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MATHEMATICAL SOLIDIFICATION MODEL OF CONTINUOUS CASTING STEEL PRODUCT

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ABSTRACT

In this paper is presented simulation solidification model of steel continuous casting, using finite element model. For this is considered a section in mould-continuous casting system. This section is divided with discreet element structure.

Using these experiments is made graphical dependents of temperature in some different point from surface crust to center of semifinished product, and also solidification speed for S235 (OL37) steel.

KEYWORDS:
continuous casting, steel, solidification

1. INTRODUCTION

Finite differential method is based on modifying the heat transfer differential equation in finite differential equations. The heat transfer differential equation on the two axes (heat transfer on vertical direction is neglected) is expressed as fallows:

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

where: T – represent the temperature, [°C];
τ – represent the time, [s];
a – thermal diffusivity, [m^2/s];
x, y – coordinates.

In order to transform the relation (1) in a finite differential equation, the temperature of a point (i, j) is expressed function of the temperature of the neighborhood points. In this case we consider an interior point (fig. 1).

2. METHOD

In order to provide the stability of the solution by 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. The solution accuracy, that means a better concordance with analytical solution, it is also desired. This depends on the shape of finite differential equation and the number of nodes. The number of nodes is established starting with the necessity of finding a solution for the fallowing contradiction: 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 every node has the same temperature as the node is decreases with the decrease of node area); on the other hand a high number of nodes lead to an increasing of processing time due to the increasing of nodes number and due to decreasing of time intervals between iterations imposed by stability conditions of the solutions.

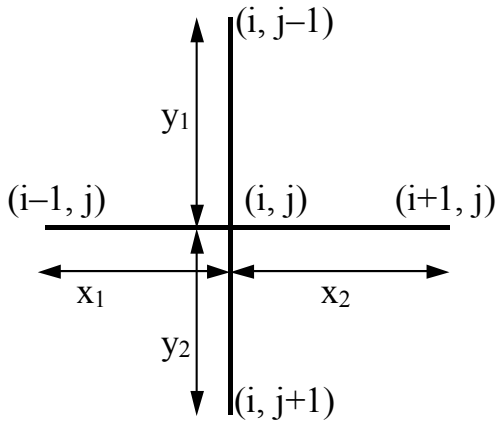

FIG.1. INTERIOR POINT OF SEMI-FINISHED PRODUCT

From stability analysis of the finite differential equation it results the fallowing criteria:

- on interior $$\Delta\tau \le \frac{1}{2a \cdot \left[\frac{1}{x_1 x_2} + \frac{1}{y_1 y_2}\right]} \quad (2)$$

- on boundary $$\Delta\tau \le \frac{1}{2a \cdot \left[\frac{1}{x_1 x_2} + \frac{1}{y^2} + \frac{W}{\lambda \cdot y}\right]} \quad (3)$$

- on corner $$\Delta\tau \le \frac{1}{2a \cdot \left[\frac{1}{x^2} + \frac{1}{y^2} + \frac{W}{\lambda \cdot x} + \frac{W}{\lambda \cdot y}\right]} \quad (4)$$

The chosen time interval represent the time in which the unsteady heat transfer process is approximate with a steady process. From this

reasons as well as the characteristics of the real process are far from that of a steady one, the iteration period should be smaller.

In order to realize a bi-dimensional mathematical modeling of a semi-finished product it is considered a section of half-finished product-crystallizer assembly, which is divided using a discretisation network (fig.2). The temperature of every node represents the mean temperature of node adjacent surface. In these nodes are written the finite differential equations presented above.

The model is realized based on the fallowing simplifying assumptions:

- the heat transfer on longitudinal axis is neglected, considering that heat transfer take place just in horizontal section of the half-finished product
- the density variation is neglected
- the crystallizer section is consider to be a equivalent rectangular section
- it is consider that the crystallizer loose heat uniformly on each surface
- it is consider that at zero moment the temperature of steel mass is uniform. For the surface nodes it is correct to assume that at the casting moment it took place the formation of a thin solidified steel layer, and the loosed heat by this layer is transmitted instantaneously to the nodes from the interior surface of the crystallizer.
- the evolving of fusion latent heat it is produced in liquidus-solidus interval, direct proportional with the temperature

