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# Analytical Identification, Simulation and Analysis of Steel Solidification Process in Crystallizer

*To do an analysis of the phenomena that lead to cracks in continuous casting process is necessary to study the heat exchange and steel solidification. Thus, this paper proposes a modeling of semi-finished product solidification during continuous cast, based on finite difference method. To validate the model, we have developed a simulation program, which had obtained important results by running comparable with the experimental results. The proposed method of modeling and simulation allows a sufficiently accurate analysis of the phenomenon of crust formation and hence the formation of solidification cracks. Although we can use it only off-line, it derives essential information necessary for designing neural system for detection of cracks and the drawing up fuzzy decision system bases rules to determine the weight correction for the cooling water flow rate and primary casting.*

***Keywords***: *analytical identification, simulation, solidification, finite difference method, crystallizer*

## 1. Introduction

In order to perform an analysis of the phenomena that lead to cracks in continuous casting process is necessary to study the heat exchange and solidification of steel in crystallizer [9]. Common methods involving a linear temperature distribution in the solid crust, leading to significant errors. Also, the temperature field in the solid crust depends on the speed of casting, and construction crystallizing apparatus semi-finished profile.

Solving the differential equation of thermal conductivity [5], [6], in real situations when the semi-finished surface temperature varies over time, is possible only with coarse approximations which distort the results. Therefore, this paper provides a modeling of the phenomenon of solidification and cooling of continuously cast semi-finished s, based on the finite difference method.

Thus, the simulation program was developed to gets some results comparable to the experiments.

The proposed method of modeling and simulation allows an accurate analysis of the phenomenon of crust formation and hence the formation of solidification cracks. Although it can be used only off-line, we have got any essential information we needed for designing neural system for cracks detection [10] and provide the set of rules of fuzzy decision system to determine the share correction primary cooling water flow and casting speed [11].

## 2. Identifying analytical solidification process continuously semi-finished cast products

Mathematical modeling of the phenomenon of solidification and cooling of the semi-finished continuous casting is based on mathematical representations of this phenomenon [4]. The solution to this problem is the settlement under no stationary equation of heat transmission [3].

To define the heat transfer between the semi and crystallizer is necessary to know the initial conditions, the law of variation of semi-crystallizer heat flux, heat flux, water cooling crystallizer. Some conditions can easily schematizing, but others lead to systems of equations whose solution by analytical raises special problems [2], [8].

### Modeling by finite difference method

The procedure is to turn the heat transmission differential equation with finite difference equations.

Differential equation of heat transmission by the three axes has the form [1], [7]:

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

where:

- t - is temperature ([° C] ;
- $\tau$ - time [s];
- a - is thermal diffusivity [$m^2$/s],
- x, y, z - space coordinates;

If we neglect heat transfer on z-axis the $\frac{\partial}{\partial z} \equiv 0$ relationship becomes [7]:

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

where:

$$a = \frac{\lambda}{\rho \cdot c} \tag{3}$$

- density - $\rho$ - is approximately constant, and thermal conductivity - $\lambda$ - and c mass specific heat, according to temperature.

Choose an arbitrary reference temperature $t_0$ at which the thermal conductivity is $\lambda_0$ and we introduce the notion of reduced temperature:

$$\Phi = \int_{t_0}^{t} \frac{\lambda}{\lambda_0} dt \tag{4}$$

where:

$$\frac{d\Phi}{dt} = \frac{\lambda}{\lambda_0} \tag{5}$$

We calculate:

$$\frac{\partial^2 \Phi}{\partial x^2} = \frac{\partial}{\partial x}\left(\frac{\partial \Phi}{\partial x}\right) = \frac{\partial}{\partial x}\left(\frac{d\Phi}{dt}\frac{\partial t}{\partial x}\right) = \frac{\partial}{\partial x}\left(\frac{\lambda}{\lambda_0}\frac{\partial t}{\partial x}\right) = \frac{\lambda}{\lambda_0}\frac{\partial^2 t}{\partial x^2} \tag{6}$$

where, we consider that "$\lambda$" is calculated referring to temperature; the partial derivative with respect to "x" is zero.

