

Simulation of continuous cast steel product solidification*

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Abstract

Primary cooling – inside the tundish – has a great impact over the thickness of the solidified steel crust. If on exiting the tundish the crust is too thin, it can punch and break, as a result of the ferrostatic pressure exerted from the inside by the liquid steel as well as because of the weight of the molten steel. The parameters that influence the amount of dissipated heat depend on the cooling water flow of the tundish, on the pressure and temperature of the cooling water but also on the overheating of the continuously cast steel. The secondary cooling takes place at the exit of the semi-finished product from the tundish, when the solidification is supposed to take place all along the cross section of the strand. In order to achieve it, in addition to a correctly managed primary cooling, it is necessary to obtain the proper correlation of the factors that influence the secondary cooling as well: the water flow rate long the three zones of the installation and its pressure in the secondary circuit. All these have in view a proper solidification length; an intense cooling can generate cracks due to the thermal stress, while a too slow cooling can generate a partial solidification of the strand up to the cropping machine area^[1 y 2]. The paper presents a mathematical simulation of the continuously cast steel solidification.

Keywords

Simulation. Continuous casting. Semi-finished product. Primary cooling. Secondary cooling.

Simulación de la solidificación de los semiproductos de acero, fundidos continuamente

Resumen

El enfriamiento primario del cristalizador tiene una gran importancia sobre el espesor de la costra de acero solidificado. Si al salir del cristalizador, esta costra es demasiado sutil, bajo la acción de la presión ferro estática ejercitada por el acero líquido del interior y gracias el peso propio del hilo, ésta, puede perforar resultando su rompimiento. Los parámetros que influyen sobre la cantidad de calor cedida dependen del agua de enfriamiento del catalizador, de la presión y de la temperatura de agua de enfriamiento, pero también del sobrecalentamiento del acero fundido continuamente. A la salida del semiproducto del cristalizador, tiene lugar el enfriamiento secundario, a lo largo del que la solidificación tiene que realizarse en toda la sección transversal del hilo. Para eso, además de un enfriamiento primario manejado correctamente, tienen que correlacionarse a los factores que influyen en el enfriamiento secundario, también; el flujo del agua en las tres zonas de la instalación, la presión del agua en el circuito secundario, etc. Todo esto tiene que ver con una longitud correspondiente de solidificación; un enfriamiento intenso que puede llevar a la aparición de grietas debidas a las tensiones térmicas y un enfriamiento lento puede llevar a una solidificación parcial del hilo hasta la zona del agregado de flujo^[1 y 2]. El trabajo representa un modelo de simulación de la solidificación de los semiproductos de acero fundidos continuamente.

Palabras clave

Simulación. Colada continua. Semiproducto. Enfriamiento primario. Enfriamiento secundario.

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1. INTRODUCTION

In view of studying the quality of continuously cast semi finished products^[3], besides the classical methods, (sampling and sample analysis), the reference literature offers a lot of attempts at simulating the continuous casting process, making use of various applications^[4] or starting from simplifying hypotheses.

The finite differential method is based on turning the heat transfer differential equation into finite differential equations. The heat transfer differential equation along the two axes (heat transfer on vertical direction is neglected) is expressed as follows:

$$\frac{\partial T}{\partial \tau} = a \cdot \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) \tag{1}$$

where,
 T represents the temperature, (°C);
 τ – time, (s);
 a – thermal diffusivity, (m²/s);
 x, y – coordinates.

In order to transform relation (1) in a finite differential equation, the temperature of a point (i, j) is expressed as a function of the temperatures of the neighboring points. In this case we consider an inside point (Fig. 1).

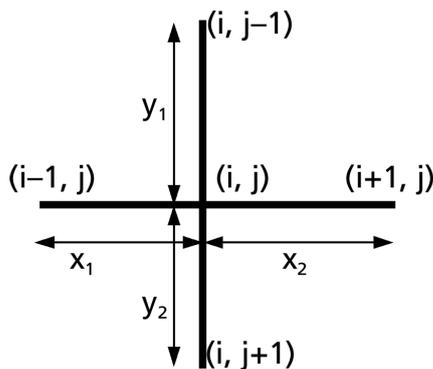


Figure 1. Point inside a semi-finished product.

Figura 1. Nudo en el interior del semiproducto.

