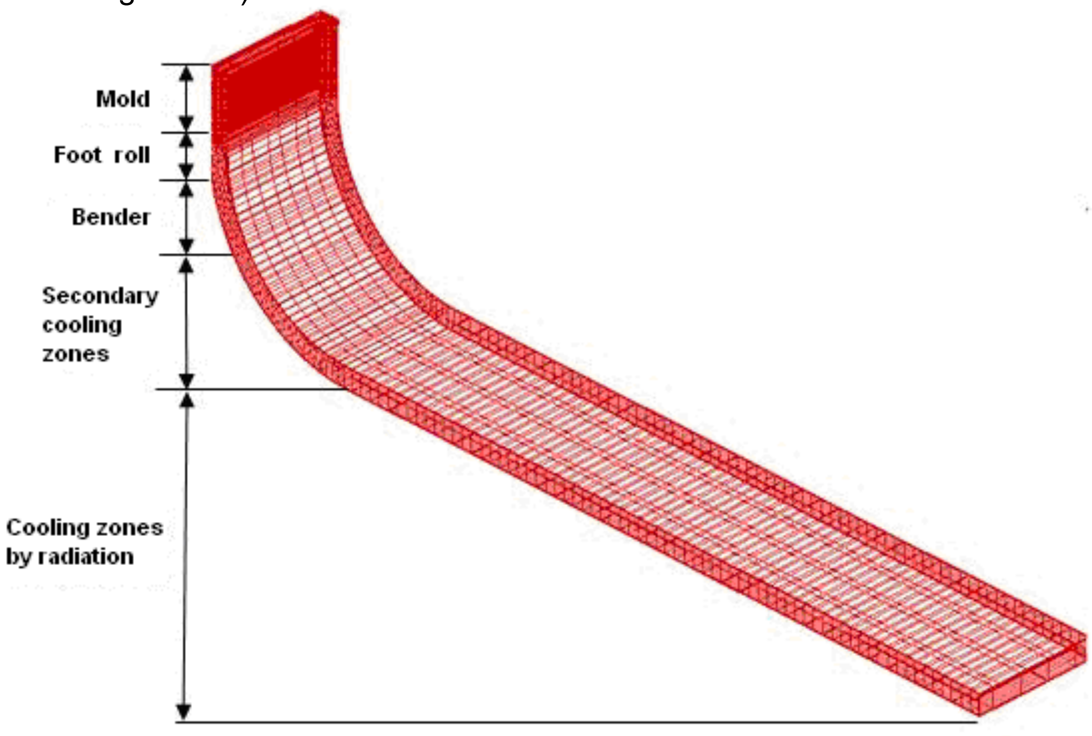

Figure 2 – schematic view of continuous casting with sellected grid and boundary conditions

The slab heat flux to the surface in the water cooling areas is described by Newton equation:

$$-k\frac{\partial T}{\partial x_j} = h\left(T_{sur} - T_e\right) \qquad (5)$$

where h is heat transfer coefficient, T_{sur} the slab temperature and T_e the environment temperature. Analogously in the radiation zone the heat flux can be described by equation:

$$-k\frac{\partial T}{\partial x_j} = \delta\varepsilon\left(T_{sur}^4 - T_e^4\right) \qquad (6)$$

where δ is the Stefan Boltzmann constant and ε the emissivity.

The heat change coefficient in the sprays zones (foot roll, bender and secondary cooling zone) was calculated equalizing an average heat flux obtained from water temperature difference and water flow observed with the average heat flux calculated in function of a difference temperature.

In the mold region a steel residence time dependent heat change coefficient was used. This coefficient considers a thermal resistance due to air gap formation;[18]

$$h_{mold} = 1004{,}6.\exp\left(-0{,}02t_m\right) \quad , \text{W/m}^2\text{K} \qquad (7)$$

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

$$t_m = \frac{Y}{V_c} \qquad (8)$$

In the near net shape continuous casting of IF steel simulations the data presented in table 2 were used.

For the solid phase the specific heat and the thermal conductivity were assumed as temperature functions, as shown in equations 8-9, respectively found in Holman.[19]

$$k = 53{,}719 - 2{,}728x10^{-2}T \qquad (8)$$

The specific heat in the solid phase was obtained according Colin et al[20];

$$c_P = 4{,}1868\left(a + 10^{-3}bT\right)cT^{-1/2} \qquad (9)$$

where: $a = 8{,}873$, $b = 1{,}474$ e $c = 270{,}0$

Table 2 – Simulation data

Slab width	1,6 m
Slab depth	0,0010 m
Pouring temperature	1.574 ºC
Casting speed	20,5 m/min
Cooling water temperature	30 ºC
Environment Temperature	40 º C
Solidify begin temperature	1.533 ºC
Solidify final temperature	1.528 ºC
Slab material	IF steel (0,003 % C)
Emissivity	0,6
Thermal conductivity in liquid phase	12,0 W/m K
Specific heat in liquid phase	448,5 J/kg K
Density	7.640 kg/m^3
Latent heat of solidification, L	2,07x10^8 J/m^3

