NUMERICAL SIMULATION OF HEAT TRANSFER IN CONTINUOUS CASTING[1]

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Abstract

In this work a mathematical model for thermal evolution is proposed to achieve a better understanding of solidifying process of the liquid metal in the continuous casting. Heat Transfer in the continuous casting of carbon steel slabs was described through a mathematical modeling. The process can be described by means of the three-dimensional heat conduction equation in the steady state flow and is numerically solved with help of the Finite Volume Method (FVM). The model takes into account the different thermal boundary conditions. Numerical solutions are obtained for different casting speeds. For model validation and adjustment, comparisons between the numerical data and the real data had been made.

Key words: Continuous casting; Finite volume method; Numerical simulation.

SIMULAÇÃO NUMÉRICA DA TRANSFERÊNCIA DE CALOR NO LINGOTAMENTO CONTÍNUO

Resumo

Neste trabalho é proposto um modelo matemático para a evolução térmica que permite uma melhor compreensão do processo de solidificação do metal líquido no lingotamento contínuo. A transferência de calor no lingotamento contínuo de uma placa de aço carbono foi descrita através de um modelo matemático. O processo foi descrito por meio da equação de calor tridimensional no estado estacionário e foi resolvida numericamente usando o Método dos Volumes Finitos. O modelo leva em consideração as diferentes condições de contorno. São obtidas diferentes soluções numéricas para diferentes velocidades de lingotamento. Para a validação e ajuste, foram feitas comparações entre os valores obtidos e dados reais.

Palavras-chave: Lingotamento continuo; Método de volumes finitos; Simulação numérica.

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1 INTRODUCTION

Technological advances in several metallurgical sectors have been observed with the development of computers and numerical methods on the latest decades. The progress in the computational simulation area has improved understandings of the continuous casting process.

Several works have been developed aiming at studying the metal behavior in the continuous casting, especially those related with the heat transfer phenomena within the mold region. The mold is one of the most important components of the continuous casting machine, because the metal casting quality is strongly affected by surface quality and temperature distribution within the mold. Due to its importance, some researches have concentrated efforts only in the mould region.(1-5)

In this paper, a three-dimensional steady state heat transfer model is presented and industrial data is used to validate the calculations. The boundary conditions for heat transfer equation are given by measurements of cooling water flows and temperatures. The objective is to present a continuous casting modeling based on real process operational conditions and compare model preditions with industrial data.

2 MATHEMATICAL MODELING

The numerical simulation was carried out dividing the computational domain in eight regions: mould, foot roll, bender, four secondary cooling zones (with different heat transfer coefficients) and the radiation cooling zone presented in Figure 1. The Table 1 shows the dimensions of each zone.

Table 1 – Dimension of cooling zones

Mold	0.9 m
Foot Roll	0.4 m
Bender	2.4 m
Region 1	1.3 m
Region 2	3.8 m
Region 3	3.8 m
Region 4	4.5 m
Radiation cooling region	9.3 m

The temperature distribution in the slab during the continuous casting can be described by the three-dimensional heat conduction equation considering steady state.

$$div\left(\rho c\vec{U}T\right) = div\left(\frac{k}{c}grad\left(T\right)\right) + S = 0 \tag{1}$$

where T is the temperature, k is the thermal conductivity, c is the specific heat, ρ is the density, $\vec{U}$ is the velocity field and the source term S is the heat due to the phase changing, expressed by eq.(2):

$$S = \rho L \frac{\partial f_S}{\partial t} \tag{2}$$

where L is the latent heat of fusion, f_s is the solid fraction calculated by eq.(3)

$$f_S = 1 - \left(\frac{T_f - T}{T_f - T_l} \right) \tag{3}$$

where T_f is the fusion temperature and T_l is the liquidus temperature.