2. METHOD

In order to grant the stability of the solution using the finite differential method, the time interval between iterations and the network dimensions need to be chosen taking into account the deduced stability criteria. What we also need is the accuracy of the solution, i.e. a better concordance with the analytical solution. This

depends on the shape of finite differential equation and the number of nodes. The number of nodes is established starting from the necessity of finding a solution for the following contradiction: on the one hand, the use of a high number of nodes increases the precision of the model (the error introduced by the hypothesis that the adjacent surface of each node has the same temperature as the node decreases with the decrease of node area); on the other hand a high number of nodes leads to an increase of processing time, due to the increased number of nodes and due to decreasing the time intervals between iterations, imposed by the stability conditions of the solution.

Analyzing the stability of the finite differential equation results in the following criteria:

— inside

$$\Delta \tau \leq \frac{1}{2a \cdot \left[\frac{1}{x_1 x_2} + \frac{1}{y_1 y_2} \right]} \tag{2}$$

— on boundary

$$\Delta \tau \leq \frac{1}{2a \cdot \left[\frac{1}{x_1 x_2} + \frac{1}{y_2} + \frac{W}{\lambda \cdot y} \right]} \tag{3}$$

—on corner

$$\Delta \tau \leq \frac{1}{2a \cdot \left[\frac{1}{x_1 x_2} + \frac{1}{y_2} + \frac{W}{\lambda \cdot x} + \frac{W}{\lambda \cdot y} \right]} \tag{4}$$

The time interval chosen represents the time in which the unsteady heat transfer process is assimilated to a steady process. For this reason, the farther the characteristics of the real process from that of a steady one, the smaller the iteration period should be.

In order to obtain a bi-dimensional mathematical modeling of a semi-finished product we considered a section of the ensemble semi-finished product-crystallizer, which is divided by means of a discretisation network (Fig. 2). The temperature of every node represents the mean temperature of the node adjacent surface. In these nodes are written the finite differential equations presented above.

The model is realized based on the following simplifying assumptions:

- the heat transfer along the longitudinal axis is neglected, considering that heat transfer takes place just in the horizontal section of the semi-finished product;
- the density variation is neglected;
- the tundish section is considered to be equivalent to a rectangular section;

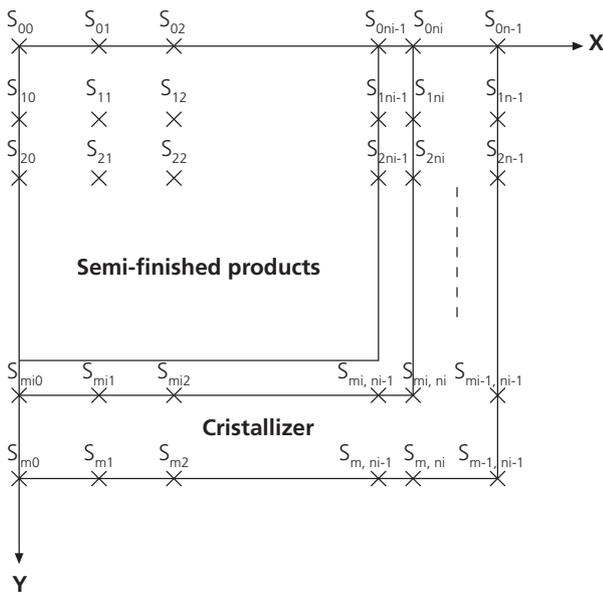


Figure 2. The network schema used in finite difference method.

Figura 2. Esquema de la red utilizada en el método de las diferencias finitas.

- it is considered that the tundish loses heat evenly on each surface;
- it is considered that, at moment zero, the temperature of the steel mass is uniform;
- for the surface nodes it is correct to assume that at the casting moment the formation of a thin solidified steel layer has already taken place, and the heat dissipated by this layer is transmitted instantaneously to the nodes from the inner surface of the tundish;
- the dissipation of the fusion latent heat is produced in the liquidus-solidus interval, and is directly proportional to the temperature.

As a result of the hypotheses under consideration, the semi-finished product-tundish ensemble is symmetric to the longitudinal axis of the semi-finished product. The origin of the system of coordinates will be in the center of the semi-finished product and the calculus will be made just for positive x and y.