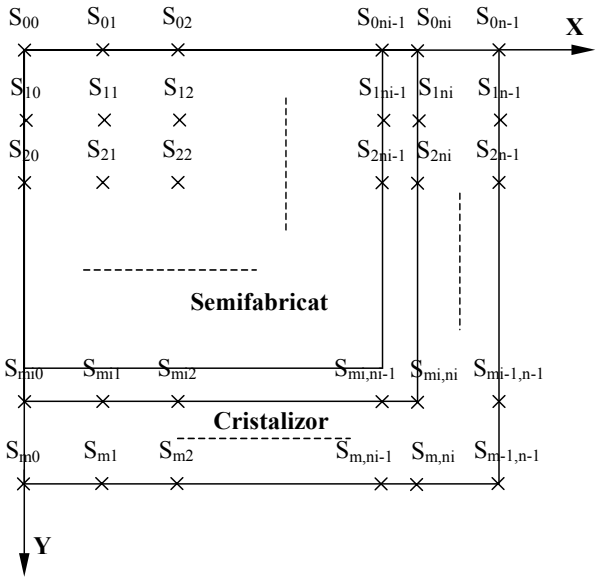

FIG.2. THE NETWORK SCHEME USED IN FINITE DIFFERENTIAL METHOD

As results of the considered hypothesis, the half-finished product-crystallizer assembly is symmetric with respect to longitudinal axis of the half-finished product. The origin of the system of coordinates will be in the center of the half-finished product and the calculus will be made just for positive x and y.

For implementation of an algorithm of the above described model we need the fallowing initial data: ambient temperature, casting temperature, initial temperature of the crystallizer, number of nodes from half-finished

product and from crystallizer with respect to both axes, values of thermal conductibility for steel and cupper function of temperature, values of enthalpy for steel and copper function of temperature. In case of steel this functional dependence need to include fusion latent heat; tapping condition of half-finished product from equipment; 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 half-finished product, maximum variation of enthalpy at an iteration.

The simulation is realized for a half-finished product (bloom), having the cross-section 240x270 mm, made of steel OL37-2k.

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

For simplifying of the calculus there are used discrediting networks having the nodes uniformly distributed along X and Y axes. There are obtained the fallowing specific cases:

1. Coordinates system origin (i=j=0):

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

2. Y axes (i=0):

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

3. X axes (j=0):

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

4. Interior:

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

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

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

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

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

7. Corner:

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

The computing program was realized in C++ and it runs under Win32 systems (that means Windows 95, 98, Me, NT4, 2000, XP – with Intel processor). For graphical interface the program uses MFC (Microsoft Foundation Classes), a classes library that include the functionality of Windows standard programming interface (API – Application Program Interface). The 3D graphs are realized with the Windows implementation of OpenGL specification (Open Graphics Library).

For configuration of specific dates for every steel grade, using the principal interface (fig.3.) the program opens the dialog box presented in fig.4.

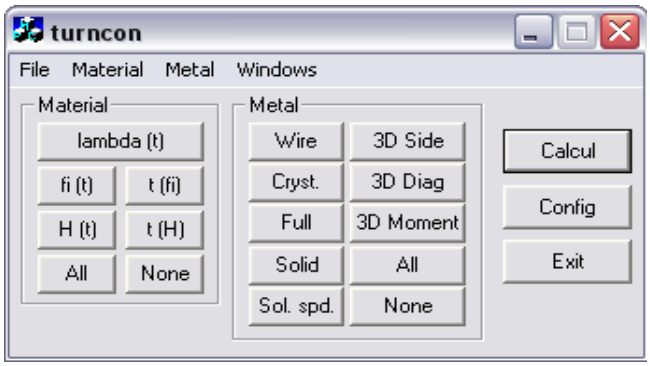

FIG.3 PROGRAM PRINCIPAL INTERFACE

FIG.4. DIALOG BOX FOR ESTABLISHING THE STARTING DATA OF THE PROGRAM

When the program is running it is opened a dialog box for calculus progress, as is presented in fig.5.