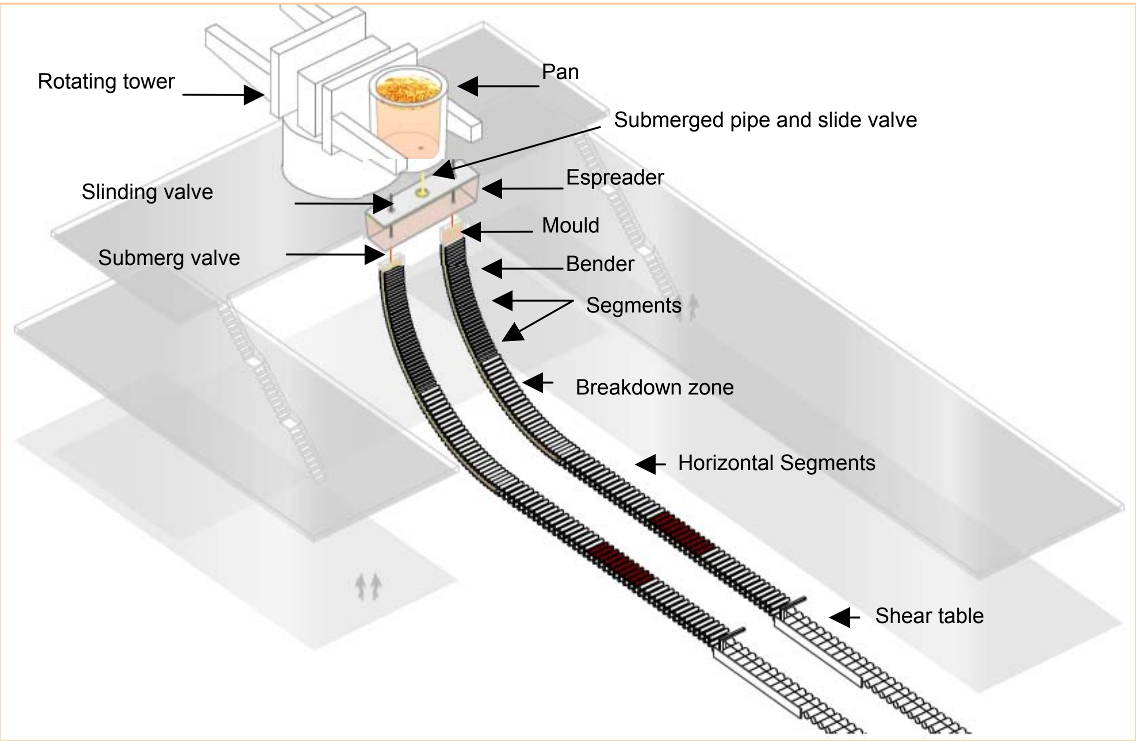

Figure 1 – Continuous casting scheme.

3 BOUNDARY CONDITIONS

The different zones were considered by specification of boundary conditions that takes into account heat flow rates as function of cooling water flow rates. The mould and the foot roll regions considers cooling water flow rates into the four faces (inner and out wide faces and left and right tight faces) while the other zones have only in two faces (inner and out wide faces). These considerations were done to describe the behavior of the imposed water jet impinged into the surfaces while in other regions water is not directly injected at the surfaces.

The heat flux from the slab to the water cooling surface is described by the Newton`s equation:

$$-k \frac{\partial T}{\partial y} = h\left(T_{\sup} - T_{amb}\right) \tag{4}$$

where h is the overall heat transfer coefficient, $T_{\sup}$ surface temperature and T_{amb} the room temperature.

The heat flux in the radiation zone can be described by the equation:

$$-k\frac{\partial T}{\partial y} = \delta\varepsilon\left(T_{\sup}^{4} - T_{amb}^{4}\right) \tag{5}$$

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

The heat transfer coefficient in the spray zones (foot roll, bender and secondary cooling zones) were calculated equating a medium heat flow obtained from the difference of the water temperature and the observed heat flow rate obtained from measured temperature differences for each zone.

$$h = \frac{mc\Delta T}{A\left(T - T_{\infty}\right)} \tag{6}$$

where m is the water mass flow, c is the water specific heat, ΔT is the water difference temperature, A is the area and T_{∞} is the ambient temperature.