For the implementation of an algorithm of the model described above we need the following initial data: the ambient temperature, the casting temperature, the initial temperature of the tundish, the number of nodes of the semi-finished product and from the tundish with respect to both axes, the values of the thermal conductivity for steel and copper depending on temperature, the values of the enthalpy for steel and copper depending on temperature. In the case of steel, this functional dependence needs to include fusion latent heat; the condition of the semi-finished

product quitting the equipment; the stopping condition of the algorithm. This could be: manual stopping, after a given time period, at a specified minimum, average, or maximum temperature of the semi-finished product, the maximum variation of enthalpy at one iteration.

The simulation is realized for a semi-finished product (bloom), having the cross-section 240x270 mm, made of S235 steel.

Due to the use of central symmetry it is possible to have cases when one (or both) indices i, j will be -1. This is the case when we calculate a node placed on one of the axes X, Y or in the origin of the coordinates system.

For simplifying the calculus, we used discrediting networks having the nodes evenly distributed along the X and Y-axes. The following specific cases are obtained:

1. The coordinate system origin (i=j=0):

$$\frac{H_{i,j,k+1} - H_{i,j,k}}{\tau_{k+1} - \tau_k} = \frac{\lambda_0}{\rho \cdot x^2} [0 + 2\Phi_{i+1,j,k} - 2\Phi_{i,j,k}] + \frac{\lambda_0}{\rho \cdot y^2} [0 + 2\Phi_{i,j+1,k} - 2\Phi_{i,j,k}] \quad (5)$$

2. Y axes (i=0):

$$\frac{H_{i,j,k+1} - H_{i,j,k}}{\tau_{k+1} - \tau_k} = \frac{\lambda_0}{\rho \cdot x^2} [0 + 2\Phi_{i+1,j,k} - 2\Phi_{i,j,k}] + \frac{\lambda_0}{\rho \cdot y^2} [\Phi_{i,j-1,k} + \Phi_{i,j+1,k} - 2\Phi_{i,j,k}] \quad (6)$$

3. X axes (j=0):

$$\frac{H_{i,j,k+1} - H_{i,j,k}}{\tau_{k+1} - \tau_k} = \frac{\lambda_0}{\rho \cdot x^2} [\Phi_{i-1,j,k} + \Phi_{i+1,j,k} - 2\Phi_{i,j,k}] + \frac{\lambda_0}{\rho \cdot y^2} [0 + 2\Phi_{i+1,j,k} - 2\Phi_{i,j,k}] \quad (7)$$

4. Inside:

$$\frac{H_{i,j,k+1} - H_{i,j,k}}{\tau_{k+1} - \tau_k} = \frac{\lambda_0}{\rho \cdot x^2} [\Phi_{i-1,j,k} + \Phi_{i+1,j,k} - 2\Phi_{i,j,k}] + \frac{\lambda_0}{\rho \cdot y^2} [\Phi_{i,j-1,k} + \Phi_{i,j+1,k} - 2\Phi_{i,j,k}] \quad (8)$$

5. Y boundary (i=n-1):

$$\frac{H_{i,j,k+1} - H_{i,j,k}}{\tau_{k+1} - \tau_k} = \frac{\lambda_0}{\rho \cdot x^2} [2\Phi_{i-1,j,k} + \frac{2x}{\lambda_0} W - 2\Phi_{i,j,k}] + \frac{\lambda_0}{\rho \cdot y^2} [\Phi_{i,j-1,k} + \Phi_{i,j+1,k} - 2\Phi_{i,j,k}] \quad (9)$$

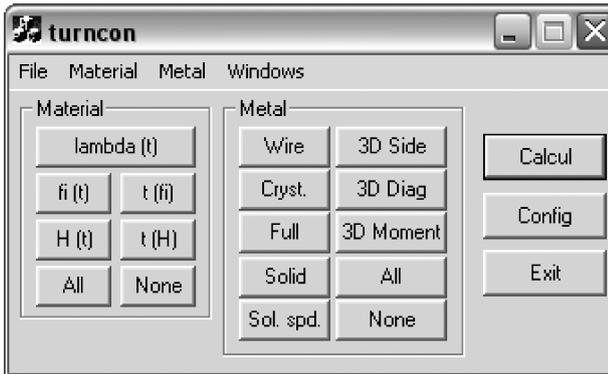


Figure 3. Program main interface.

Figura 3. Interfaz principal del programa.