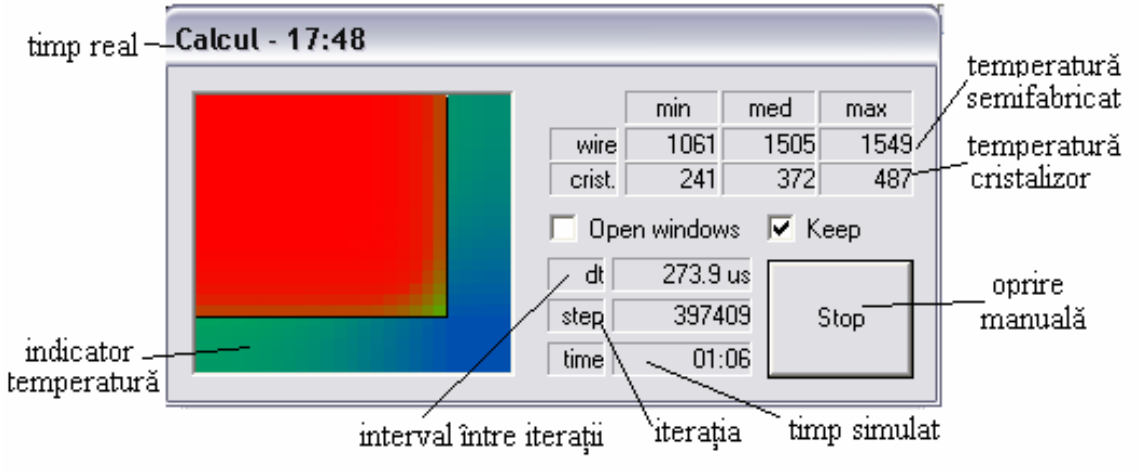

FIG.5. DIALOG BOX FOR CALCULUS PROGRESS

The temperatures are indicated by the mean 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.

A first obtained dependence is represented by temperature variation of the half-finished product function of time (fig.6.). The distribution of the discredited points is also presented.

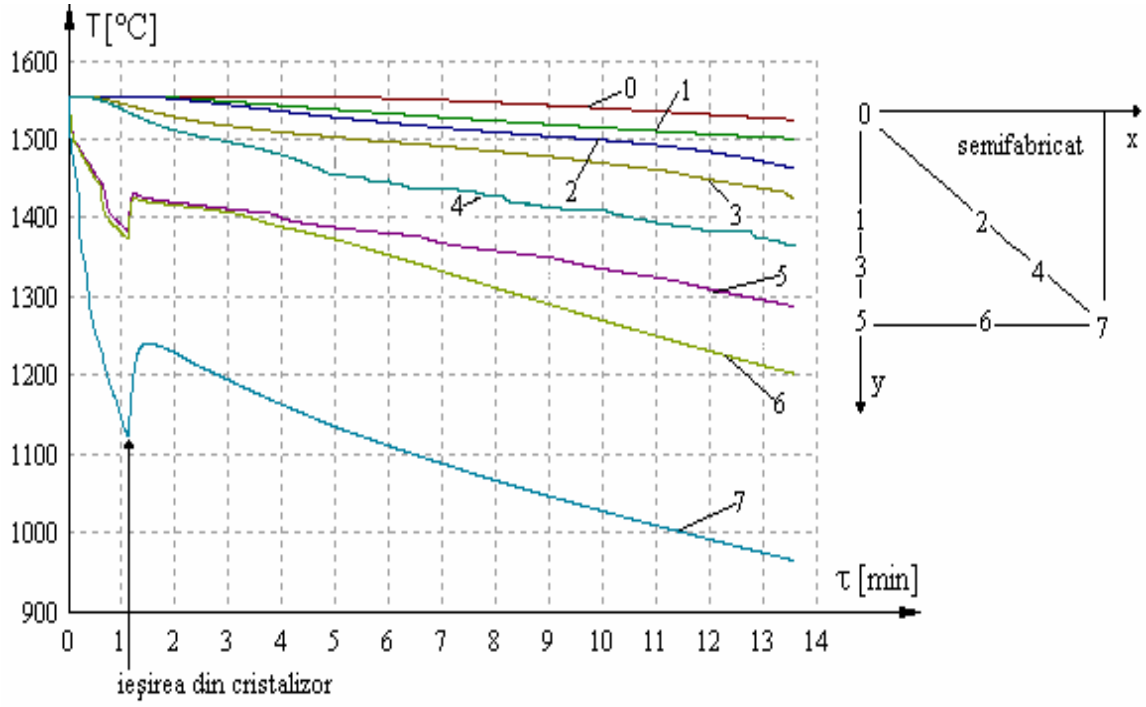

FIG.6. TEMPERATURE VARIATION FUNCTION OF TIME

It is observed a slowly decreasing of the temperature of points placed near the center of the half-finished product, but also the variation mode of the temperature from layers closer to wire surface.