2.3 Numerical Methodology

The equations for motion and heat transfer were discretizated using the Finite Volume Method (FVM) applied for general coordinates system recomended by Melaaen,(21) where the integration is taken over a control volume as shown in Figure 3 and equation 10. The final product of this operation is an algebraic equation resumed in equation 11 and the coefficients obtained by the so-called power law scheme according Patankar.(22)

$$\int_{\delta t}\int_{\delta V}\frac{\partial(\rho\varepsilon\phi)}{\partial t}dvdt+\int_{\delta t}\int_{\delta V}\left[div\left(\rho\varepsilon\vec{U}\phi-\varepsilon\Gamma_{\phi}grad(\phi)\right)\right]dvdt=\int_{\delta t}\int_{\delta V}S_{\phi}dvdt \qquad (10)$$

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

$$a_P\phi_P = a_W\phi_W + a_E\phi_E + a_B\phi_B + a_T\phi_T + a_S\phi_S + a_N\phi_N + b \qquad (11)$$

$$a_P = a_W + a_E + a_B + a_T + a_S + a_N + a_P^0 - S_P \qquad (12)$$

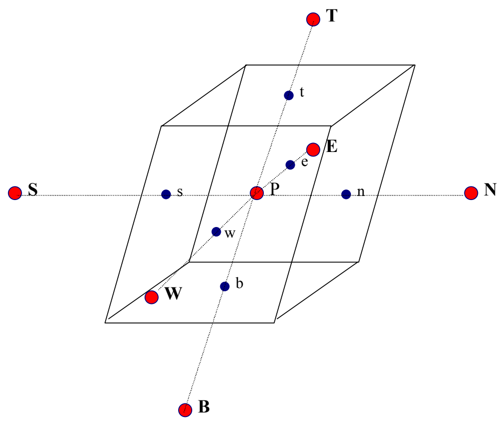

Figure 3 – Control volume

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 work. This code uses the line-by-line method based on the tri-diagonal matrix solution. The ADI iterative procedure is used within a common solver for all equations. The convergence criteria for all calculated fields was adopted 10^{-6} and the computational grid was 6x10x150= 9000 control volumes.

3 RESULTS

The IF steel was chosen in this work because is largely used in several sectors of industries such as automobilist and electro electronics. This class of steel presents excellent propriety for these industries due to the low concentration of carbon.

The model developed was validated with industrial data for conventional continuous casting. In 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 near net shape slabs of IF steel. As reference, it was iteratively determined the cooling and speed conditions which give similar temperature profiles of the solidified shell, which, in turn, indicate smooth caster operation without break out. Figure 4 – 5 show the comparison of temperature profiles for the shell region and the center of the slab.