Thus,

$$\frac{\partial^2 t}{\partial x^2} = \frac{\lambda_0}{\lambda}\frac{\partial^2 \Phi}{\partial x^2} \tag{7}$$

doing the same on the "y"-axis:

$$\frac{\partial^2 t}{\partial y^2} = \frac{\lambda_0}{\lambda}\frac{\partial^2 \Phi}{\partial y^2} \tag{8}$$

Introducing (8) and (3) in (2), we get:

$$\frac{\partial t}{\partial \tau} = \frac{\lambda}{\rho \cdot c}\frac{\lambda_0}{\lambda}\left(\frac{\partial^2 \Phi}{\partial x^2} + \frac{\partial^2 \Phi}{\partial y^2}\right) = \frac{\lambda_0}{\rho \cdot c}\left(\frac{\partial^2 \Phi}{\partial x^2} + \frac{\partial^2 \Phi}{\partial y^2}\right) \tag{9}$$

Specific heat is defined by the definition: $c = \frac{\partial H}{\partial t}$ (10)

where

$$c\frac{\partial t}{\partial \tau} = \frac{\partial H}{\partial t}\frac{\partial t}{\partial \tau} = \frac{\partial H}{\partial \tau} \tag{11}$$

From (9) and (10) it results:

$$\frac{\partial H}{\partial \tau} = \frac{\lambda_0}{\rho}\left(\frac{\partial^2 \Phi}{\partial x^2} + \frac{\partial^2 \Phi}{\partial y^2}\right) \tag{12}$$

where $\lambda_0$ and $\rho$ are constants.

Equation (11) turns into a finite difference equation (12), expressing the temperature of a point (i, j) according to the temperature of related points.

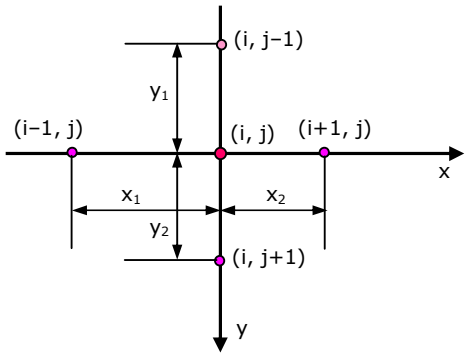



**Figure 1.** Blank node inside

The finite difference equation we obtain makes possible the determination of enthalpy, according to a time lapse of $\tau_{k+1}-\tau_k$.

For a surface parallel to the X axis we obtain:

$$\frac{H_{i,j,k+1} - H_{i,j,k}}{\tau_{k+1} - \tau_k} = \frac{2\lambda_0}{\rho \cdot x_1 x_2 (x_1 + x_2)} \cdot \left[x_2 \Phi_{i-1,j,k} + x_1 \Phi_{i+1,j,k} - (x_1 + x_2)\Phi_{i,j,k}\right] + \frac{2\lambda_0}{\rho \cdot y^2} \cdot \left[\Phi_{i,j-1,k} - \frac{y}{\lambda_0} W - \Phi_{i,j,k}\right] \tag{13}$$

To clear a corner point we get the relationship:

$$\frac{H_{i,j,k+1}-H_{i,j,k}}{\tau_{k+1}-\tau_k}=\frac{2\lambda_0}{\rho x^2}\cdot\left[\Phi_{i-1,j,k}-\frac{x}{\lambda_0}W-\Phi_{i,j,k}\right]+$$
$$\frac{2\lambda_0}{\rho\cdot y^2}\cdot\left[\Phi_{i,j-1,k}-\frac{y}{\lambda_0}W-\Phi_{i,j,k}\right] \quad (14)$$

### 3. Simulation of solidification process, implementation and operation of the "TirSim" software

For all further simulations we have performed we had used **OLT 35K** steel brand characteristics, namely:

- specific mass (density): $\rho$ =7850 kg/m3;
- solid's temperature $T_{sol}$ = 1480 ° C;
- liquid temperature $T_{liq}$ = 1520 ° C;
- latent heat of melting $q_t$ = 64 kcal/kg = 267.87 kJ/kg;
- specific heat of liquid phase $c_l$ = 1.118 kJ/kg° C;
- functional dependencies $\lambda$ (T) and $\Phi$ T) and H(T) described above.

