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TEMPERATURE PROFILE IN THE MOLD OF THE CONTINUOUS CASTING

Luiz Joaquim Cardoso Rocha
Department of Engineering of Control and Automation and Fundamental Techniques (DECAT)- School of Mine (EM) – Federal University of Ouro Preto (UFOP) – Campus Universitário, Morro do Cruzeiro, Ouro Preto- MG- Brazil – 35400-000
ljoaquim@em.ufop.br

Henor Artur de Souza
Department of Engineering of Control and Automation and Fundamental Techniques (DECAT)- School of Mine (EM) – Federal University of Ouro Preto (UFOP) – Campus Universitário, Morro do Cruzeiro, Ouro Preto- MG- Brazil – 35400-000
henor@em.ufop.br

Abstract. One of the most important process parameters in the final quality determination of the steel is its superheat degree in the mold. Thus, the mold cooling becomes a relevant factor in the continuous casting process. The thermal resistance in the mold-metal interface influences the heat transfer in the mold substantially. This interfacial thermal resistance increases with the increase of the film melt thickness during the casting process. This resistance is a result of a combined convection and radiation flows. In the external mold surface is important the control of the cooling water flow, because, a not uniform heat transfer in metallic mold affects the production process and the final product quality. This work analyzes the cooling water flow effect in temperature profile of continuous casting mold. A numeric study of the heat transfer in the metallic mold being taken into account the external convection with the cooling water flow and the thermal interaction with the metal, on the internal side, through the air gap formed among mold and metal is presented. This result possibility the cooling water flow controls to obtain improvement in the superficial quality during the continuous casting process. They show the temperature profile in the mold being taken into account profiles of linear temperature in the metal and in the cooling water for the calculation of the heat transfer coefficient. It is still admitted a small variation of the air gap. The finite differences method is used for description the resulting equation. As the boundary condition beside the gas and water are temperature dependent of respective mold walls, it becomes necessary an iterative procedure in its calculation. The numerical method shows to be an efficient tool that it allows to evaluate the flow of heat in the mold and verify the influence of the thickness of the air gap formed between mold and metal. Although some analytical models have been proposed, the numerical analysis is an indispensable tool when there is the necessity to include complex factors as the air gap influence besides the cooling water influence.

Keys words: Continuous casting, thermal resistance, mold temperature profile.

1. Introduction

The problems of superficial quality in the continuous casting of steel process are quite affected for the heat transfer through the layer interfacial in the gas gap between the steel film solidification and the metallic mold. In continuous casting steel process the heat transfer among the liquid steel and the metallic mold has an important role in the superficial cracks formation on final product, affecting the solidification evolution. The thermal resistance in the interface between the metal film and the mold influences the mechanism of heat transfer substantially. This interfacial thermal resistance increases with the increase of the thickness of the metal film during the casting process. This resistance is associated to a combination of the convection and radiation fluxes (Cho, et. al., 1998). For Cho and Shibata (2001) the interfacial thermal resistance acts more than fifty percent of the global thermal resistance for the heat transfer close of the meniscus in the mold.

During steel solidification in the continuous casting the resistance to the heat transfer in the metal-mold interface depends on many factors, such as, contact pressure, oxides in the surface, rugosity of the surface, material coating, coating thickness, top surface turbulence (Kim and Lee, 1997; Santos, et al., 2001). Another important factor is the gas gap development between copper mold and change phase material. This gas gap deforms the solidification front and modifies the crystallization of the metal (Cho and Shibata, 2001). In accordance with Stone and Thomas (1999) one of the functions more critics in heat flux in the mold is the control of the heat transfer through the gas gap. Liquid mold flux enters this gap at the meniscus intermittently during each oscillation cycle. It solidifies in the cold side of the gap into layers that may contain either crystalline or glassy phases, depending on the composition and local cooling history. These flux layers govern the heat transfer across the gap, Figure (1). The final surface of the product is created during the initial stage of steel solidification against the water-cooled copper mold at the meniscus. In the external mold surface is important the control of the cooling water flow that affects the heat transfer coefficient directly.

In the interface metal-mold is put a powder that serves as lubricant and it avoid the metal sticking in mold. He also controls the heat conduction rate through the interfacial gap, Figure (1). In accordance with Stone and Thomas (1999) the mold flux is added as a powder to the top surface, where it insulates the molten steel from both heat losses and atmosphere contamination. The powder sinters melts to form a layer of liquid that floats on the surface of molten steel.