6. X boundary (j=m-1):

$$\frac{H_{i,j,k+1} - H_{i,j,k}}{\tau_{k+1} - \tau_k} = \frac{\lambda_0}{\rho \cdot x^2} [\Phi_{i-1,j,k} + \Phi_{i+1,j,k} - 2\Phi_{i,j,k}] + \frac{\lambda_0}{\rho \cdot y^2} [2\Phi_{i,j-1,k} + \frac{2y}{\lambda_0} W - 2\Phi_{i,j,k}] \quad (10)$$

7. Corner: (11)

$$\frac{H_{i,j,k+1} - H_{i,j,k}}{\tau_{k+1} - \tau_k} = \frac{\lambda_0}{\rho \cdot x^2} [2\Phi_{i-1,j,k} + \frac{2x}{\lambda_0} W - 2\Phi_{i,j,k}] + \frac{\lambda_0}{\rho \cdot y^2} [2\Phi_{i,j-1,k} + \frac{2y}{\lambda_0} W - 2\Phi_{i,j,k}] \quad (11)$$

The computing program was written in C++ and it runs under Win32 systems (that means Windows 95, 98, Me, NT4, 2000, XP – with Intel processor). As graphical interface, the program uses MFC (Microsoft Foundation Classes), a class library that includes the functionality of Windows standard programming interface (API – Application Program Interface). The 3D graphs are realized by means of the Windows imple-

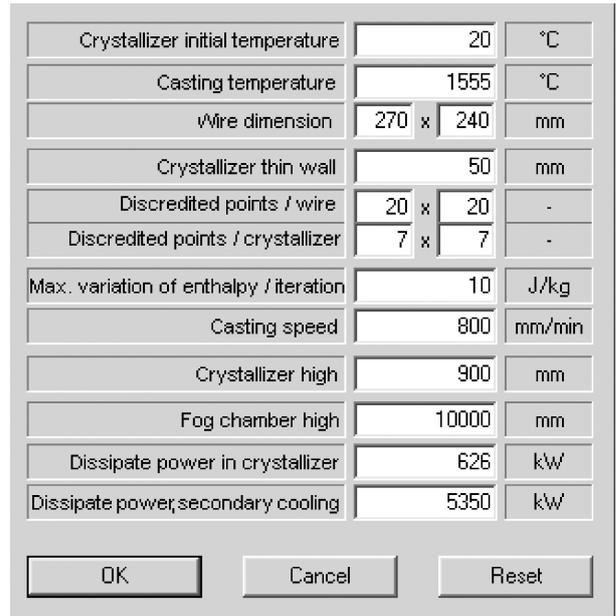


Figure 4. Dialog box for establishing the starting data of the program.

Figura 4 Ventana de diálogo para establecer los datos de desarrollo del programa.

mentation of OpenGL specification (Open Graphics Library).

For the configuration of specific data for every steel grade, using the main interface (Fig. 3) the program opens the dialog box presented in figure 4.

When the program is running a dialog box is opened showing the calculus progress, as shown in figure 5.

The temperatures are indicated by the means of a colored gradient, having the values: red for casting temperature, blue for ambient temperature and green for their average. Any intermediary temperature is a combination of these.

One of the dependencies first obtained is represented by the temperature variation of the semi-finis-

Table I. Comparison of measured values to those obtained from simulation

Tabla I. Comparación de los valores medidos y de los obtenidos después de la simulación

Measured points	Variation interval of the measured temperature, (°C)	Temperatures obtained by simulation in theby simulation in the points placed on the surface of the semi-finished product, (°C)		
		5	6	7
1	1286-1400	1405.4	1397.4	1259.8
2	1205-1365	1378.6	1360.5	1197.7
3	1130-1345	1359.8	1339.2	1130.5
4	960-1175	1200.3	1168.8	968.5

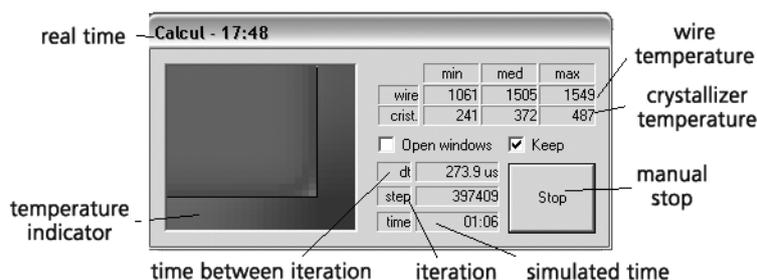


Figure 5. Dialog box for calculus progress.

Figura 5. Ventana de diálogo para el progreso de los cálculos.