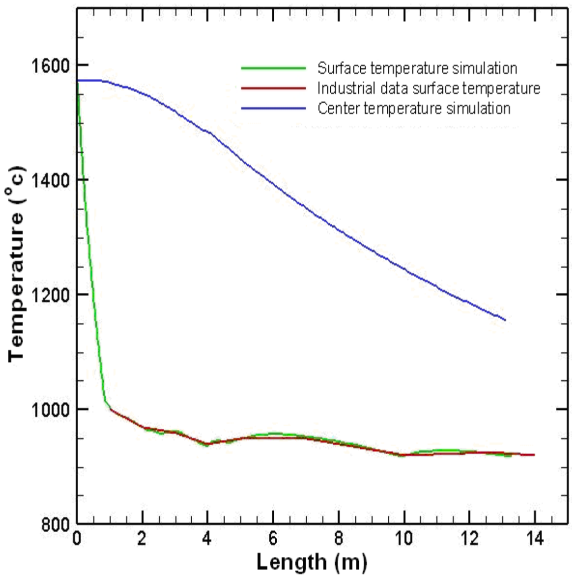

Figure 4 – Conventional continuous casting (255 mm) slab

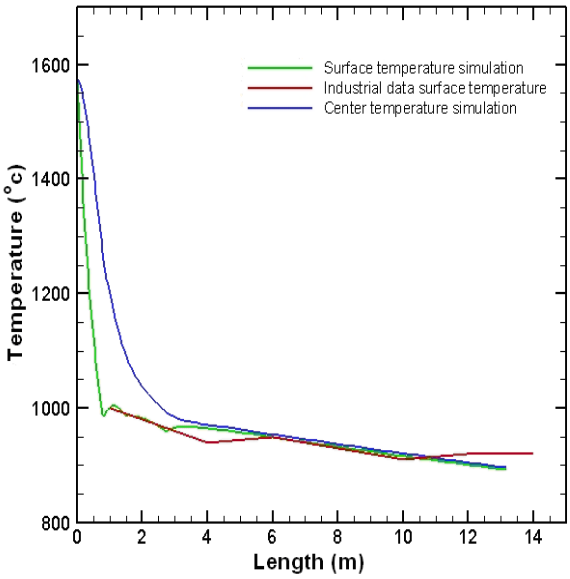

Figure 5 – Steel IF near net shape slab (10 mm)

As it can be observed, the shell temperature could be kept nearly constant for all the casting conditions simulated while the center temperature is strongly modified. Under the conditions of near net shape continuous casting, the center temperature reached around 1200°C at the foot roll zone where strong deformation is need for bending and final cooling. As shown in Figure 5 occurred a little recalescence after mold region. It is justified by the fact that in the mold region when the process executed is near net shape slab there is low recirculation of liquid metal reducing the thermal conductivity. In addition, this steel class presents low thermal conductivity and specific heat.

Specific heat transfer coefficient is placed in each region for the steel slab cooling as shown in Figure 6 – 7.

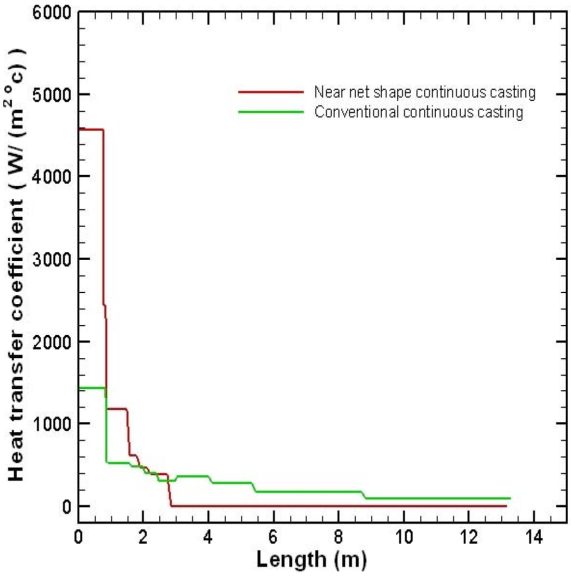

Figure 6 – Effective heat transfer coefficient – top and bottom faces

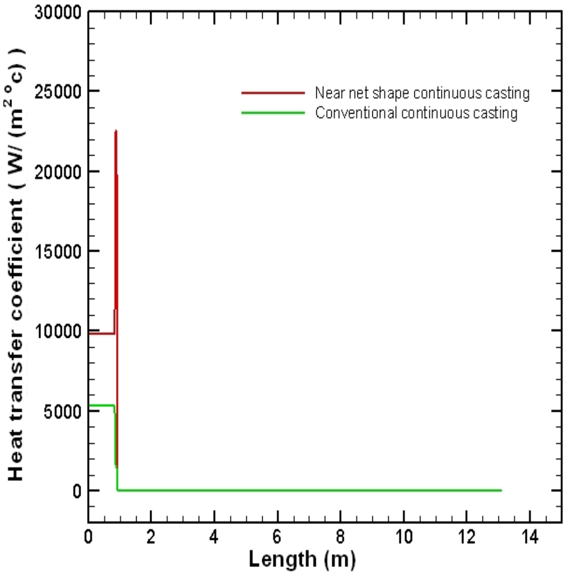

Figure 7 – Effective heat transfer coeficient for lateral faces

The temperature field distribution for both cases above is shown, Figure 8 – 9.