At a time moment (in the presented case equal with 1,07 min), when it took place the driving out of considered surface from crystallizer, it took place an increasing of temperature in the superior layers of the half-finished product (with approximately 100°C in the corner and with 35-50°C in points 5 and 6 of the surface).

This increasing of the temperature is due to the lack of cooling of the wire immediately after the driving out from crystallizer to the firs ring of secondary cooling. After this moment the cooling and the solidification of the wire took place normally, the recorded temperatures corresponding to the measured ones (for the surface – TAB.1)

TAB.1 COMPARISON OF MEASURED VALUES WITH THOSE OBTAINED FROM SIMULATION

Measured Points	Variation interval of the measured temperature	Temperatures obtained from simulation in the points placed on the surface of the half-finished product		
		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

It needs to be specified that the simulation was realized just for primary and secondary cooling, not for the entire running of the wire in the equipment. This explains steel's high temperature values in the interior of the half-finished product (middle layers), but they are decreasing under the solidus temperature value until the cutting of the half-finished product.

As regards the temperatures distribution in the crystallizer (which take over the heat transferred by the half-finished product and transfer it to the cooling water), it is presented in fig.7. In this case to it is presented also the position of the discredited points.

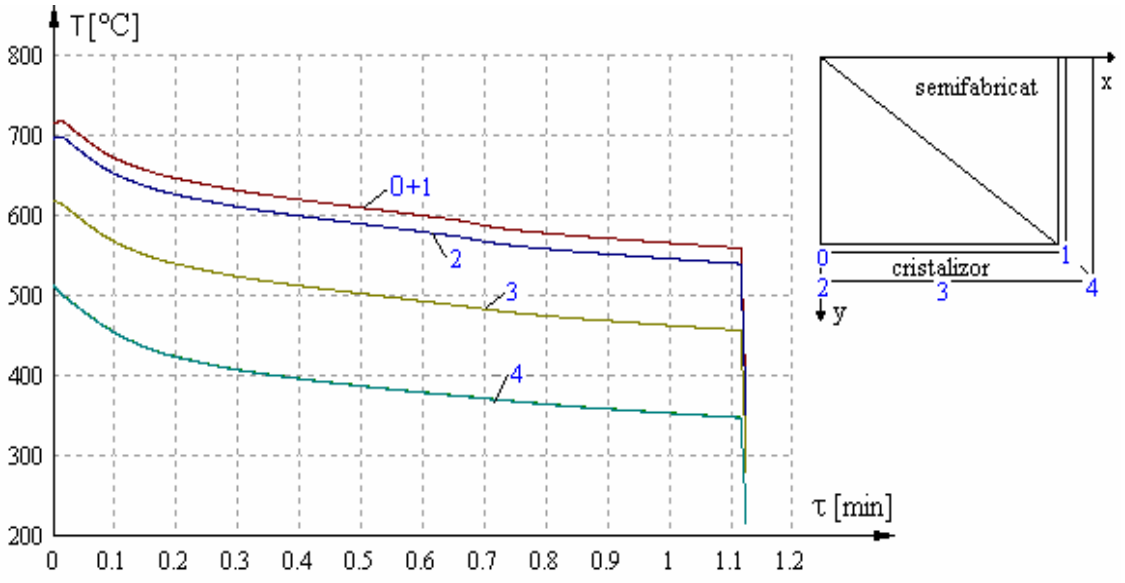

FIG.7. TEMPERATURE VARIATION IN THE CRYSTALLIZER, FUNCTION OF TIME

Another type of temperature distribution, when the half-finished product is droved out from secondary cooling zone, it is presented in fig.8.

