Simulation of solidification process for billet with $\phi 350$mm section, continuous casted

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Abstract. The quality of continuous casting product depends both on the quality of the steel, and on technological parameters adopted during the casting and how solidification of billets is conducted. A simulation of the solidifying process is very useful in the industrial casting practice, providing specialists with information about the phenomena during the process and the manner in which certain parameters may vary in order to obtain the desired effects. This paper presents a two-dimensional simulation model that can be used in the continuous casting process, when micro-coolers are used in order to control thermal regime during solidification.

1. Introduction

Mathematical modeling and solidification simulation of continuously cast semi-finished products is presented in the literature [1-16], each model having specific particularities; can be studied general models or models designed specifically for certain types and size [1], [13].

Mathematical modeling of cooling and solidification process of continuous cast round blanks, shown below, is based on the mathematical description of this phenomenon. The solution to this problem is actually the solution of non-steady state heat transfer.

The method is based on the differential equation of heat transfer in finite difference equations. The differential equation of heat transfer by three axes has the form:

$$\frac{\partial t}{\partial \tau} = a \cdot \nabla^2 t$$

where: $t$ – temperature, ($^\circ$C) (or (K));
- $\tau$ - time, (s);
- $a$ - thermal diffusivity, (m$^2$/s).

Scalar Laplacian in cylindrical coordinates is:

$$\nabla^2 t = \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial t}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 t}{\partial \varphi^2} + \frac{\partial^2 t}{\partial z^2}$$

or:

$$\frac{\partial^2 t}{\partial r^2} + \frac{1}{r} \frac{\partial t}{\partial r} + \frac{1}{r^2} \frac{\partial^2 t}{\partial \varphi^2} + \frac{\partial^2 t}{\partial z^2}$$
Neglecting the heat transfer in the longitudinal direction is obtained:

$$\frac{\partial t}{\partial \tau} = a \cdot \left( \frac{\partial^2 t}{\partial r^2} + \frac{1}{r} \frac{\partial t}{\partial r} + \frac{1}{r^2} \frac{\partial^2 t}{\partial \phi^2} \right)$$  \hspace{1cm} (4)

Taking into account the temperature dependence of thermal conductivity $\lambda$, can be insert a lower temperature that include this variation:

$$\Phi = \int_{t_0}^{t} \frac{\lambda}{\lambda_0} dt$$  \hspace{1cm} (5)

where $\lambda$ and $\lambda_0$ are thermal conductivity at arbitrary $t$ respectively $t_0$ temperature. It follows:

$$\frac{\partial \Phi}{\partial \tau} = a(\Phi) \cdot \left( \frac{\partial^2 \Phi}{\partial r^2} + \frac{1}{r} \frac{\partial \Phi}{\partial r} + \frac{1}{r^2} \frac{\partial^2 \Phi}{\partial \phi^2} \right)$$  \hspace{1cm} (6)

$$\frac{\partial \Phi}{\partial t} \cdot \frac{\partial t}{\partial \tau} \cdot \frac{\rho \cdot c}{\lambda} = \frac{\partial^2 \Phi}{\partial r^2} + \frac{1}{r} \frac{\partial \Phi}{\partial r} + \frac{1}{r^2} \frac{\partial^2 \Phi}{\partial \phi^2}$$  \hspace{1cm} (7)

$$\frac{\lambda}{\lambda_0} \cdot \frac{\partial t}{\partial \tau} \cdot \frac{\partial H}{\partial \tau} \cdot \frac{\rho}{\lambda} = \frac{\partial^2 \Phi}{\partial r^2} + \frac{1}{r} \frac{\partial \Phi}{\partial r} + \frac{1}{r^2} \frac{\partial^2 \Phi}{\partial \phi^2}$$  \hspace{1cm} (8)

$$\frac{\partial H}{\partial \tau} = \frac{\lambda_0}{\rho} \cdot \left( \frac{\partial^2 \Phi}{\partial r^2} + \frac{1}{r} \frac{\partial \Phi}{\partial r} + \frac{1}{r^2} \frac{\partial^2 \Phi}{\partial \phi^2} \right)$$  \hspace{1cm} (9)

2. The two-dimensional solidification and cooling of the semi-finished product

To achieve two dimensional mathematical modelling of solidification for a 350mm diameter round billet continuous casted is considered a section of crystallizer - billet which is divided by a mesh network. The simulation it also allows introducing a varying percentage of micro-coolers, for a more rigorous temperature control and achieving an adequate casting structure.

The mathematical model is based on the following simplifying assumptions:
- crystallizer section shall be considered equivalent to a circular section;
- it is considered that heat loss is uniform on all surfaces crystallizer;
- crystallizer thermal conductivity of the material is considered constant;
- is neglected heat transmission to the longitudinal axis, considering that it occurs only in the horizontal section of the wire;
- density variation is neglected;
- is considered zero moment when the liquid steel temperature is uniform and micro-coolers temperature is equal to ambient temperature;
- the thermal conductivity of the slag layer on the surface of the wire is considered to be constant;
- the release of melting latent heat occurs between liquidus - solidus temperature directly proportional.