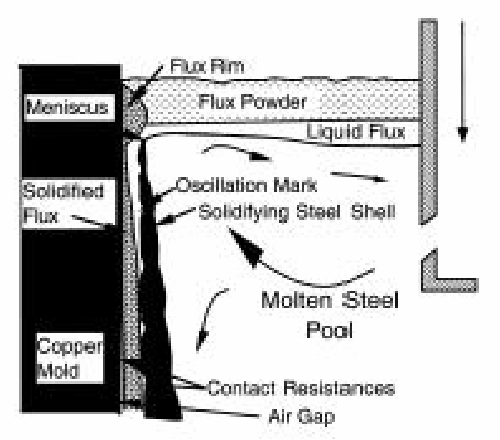


Figure (1). Scheme of the continuous casting process showing the layers in the interface mold-metal Source: Stone and Thomas, 1999

The literature contains a great number of works presenting analytical models and experimental studies (Huespe et. al., 2000; Martorano and Capocchi, 2000). However, to contemplate the whole process is necessary including more complex factors, as the thermal interaction in interface mold-metal, becoming the numeric analysis an indispensable tool (Krishnan and Sharma, 1996, Huespe et. al., 2000).

This work presents a numeric study of the heat transfer in the metallic mold accounting the external convection with the cooling water flow and the thermal interaction with the metal and gas gap. It is studied the cooling water flow influence in temperature profile of mold. Results are compared with experimental data of Taconi. (Taconi, L.L., 2006). With the results it can, besides optimizing the consumption cooling water, to obtain improvement in the superficial quality of the steel during the process of continuous casting, because, a not uniform heat transfer in metallic mold affects the production process and the quality of the final product.

2. **Methodology**

Continuous casting is the process whereby molten steel is solidified into semifinished billets, blooms, or slabs for subsequent rolling in finishing mills. In continuous casting, liquid steel is transferred in a ladle to the casting machine. When the casting operation starts, the sliding shutter at the bottom of the ladle is opened and the steel flows at a controlled rate into the tundish and from the tundish into one or more molds, Figure (2). The basic objectives of the tundish are server of reservoir of steel during the exchange of ladle, promote the detachment of not metallic enclosures, control the speed of the continuous casting and feed the mold. The mold has like fundamental function the primary cooling, providing the formation of a solid layer of metal in such a way that upon leaving of the mold this solid layer is sufficiently thick for resists to the pressure of the liquid steel in his nucleus. This work studies the temperature profile in mold wall of a continuous casting process.

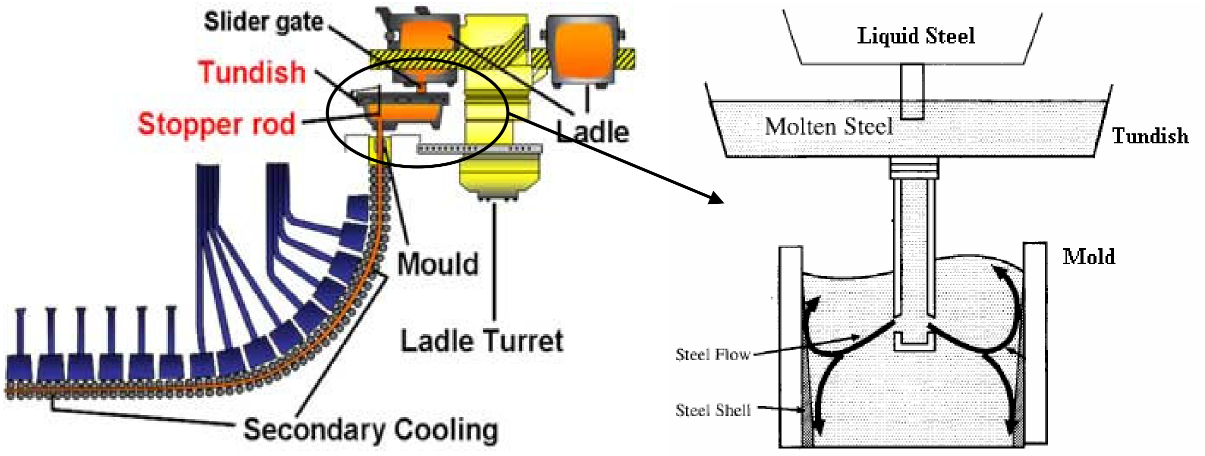


Figure (2). Schematic presentation of a steel continuous casting machine
(Source: Rautaruukki Oyj, 2005)