In the mould was used a heat transfer coefficient that depends on the steel residence time in the mould. This coefficient takes in count the thermal resistance due the air gap formation.(6)

$$h_{molde} = 1004{,}6\,.\exp\left(-0{,}02t_{m}\right) \tag{7}$$

And the residence time was calculated using the casting speed (V_l) and mould length (Y).

$$t_{m} = \frac{Y}{V_{l}} \tag{8}$$

For the simulation were used the follows data:

Table 2 – Data used in simulation

Slab wide	1.6m
Slab thickness	0.255m
Casting temperature	1,574 °C
Cooling water temperature	30 °C
Room temperature	40 °C
Solidification beginning temperature	1,539 °C
Solidification finish temperature	1,534 °C
Slab material	Steel carbon (0.15 %)
Emissivity	0.6
Thermal conductivity in the liquid phase	41.0 W/m K
Specific heat in the liquid phase	749.5 J/kg K
Metal density	7,830 kg/m^3

In the solid phase was used the thermal conductivity and the specific heat varying with the temperature. The thermal conductivity was obtained using the equation (9).(7)

$$k = 53{,}719 - 2{,}728x10^{-2}\,T \tag{9}$$

And the specific heat using the equation (10).(8)

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

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

4 RESULTS

The model validation was carried out comparing the measured and calculated temperatures of external faces.

In the Figure 1, are compared measured and predicted temperature for casting speed of 0.81 m/min, which corresponds to the operatinal conditions of a standard operation of the casting machine. Good agreement of mesured and calculated temperature where obtained for the regions of severe cooling conditions.

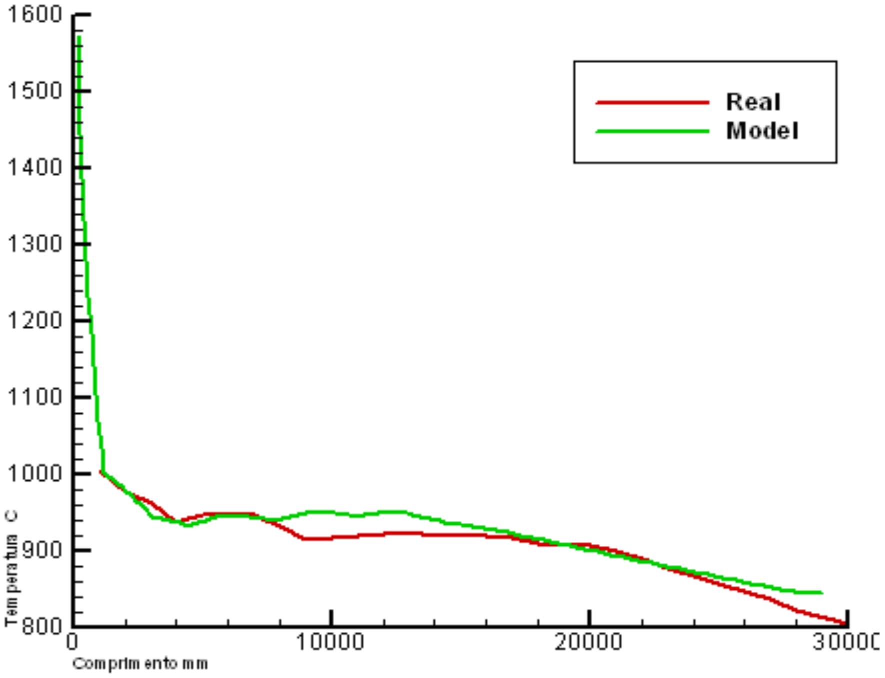

Figure 2 – Comparison between the measures temperatures and the calculated temperatures

Small deviations of model predictions are observed in the regions of breakdown and horizontal segments. This behavior is justified by a recalescence of the surface regions by heat conduction.

In Figures 3, 4 and 5 are presented the calculated temperature distribution in the vein for casting speeds of: 0.81 m/min, 1.1 m/min and 1.4 m/min, respectively. Strong effect of casting speed is observed on the solidified region and consequently on the casting stability. The surface temperatures also consistently increased when the casting speed are increased. These results could be used to determine smooth operational conditions for high casting machine productivity without breakout. It is possible to observe in all temperature fields that strong temperature gradients occur near the slab surface within the solidified shell. These temperature gradients are responsible for some superficial deffects and in severe situations leads to breakout.