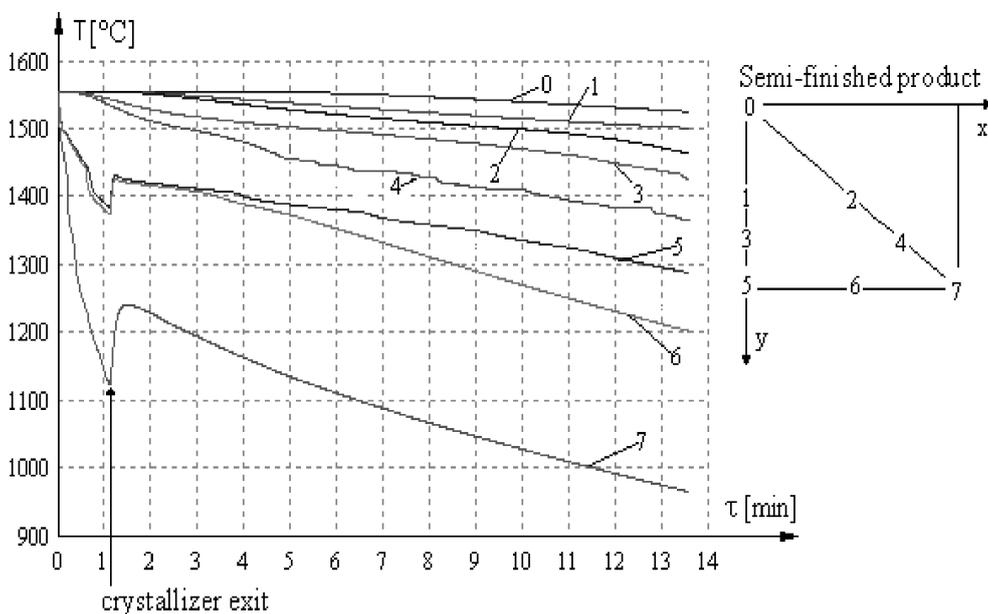


Figure 6. Temperature variation depending on time.

Figura 6. Variación de las temperaturas en hilo, dependiendo del tiempo.

hed product depending on time (Fig. 6.). The distribution of the discretized points is also presented.

A slight decrease of the temperature of points placed near the center of the semi-finished product can be noticed, but also the variation mode of the temperature from layers closer to the strand surface.

At a given time moment (in the case under consideration equal to 1,07 min), when the surface under consideration leaves the tundish, there is an increase of temperature in the upper layers of the semi-finished product (by approximately 100 °C in the corner and by 35-50 °C in points 5 and 6 of the surface).

This increase of the temperature is due to the lack of strand cooling right after leaving the tundish and up to the first ring of secondary cooling. After this moment the cooling and the solidification of the strand takes place normally, the recorded temperatures corresponding to the measured ones (for the surface – Table I).

It has to be specified that the simulation is achieved just for the primary and secondary cooling, not for the entire running of the strand in the equipment. This explains the high temperature values of the steel inside the semi-finished product (middle layers), but they are decreasing under the solidus temperature value until the cropping of the semi-finished product^{5 y 6}.

As to the temperature distribution in the tundish (which takes over the heat transferred by the semi-finished product and transfers it to the cooling water), is it shown in figure 7. In this case too, we also showed the position of the discretized points.

Another type of temperature distribution, when the semi-finished product is driven out from secondary cooling zone, is presented in figure 8.

The regression surface obtained corresponds to a quarter of the semi-finished product section, being the same for the remaining parts of the section. From

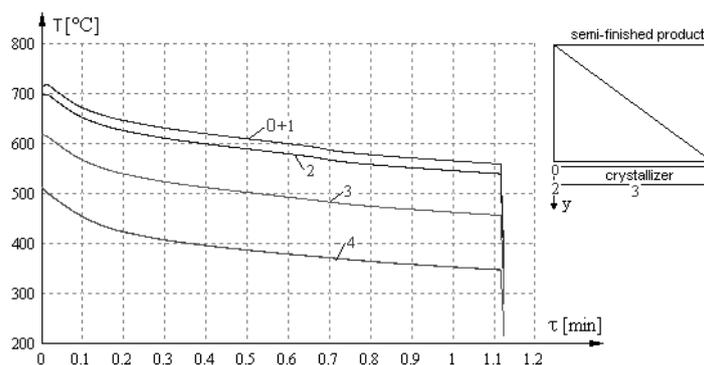


Figure 7. Temperature variation in the tundish, depending on time.