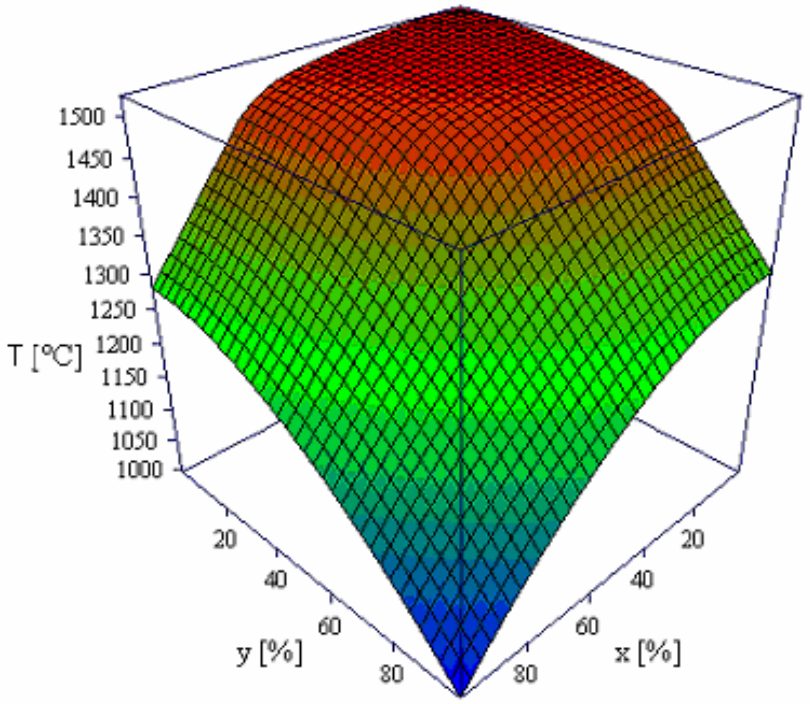

FIG.8. TEMPERATURES DISTRIBUTION IN THE BLOOM HAVING THE CROSS-SECTION 240X270 mm AT 13,33 min FROM THE BEGINNING OF CASTING

The obtained regressing surface it correspond to a quarter of half-finished product section, being similar for the remained parts of the section. From temperature values point of view, the corner of the half-finished product is that one which is cooled more powerful, and the center is cooled slowly.

Based also on the TURNCON calculus program it was obtained variation type for the solidification speed, function of time. It refers to a solidification speed calculated between two consecutive iterations, fact that partially explain the oscillating aspect of the curves presented in fig.9.

On the other hand, the oscillating guidance could be explained due to the oscillating motion of the crystalizer. It could observed a negative value, at 1,07 min from the beginning of the casting, when, due to a big heat quantity which could not be taken aver by the secondary cooling water, a part of the crust interior layer is remelted, after which it comes back to positive values for this parameter.

With the help of solidification speed and the others parameters used by the program , the mean interface allowed the obtaining of solidified steel crust variation function of time for the points located in the superior layers. In fact we can say that the obtained variations (the curves presented in fig.10) represent the shape of solidification front for the considered points.