2.1. Formulation for the heat transfer in the mold

The mold is considered as a duct of square section, Figure (3). The resultant equation of the transport problem, in the mold wall, is two-dimensional and non steady state with constant properties, as shown in the Equation (1).

$$\frac{\partial}{\partial x}\left(\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{\partial T}{\partial y}\right)=\frac{1}{\alpha}\frac{\partial T}{\partial t} \quad (1)$$

where T is the temperature, x and y are the coordinate system directions t is the time and $\alpha=\kappa/\rho c$ is the thermal diffusivity.

The boundary conditions are shown in the Figure (3). In the external surface of the mold, x = L, the heat flux is given by convection, as show the Equation (2).

$$-k_{mold}\left(\frac{\partial T(x,t)}{\partial x}\right)_{x=L}=h_{ext}(T)\left[T(L,t)-T_{ext}\right] \quad (2)$$

k_{mold} is the mold thermal conductivity and h_{ext} is the external heat transfer coefficient that can be evaluated by the relationship presented in the Equation (3).

$$h_{ext}(T)=\frac{k_f(T)}{D_H}\left[0.023\,Re^{0.8}\,Pr^{0.4}\right] \quad (3)$$

where k_f is the water thermal conductivity, D_H is the hydraulic diameter. The Reynolds number (Re), Equation (4), and the Prandtl number (Pr), Equation (5), are defined as:

$$Re=\frac{VD_H}{\nu} \quad (4)$$

$$Pr=\frac{\nu}{\alpha} \quad (5)$$

where V is the cooling water flow velocity, ν is the cinematic viscosity and α is the thermal diffusivity.

In the internal surface of the mold, the boundary condition takes into account radiation and convection heat exchanges through the gas gap formed between the mold surface and the solidified metal, as shows the Equation (6).

$$\left(h_{int}(T)+h_{conv}(T)\right)\left[T_{int}(t)-T(0,t)\right]=-k_{mold}\left(\frac{\partial T(x,t)}{\partial x}\right)_{x=0} \quad (6)$$

where h_{int} is the radiation heat transfer coefficient through the gas gap formed between the solidified metal surface and the surface of the mold. It can be given by the relationship shown in the Equation (7). The convective heat transfer coefficient h_{conv} is had by the relationship, Equation (8),

$$h_{int}(T)=\varepsilon\sigma\left[T_{int}(t)+T(0,t)\right]\left[T_{int}(t)^2+T(0,t)^2\right] \quad (7)$$

$$h_{conv}(T)=\frac{k_{gas}(T)}{\delta_{gas}(y)} \quad (8)$$

k_{gas} is the thermal conductivity of the gas and δ_{gas} is the gas gap thickness.

The top and bottom of the mold surfaces are insulated, as shows Figure (3). Also, part of the internal surface, near of the top, is insulated too. The initial condition is a uniform temperature (25 ^{0}C).

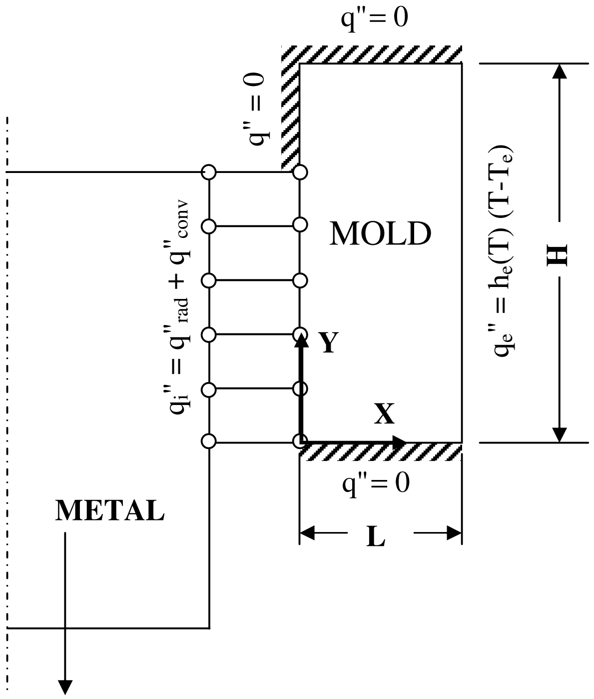


Figure (3). Boundary conditions and coordinate system

Figure (4) presents a structure of the wall of the mold, showing the liquid metal, the gas gap, the mold and the gap of water.