Environmental data used are:

- environment temperature - 20° C;
- casting temperature - 1600 ° C;
- convection constant - K = 15.

Simulations are made with the following data:

- number of mesh nodes for the semi- finished 25x25;
- number of mesh nodes for crystallizer 6x6;
- maximum enthalpy change in an iteration 100J/kg.

The simulation was carried out for section **240x240**mm semi-finished.

The data are established and used by the program through a window of data reception. The number of mesh nodes is large (for both semi-crystallizer and semi-finished), and maximum enthalpy change in a smaller iteration, the real time simulation is higher and it gets higher model accuracy. In case of the above data, the actual time was 22:53 m simulation for a simulated time of 54 s.

The stopping of the simulation, the program has an option to show time variation of simulated parameters (Figure 2).

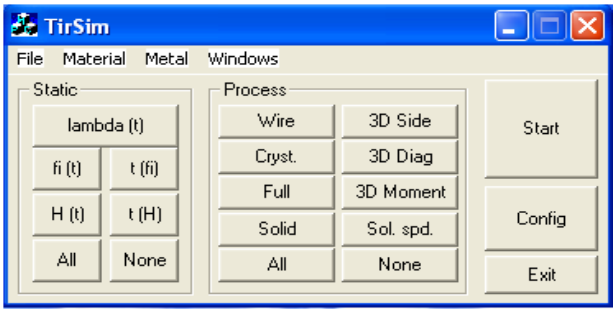
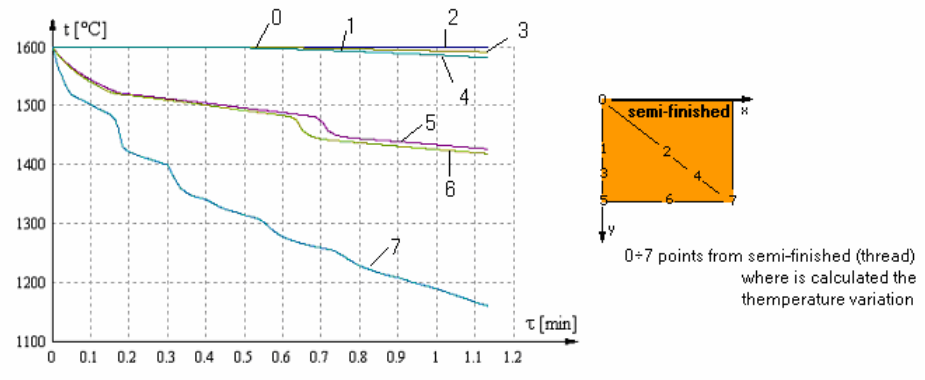



**Figure 2.** Main software interface **"TirSim"**

The first dependence is the temperature change we have obtained in the semi-finished, according to time (Figure 3., points in the chart position in wireless temperature variation is also presented.




a) b)

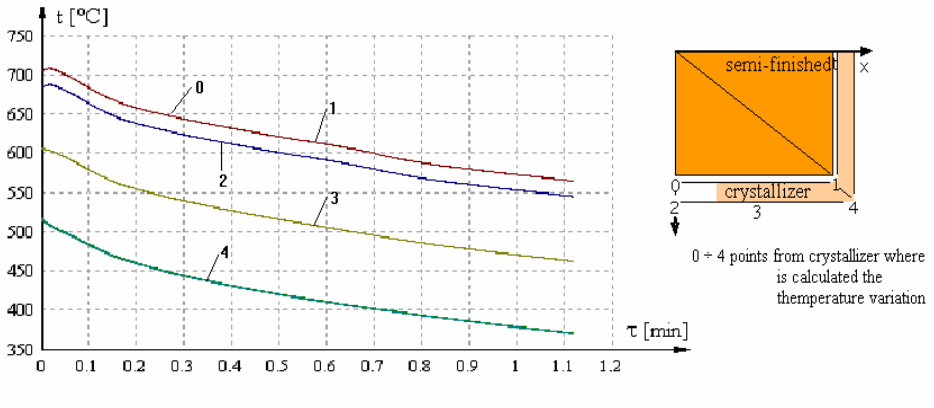
**Figure 3** a) Variation of temperature in thread, depending on time
b) Position of the points of thread temperature variation chart

Slow decrease in temperature is noted for points in the middle of the semi-finished and of the temperature change of the layers near the surface of the yarn.