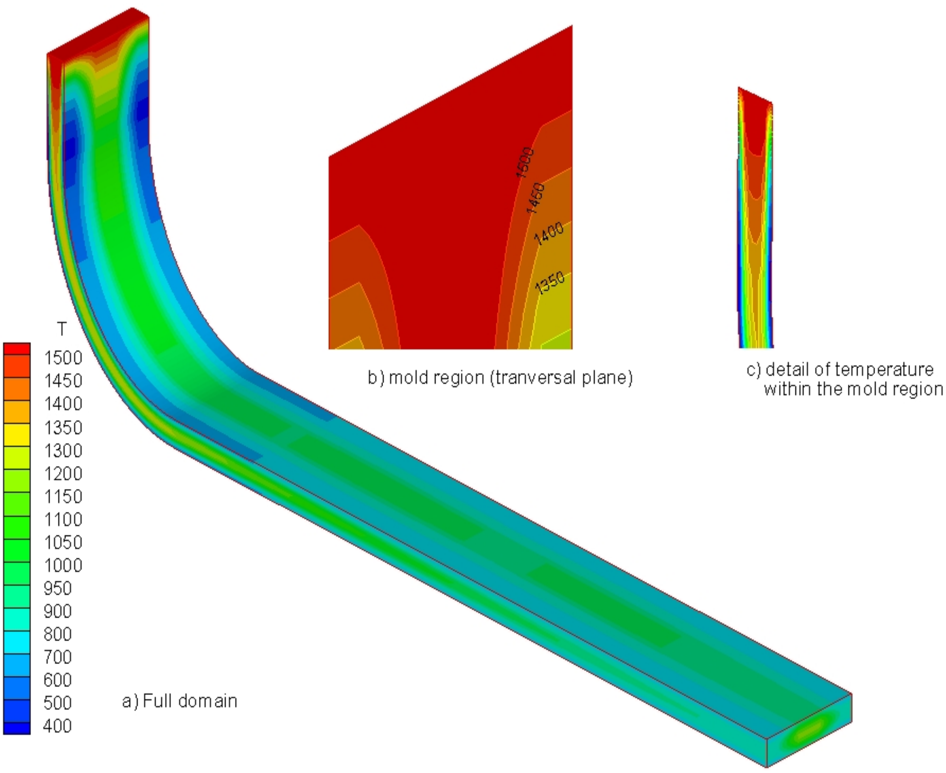

Figure 8 -Temperature distributions for conventional continuous casting process

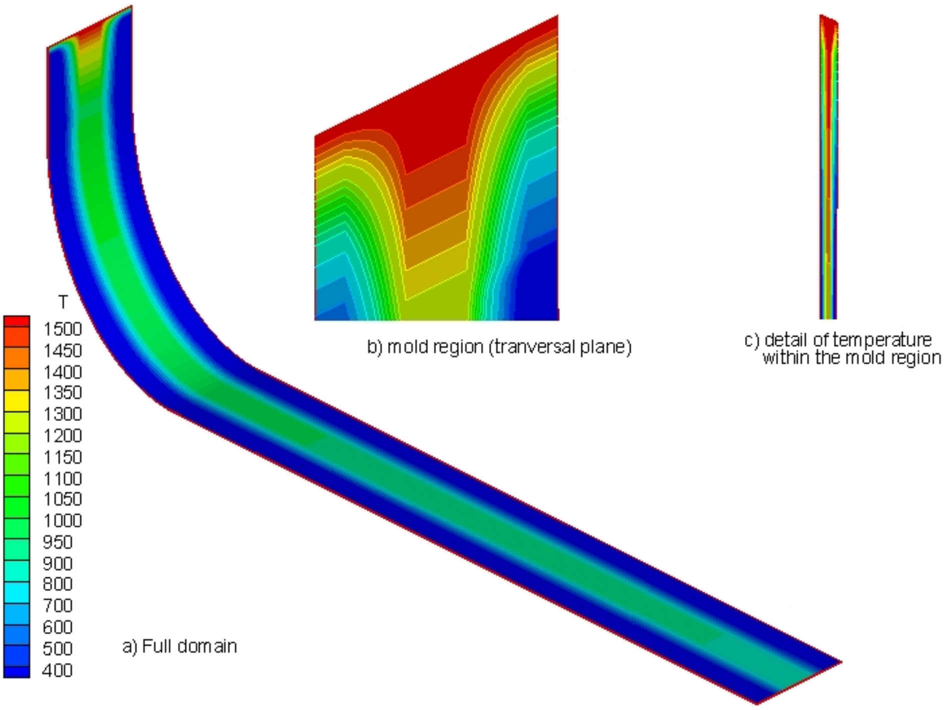

Figure 9 - Temperature pattern for near net shape slab and high casting speed

4 CONCLUSIONS

In this work the development of a computational code for simulating the near net shape continuous casting process of IF steel was presented. The model is able to simulate casting and cooling conditions. The model has been applied to model near net shape slab of IF steel production. The model was validated comparing numerical predictions with industrial data of the surface temperature evolution of conventional slab production. Model results indicated that is possible to produce near net shape slabs under severe cooling conditions and casting speed about 20,5 m/min, therefore, high casting productivity. By surface temperature is possible investigate similarities among the simulated cases that hypothetically would permit smooth casting condition for near net shape continuous casting and consequently reduction of energy consumption eliminating additional hot rolling. However, this model is not able to guarantee the aimed mechanical and structural proprieties for near net shape continuous casting as previously demonstrated in the conventional continuous casting process used to validated the model with comparison for industrial data.

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