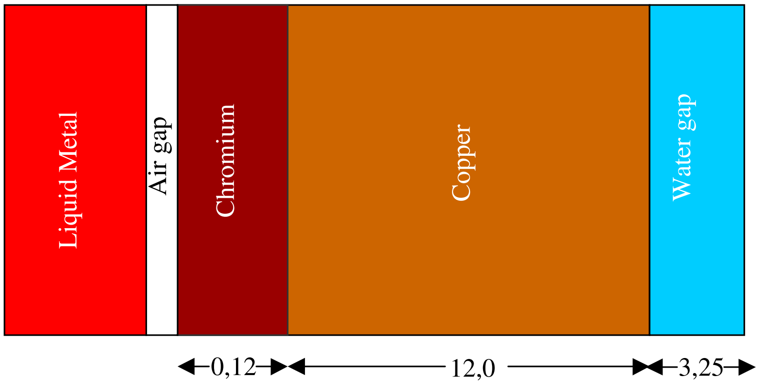


Figure (4). Structure of the wall of the mold, dimensions in mm

2.2. Numeric approach

The numerical method selected for the energy equation resolution, Equation (1) is the method of finite differences with formulation in control volumes. The power law interpolation is used for evaluate the heat flux in the faces of the control volumes. The algebraic system is resolved with the algorithm TDMA line by line with the blocks correction algorithm for accelerate the convergence. As the boundary condition in the internal and external surfaces are temperature dependent, of the respective mold walls, it becomes necessary an iterative procedure in its calculation. The convergence solution is reached when the residue of the equation description goes smaller than 10^{-6}.

3. Case studies

A mold can be modeled as a duct with 190 mm width and one meter height. The mold copper wall thickness has 12 mm and is covered by a chrome layer of 0.12 mm. The cooling water flow considered here varies of 135 l/min to 480 l/min, with entrance and exit temperatures of 25 ^{0}C and 35 ^{0}C, respectively. The channel thickness of cooling water has 3.25 mm. A linear profile is admitted for the temperature of the cooling water flow. Also, a linear profile to the gas gap thickness is considered and the maximum valor is 25 μm, selected of the work of Taconi (Taconi, L.L., 2006).

Figure (5) presents a comparison of experimental (Taconi, L.L., 2006) and numerical (present work) data. The problem described above with a cooling water flow is 462.5 l/min. The results present a good agreement with experimental data, except for one point.

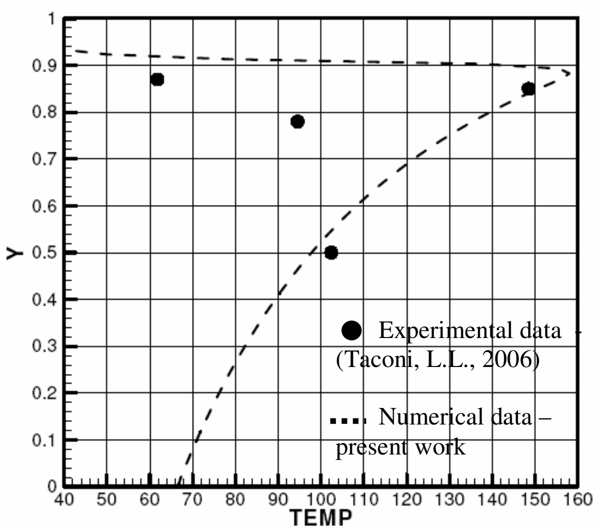


Figure (5). Experimental and numerical data

Figure (6) and Figure (7) show the evolution of global Nusselt number with the cooling water flow and the Fourier number. The global Nusselt, Nusselt and Fourier numbers are defining bellow, in Equations (9), (10) and (11), respectively.

$$\overline{Nu} = \frac{1}{A}\int Nu\, dA \tag{9}$$

$$Nu = \frac{hL}{k} \tag{10}$$

$$Fo = \frac{\alpha t}{L^2} \tag{11}$$

In Figure (6), when the cooling water flow increases, the external heat transfer coefficient, hw increases too. The global Nusselt number in mold-water interface increases with your increase, more strongly during the transient regime than in steady state. It occurs in function of the high existent temperature gradients in the beginning of the metal leak.