We must specify that simulation is performed only for primary cooling. This explains further temperature values inside the steel semi-finished.

Regarding the temperature distribution in the crystallizer (which takes heat from the semi-finished and transfers it to cooling water), it is shown in Figure 4. We have discussed about this case in the chart position of points in wire temperature variation.

At the beginning of casting crystallizer temperatures (points) were high: at 7 seconds it ranged from 450-680°C; they decreased gradually, as submitted to the crystallizer surface (370-570°C).




a) b)

**Figure 4.** a) Variation of the crystallizer temperature, according to time
b) Point position in the of the temperature variation crystallizer chart

Another type of semi-finished temperature distribution in the exit section when considered in the primary cooling area is shown in Figure 5.

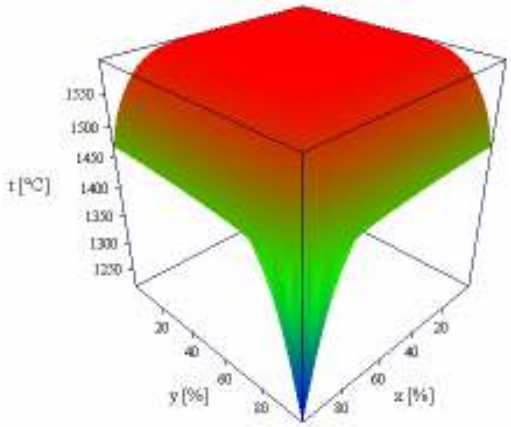



**Figure 5.** Distribution of temperatures in section **240x240** mm semi-finished products at the exit from crystallizer

Regression surface is obtained corresponding to a quarter of the semi-finished section, being similar to other parts of the section. In terms of temperature values, semi-finished corner cools the most intensely, and the center is the slowest.

The main program interface also allows obtaining temperature distribution after a certain axis, versus time (Figure 6).

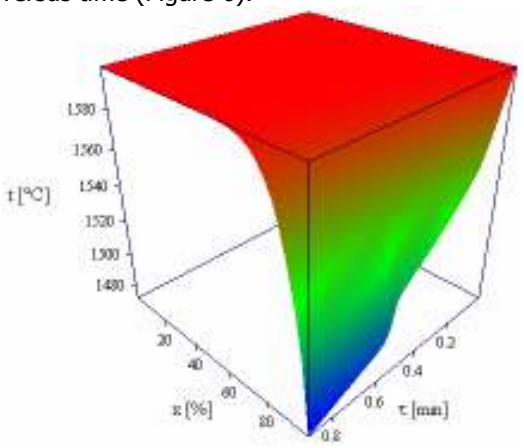



**Figure 6.** Temperature distribution of semi-finished (section **240x240** mm) along "x"-axis for "y" = 0, according to time

It also allows the temperature distribution was obtained by diagonal time (Figure 7).

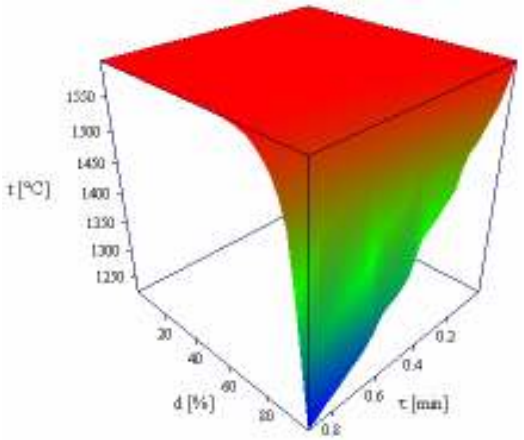



**Figure 7**. Temperature distribution of semi-finished 240x240 mm section along "x"-axis, for "y"=0, according to time

At first glance the two variations (along the axis "x", those along the diagonal) have similar allure; in case of temperature distribution (considering the "x"-axis), temperature outside the crystallizer is not as big as temperature distribution alongside the diagonal, where the corner (i.e. steel in that area) is what takes the most amount of heat and thus, is the most heated.