Figura 7. Variación de la temperatura del cristalizador, dependiendo del tiempo.

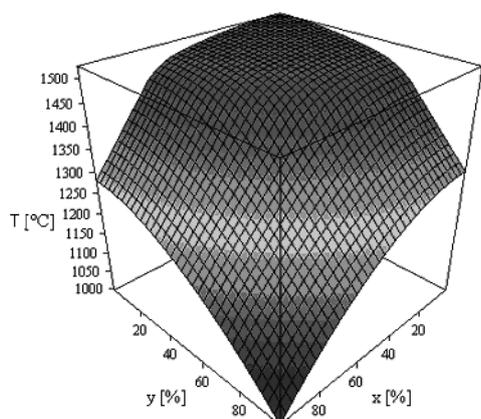


Figure 8. Temperature distribution in the bloom having the cross-section 240x270 mm at 13.33 min from the beginning of casting.

Figura 8. Distribución de las temperaturas en el semiproducto con la sección 240x270 mm a 13,33 min desde el principio de la fundición.

the point of view of the temperature values, the corner of the semi-finished product is the one that is most intensely cooled, the center being cooled the most slowly.

Based also on the TURNCON calculus program we obtained the type of variation for the solidification rate, depending on time. It refers to a solidification rate calculated between two consecutive iterations, fact that partially explains the oscillating aspect of the curves presented in figure 9.

On the other hand, the oscillating condition could be explained by the oscillations of the tundish. One can notice a negative value, at 1.07 min after the beginning of the casting, when, due to a big amount of heat, which could not be taken over by the secondary cooling water, a part of the crust interior layer is remol-

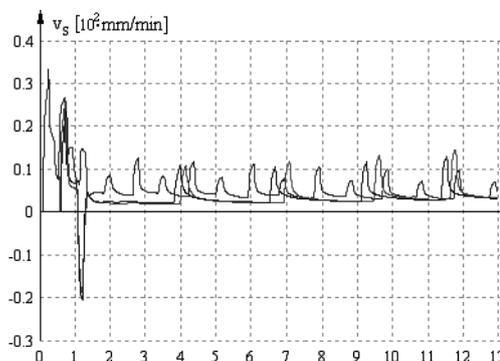


Figure 9. Solidification rate variation depending on time.

Figura 9. Variación en tiempo de la velocidad de solidificación.

ten, after which it comes back to positive values for this parameter.

With the help of the solidification rate and the other parameters used by the program, the main interface allowed us to obtain the variation of the solidified steel crust depending on time for the points located in the superior layers. In fact we can say that the variations we obtained (the curves given in figure 10) represent the shape of the solidification front for the considered points.

The variation is of percentage type, represented from the boundary (exterior) to the center of the semi-finished product (of the considered section).

3. CONCLUSIONS

Analyzing the graphical dependencies resulting from the researches, based on literature review data and from our own experimental work the following conclusions can be drawn:

- The results obtained by simulation with the program under consideration, being similar to the

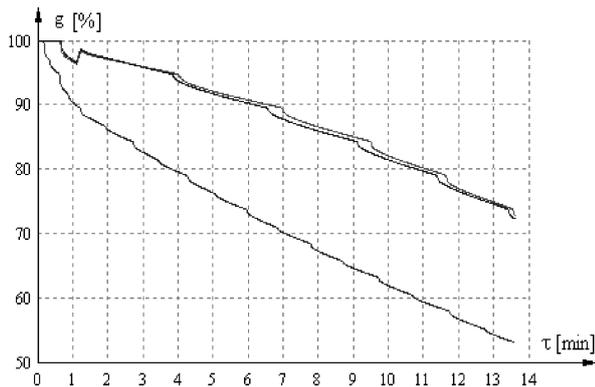


Figure 10. Solidified crust thickness variation depending on time.

Figura 10. Variación del espesor de la costra solidificada en el tiempo.

practical data (table 1) prove that the considered simplifying hypotheses are well justified;

- In every diagram one can notice a temperature leap or a solidification rate leap after about 1,07 min from the beginning of the casting, respectively immediately after the driving out from the tundish of the considered section, leap caused by

the impossibility of eliminating the heat flux from inside the semi-finished product;

- Modifying a series of parameters (number of discretized points, dissipated heat in the tundish and during the secondary cooling, data related to the steel grade) more correct values can be obtained, and they are applicable to other steel grades.

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