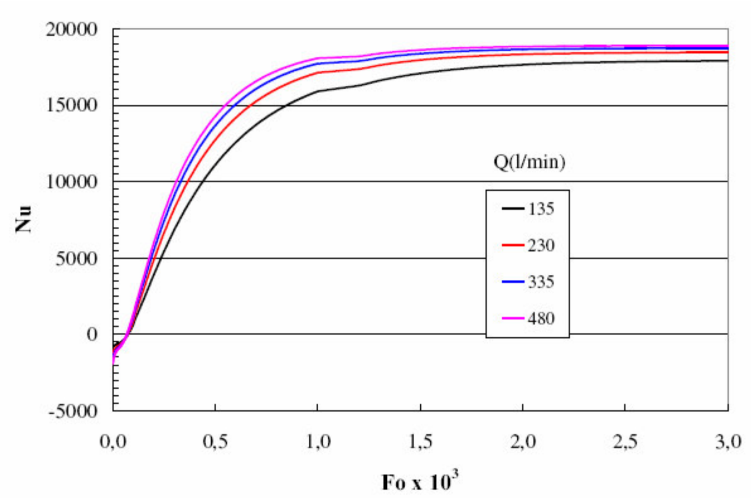


Figure (6). Global Nusselt x Fourier in function of the cooling water flow in external surface

Figure (7) shows the evolution of global Nusselt number with mold-gas gap, internal surface. The results reveal that this increase change strongly in first time steps than in final time steps. Is occurs because between the mold surface and the cooling water flow the temperature gradient steel high.

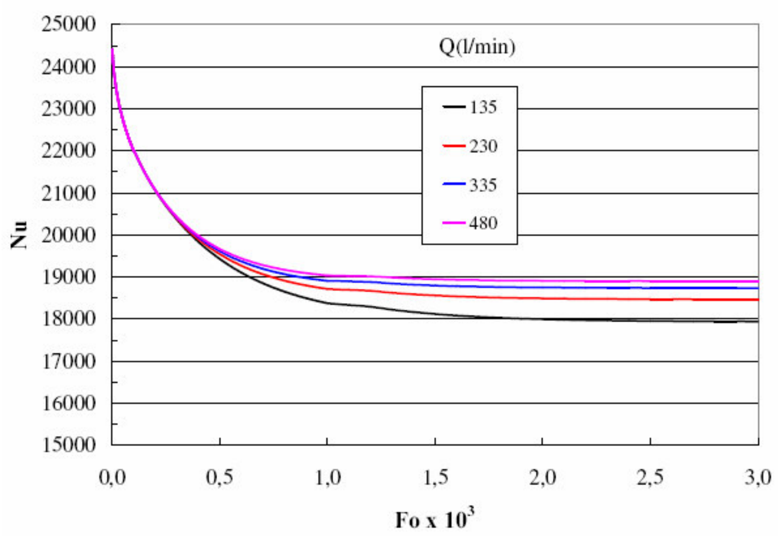


Figure (7). Global Nusselt x Fourier in function of the cooling water flow in internal surface

The Figures (8) to (12) present the results for a cooling water flow rate at 230 l/min. Figure (8) shows isotherms for an area close to the top mold surface, illustrating the insulated boundary condition.

Figures (9), (10), (11) and (12) show the evolution of the temperature in the mold with increase of the number of Fourier. In these figures, the dimensionless times (Fourier) shown are $1x10^{-5}$, $3x10^{-5}$, $5x10^{-5}$, $7x10^{-5}$, $1x10^{-4}$, $2x10^{-4}$, $3x10^{-4}$, $5x10^{-4}$, $7x10^{-4}$, $1x10^{-3}$, $3x10^{-3}$, and $5x10^{-3}$.