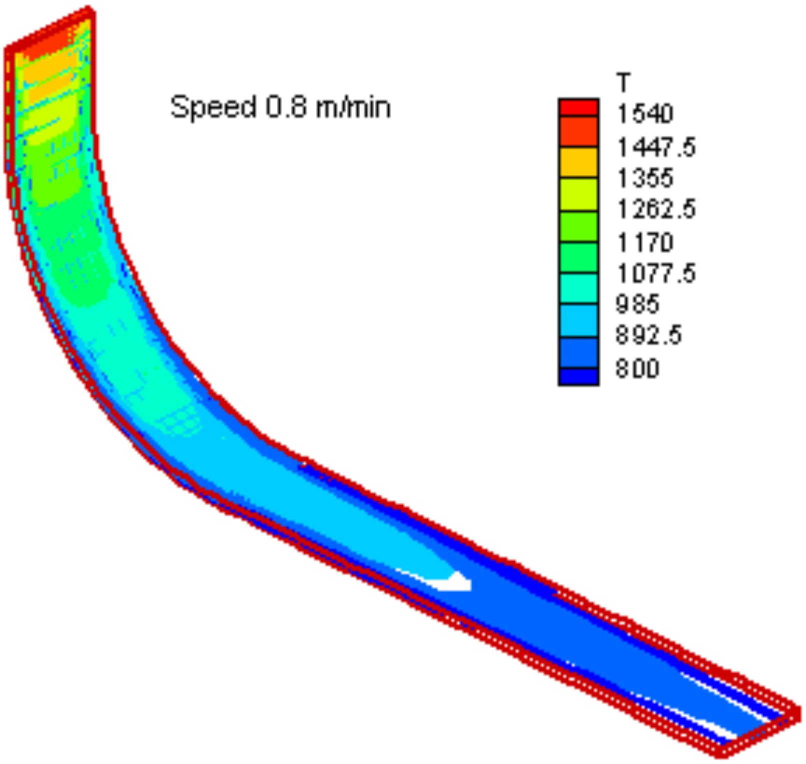

Figure 3 – Continuous casting temperature field with speed of 0.81 m/min.

Figure 6 shows the effect of casting speed in the slab surface temperature. As casting speed increased the surface temperature profile were shifted up and the solidified shell became thinner. These results were expected, however the importance of modeling is to predict accurately the conditions for safety operations. The model, therefore, offers an efficient tool to furnish operational parameters which are not allowed directly by monitoring the process and in addition, previously identify optimal operational conditions for each casting steel procedure.

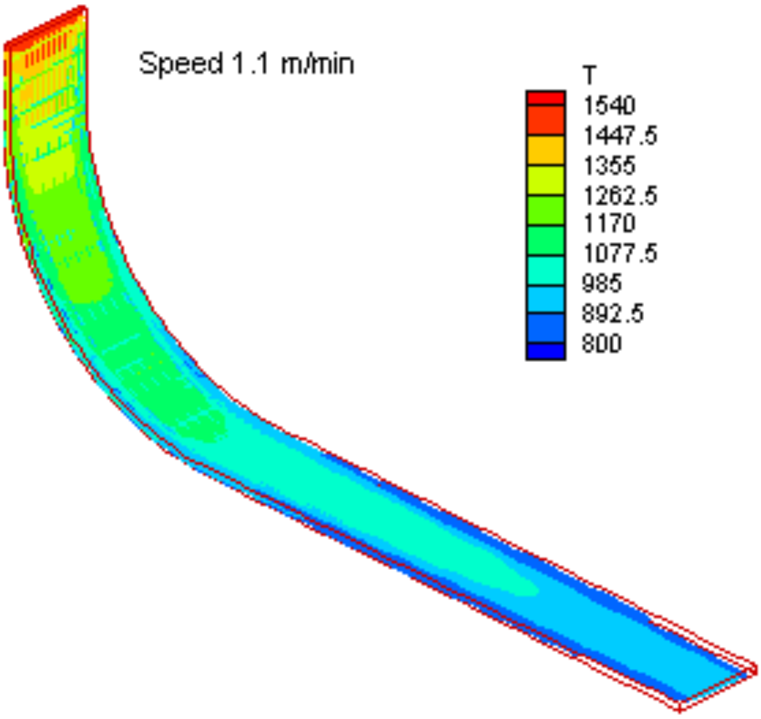

Figure 4 – Continuous casting temperature field with speed of 1.1 m/min.