Also with the help of **"TirSim"** we have obtained the variation in time of the solidification rate - calculated between two consecutive iterations - which explains in part the appearance of curves presented in Figure 8. On the other hand, the oscillating regime, can be explained due to the oscillation motion of the crystallizing apparatus.

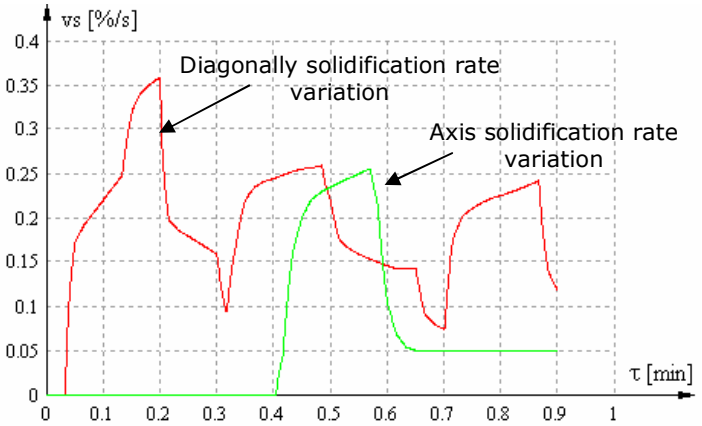



**Figure 8.** Variation in time of solidification rate

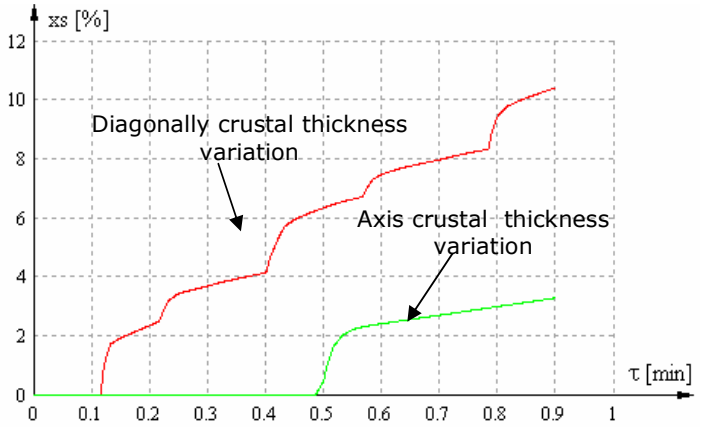



**Figure 9.** Variation of solidified crustal thickness

The most important parameter (solidification rate), as well as other parameters used by the program's main interface, has helped achieved steel crust variation (time solidification) for upper layers points. In fact one can say that the variation obtained (curves presented in Figure 9) represent the front solidification for all considered points. The variation type is expressed in percentage and it is represented from the edge (outside) to the center of the semi-finished (the section considered).

## 4. Conclusion

Analyzing the simulation results with and data from literature we have reached to the following conclusions:

- Solidification time and cooling conditions affect the thickness of the crust;
- If to determine the thickness of the crust we have adopted too many simplifying assumptions, we obtained an approximate form of the cone shape of solidification and significant deviations from the actual time of solidification;
- The tests carried out showed that the continuous casting plant with a semi-finished section of **240x240 mm**, had reached the cone length solidification of 20 m and the total solidification time of 31 minutes (at an average casting speed of 1,1 m/min).

The results we have obtained from simulations performed using the **"TirSim"** for a semi-finished section of **240x240** mm, simulations performed on MM have led to the following conclusions:

- The results of the simulation program **"TirSim"** are according to practical data;
- By simulation, situations that lead to cracks, so that technology should be avoided. However, these data were useful for understanding the process of solidification and crust formation more precisely.
- Data obtained by simulation will be used later on to design and train neural network, FDS rule base design and weighting correction of casting speed, as well as the primary cooling water flow.

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