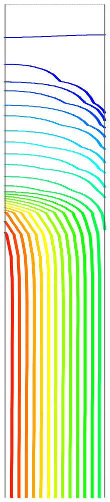
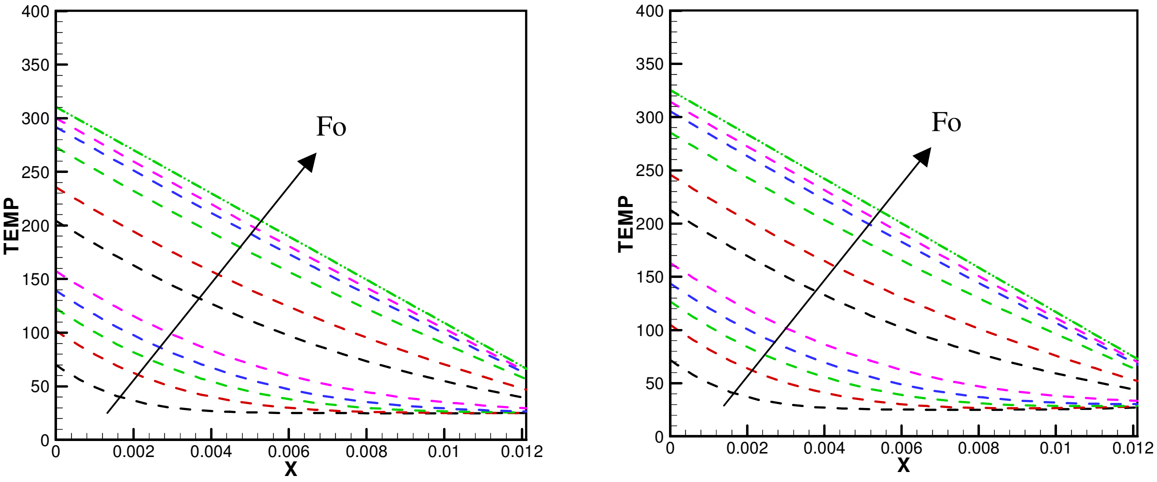


Figure (8). Isotherm close of the top surface

Figure (9) shows that the temperature profile in the mold is characterized by a lineal profile in the steady state. Also, reveals that the final temperature in the center of the mold is greater than in the bottom. This occurs in function of the solidified metal thickness that is minor in the center of the mold than in the bottom.



(a) In the bottom of the mold

(b) In the center of the mold

Figure (9). Temperature profile in the mold

On the top of the mold, Figure (10), while the time increases the profile of temperature becomes itself uniform. This is explained by the boundary condition in this region, i.e., the change phase material does not enter in contact with the mold in this region. By this, that the temperature is smaller than the temperatures in the center and in the bottom of the mold.

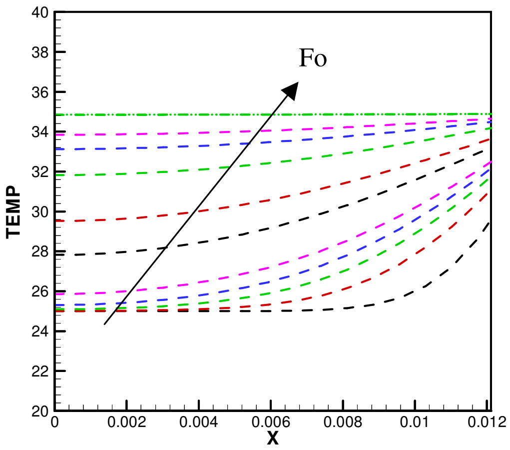
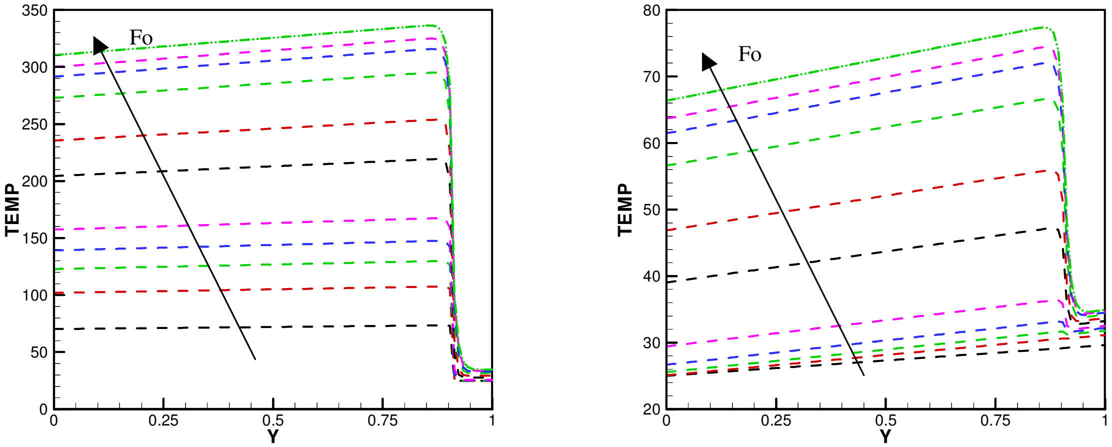