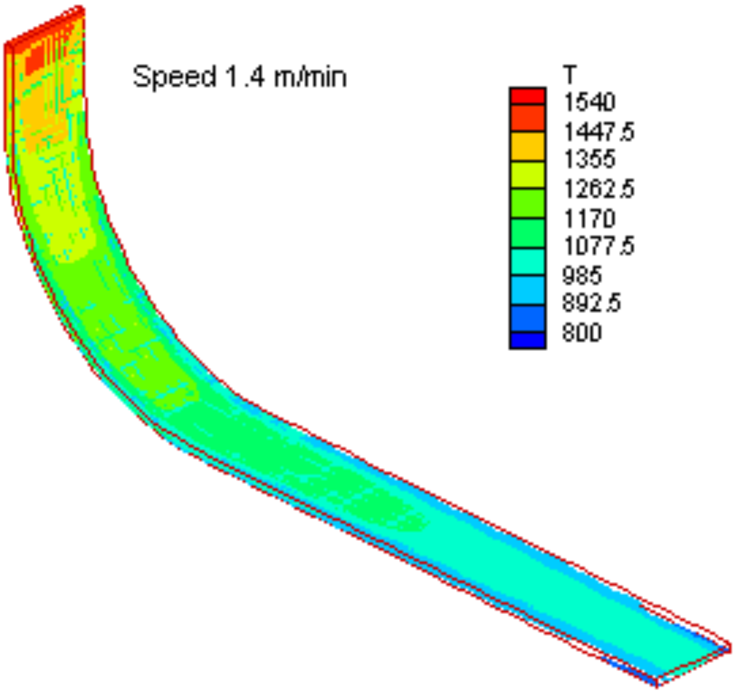

Figure 5 – Continuous casting temperature field with speed of 1.4 m/min.

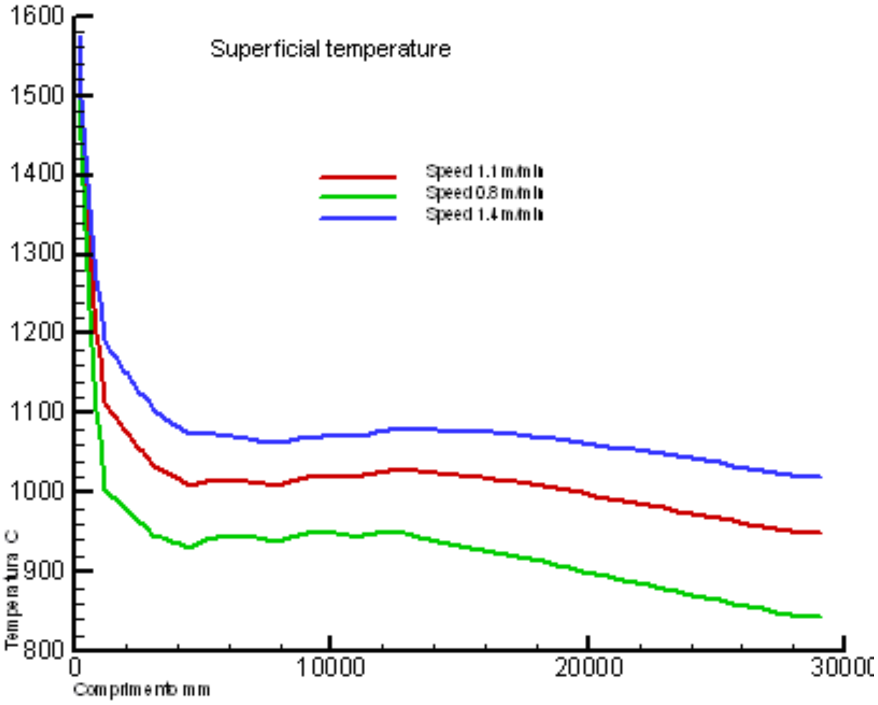

Figure 6 – Temperature variation with different speeds (0,8 m/min, 1.1 m/min and 1.4 m/min).

5 CONCLUSIONS

In this paper a computacional modeling of the continuous casting process is presented. The model is based on transport eqution of heat and momentum coupled with solidification phenomena. The model was validated using industrial data for surface temperature and showed good agreement between measured and predicted ones. The model was used to investigate the effect of casting speed on the casting process. Simulation results indicated that safety operation could be obtained with casting temperature up to 1.4 m/min. Higher speed could be possible with higher cooling rates in the regions of mould and bender. However, the limitaions are due to the heat conductions of the materials and also the water flow regime necessary to get high heat transfer coefficient in these regions.

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