In order to achieve solidification simulation of continuously semi-finished casted parts, it compiled a computer program in C ++, using the characteristics of a steel grade for steel pipes (S 235, according to EN 10297).

To achieve the simulation, first opens the program's main interface, shown in Figure 1. The simulation was performed for 350mm diameter round semi continuous casting. The program allows cooling without micro-coolers blank, uniform distribution of micro-coolers a random distribution respectively a repeatable random distribution; in this simulation is used repeated random distribution of micro-coolers - Figure 2. Micro-coolers repeatable random addition into the crystallizer was done in three variants: the addition of 1%, 2% and 3% micro-coolers and with different thicknesses of their
diameter. The simulation is performed only for the primary and secondary cooling, not for the whole path of the wire in the continuous casting installation. This explains the high values of the steel temperature inside the wire, which decrease below the solidus temperature until debiting semi-finished product.

![Program main interface](image1.png)

**Figure 1.** The program main interface

![Data's configuration](image2.png)

**Figure 2.** Data's configuration

For a better illustration of how operate the program, we have been made a screen captions at different time points (beginning, middle and end of simulation), which can give information concerning the temperature of the wire and the crystallizer, according to Figure 3 or Figure 4.

From Figure 5 it is noted that about at 4 minutes after the liquid steel contact with the crystallizer, the variation speed of radius relative is stabilized, the solidification process respectively the heat disposal resulting normal.
Still referring to the speed of change in time of the solidification front radius, for the few cases studied, we found the following:

- at 3% micro-coolers addition into crystallizer, in the first 100 seconds of casting, result a strong increase in its, an maximum (0.24%/s) is reached after 50 seconds, followed by an intense decrease up to 100 seconds; after about 300 seconds variation is maintained in the constant range (0.075 to 0.035)%/s;
• at 1% micro-coolers added, the rate of change of the solidification front radius is behaving similarly, with the observation that after 120 seconds the variation limits remain constant, the maximum being 0.25%/s, reached after 50 seconds;
• if don’t add micro-coolers, the maximum speed variation of the solidification front radius is 0.20%/s, reached after 50 seconds and its limits remain constant after about 100 seconds.

The situation is similar in the version without the addition of micro-coolers, with increased power dissipated in the secondary cooling, with the observation that the value of lower limit respectively superior limit are significantly higher.

![Figure 5. The variation speed of the radius relative of the solidification front (without micro-coolers addition and with 3% micro-coolers addition)](image)

In Figure 6 it is noted that until about 200 seconds is a sharp drop of the relative radius of the solidification front, normal situation given the direct contact between crust and crystallizer interior face, heat transfer occurs mostly through conduction. After detachment the crust, the heat transfer occurs by radiation and there is a linear decrease relative to the radius of the solidification front.

![Figure 6. The relative radius of the solidification front (100% represents the wire surface)](image)

From Figure 7 and Figure 8 it is found that in the first 70-80 seconds there is a sharp drop of temperature, during which the crust is formed, so the intense heat disposal is justified. After crustal formation, as a result of the contraction, it detaches from the crystallizer; as a result there is a brief increase of temperature (for about 40-50 seconds) followed by a linear decrease.
Figure 7. The temperature variation function of time for the polar coordinate $\varphi = 0$, at points 0\%, 50\%, 75\%, 90\% and 100\% of the strand radius, as well as the mid-thickness and its surface crystallizer-coldest (without micro-coolers addition and with 3\% micro-coolers addition)

Figure 8. The temperature variation function of time for the polar coordinate $j = 0$, at points 0\%, 10\%, 25\%, 50\% and 100\% of the strand radius (without micro-coolers addition and with 3\% micro-coolers addition)

3. Conclusions
By analyzing the obtained simulation results have some conclusions:
- modelling and simulation of temperature variation process on steel in the crystallizer allow highlighting the effect of the addition of micro-coolers on the temperature of solidifying steel;
- from the interpretation of simulation results for crystallizer thermal process intended to manufacturing steel pipes it is found that there is an appropriate heat transfer (which provide a crust thickness adequate to avoid the surface defects) for an extra 3\% micro-coolers with a 2-3mm diameter;
- the simulation software can be used for any steel grades of semi-finished steel round with various sections on condition that the parameters is reconfiguration depending by steel grade and billet size;
- the simulation can contribute to the development of suitable casting technologies by which the specific energy consumption and metal are reduced on the one hand, and on the other hand whenever appear certain discrepancies between technological parameters and quality of the molded product, is possible to study through simulation, to clarify these causes.
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