Figure (10). Temperature profile in the top of the mold

Figure (11) and Figure (12) present an accentuated gradient of the temperature, close of the top of the surface, in function of the insulated. In steady state the temperature profile in the mold is characterized by a lineal profile, except in that one insulated region.



(a) In the interface mold - gas gap

(b) In the interface mold – cooling water

Figure (11). Temperature profile in the mold

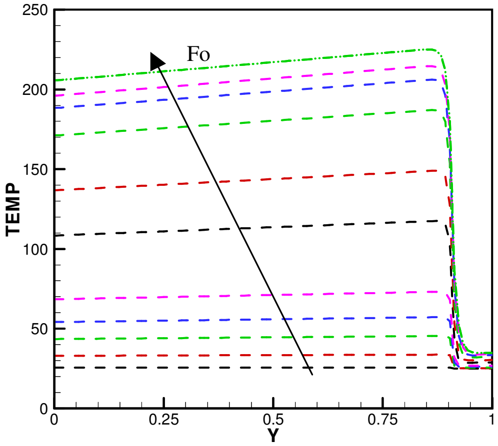


Figure (12). Temperature profile in the center of the wall of the mold

Figure (13) shows the global Nusselt number evolution, Equation (9), in two surfaces of the mold wall. The Nu_east and Nu_west represent the normalized heat transfer coefficient in contact with the cooling water and the combined coefficient of radiation and convection in the side of the interface with the metal, respectively. After Fourier numbers above 3 x 10^{-3} the solution tends to steady state.

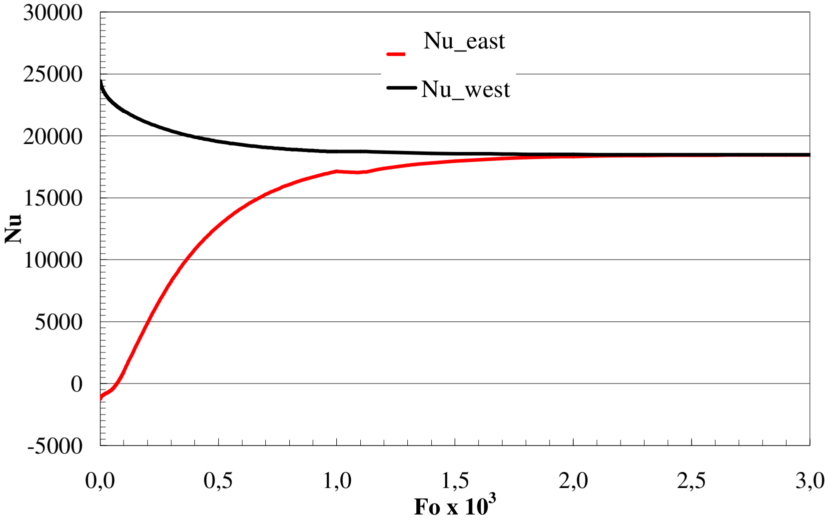


Figure (13). Global Nusselt x Fourier

4. Final considerations

A numeric study of the heat transfer in the metallic mold being taken into account the external convection with the cooling water flow and the thermal interaction with the metal, on the internal side, through the gas gap formed among mold and metal is presented. The results show the temperature profile in the mold being taken into account profiles of linear temperature in the metal and in the cooling water for the calculation of the heat transfer coefficient. It is still admitted a small variation of the gas gap. It is observed that the influence of the cooling water flow is an important parameter in the formation of the final surface of the product. The mold has fundamental function in the formation of a solid layer of metal. This solidified layer has to be sufficiently thick for resists to the pressure of the liquid steel in his nucleus.

Acknowledgments

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