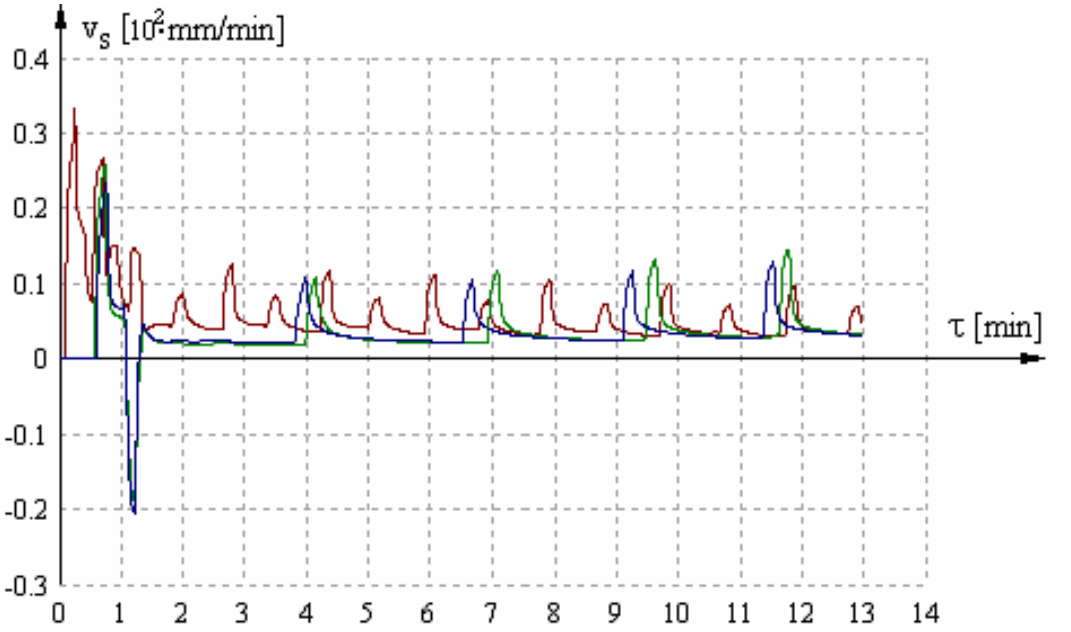

FIG.9. SOLIDIFICATION SPEED VARIATION FUNCTION OF TIME

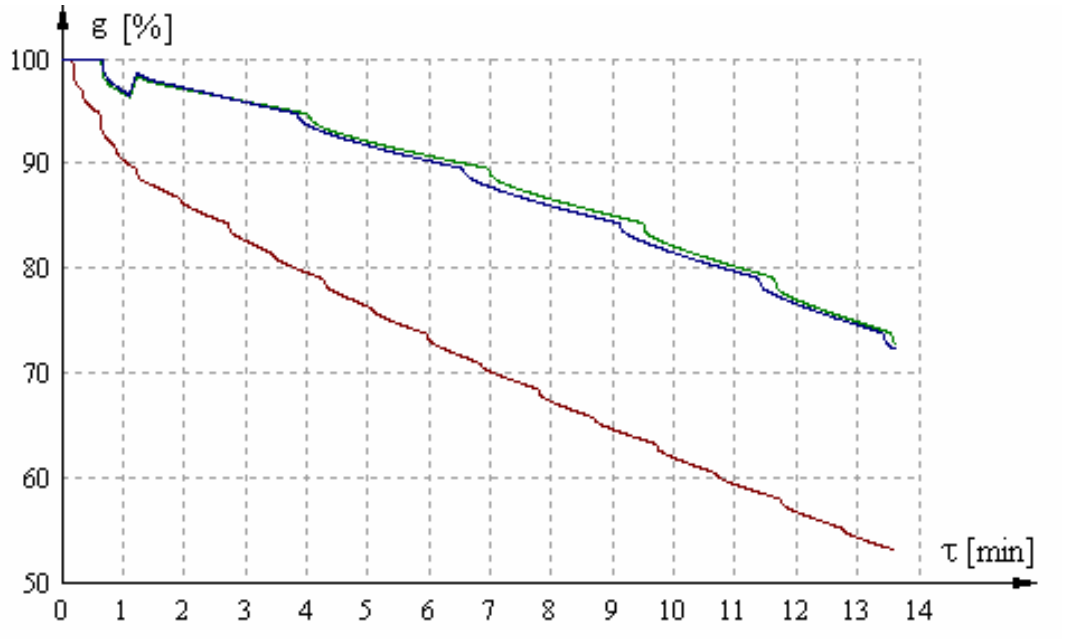

FIG.10 SOLIDIFIED CRUST THICKNESS VARIATION FUNCTION OF TIME

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

3. CONCLUSIONS

Analyzing the graphical dependences from the performed researches, based on literature review data and from own experimental work it results the fallowing conclusions:

- The results obtained by simulation with presented program being similar with practical data (tab.1) proof that the considered simplifying hypothesis are well justified;
- In every diagram there are observed a temperature leap or a solidification speed leap after approximately 1,07 min from the beginning of the casting, respectively immediately after the driving out from the crystallizer of the considered section, leap caused by the impossibility of elimination of a heat flux from the half-finished product interior;
- Modifying a series of parameters (number of discretised points, dissipated heat in crystallizer and in secondary cooling, data of steel grade) it could be obtained more correct values, applicable to other steel grades.

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