ESTIMATION OF STEEL SOLIDIFIED LAYER THICKNESS, FOR CONTINUOUS CASTING CONTROL PURPOSES

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Abstract: An important goal in continuous casting automation process rest in establishing a proper casting speed being able to assure a compromise between machine productivity and solidified skin cracking protection on the mould level. Contextually, this paper presents new solutions regarding solidified layer thickness estimation for steel continuous casting. The new model starts from actual stadium analysis and propose a solution for analytical model modification, in such a way that the model to approximate solidification dynamics at different casting speeds, using both important parameters for continuous casting process, meaning casting speed and time. A series of results obtained using numeric simulation are presented as a validation for proposed solution.

Keywords: continuous casting, layer solidified thickness, mathematical modeling, automatic control.

1. INTRODUCTION

Continuous casting process is one of the most important processes in the steel production industry and consists in transformation of steel aggregation status from molten to solid. A fully and comprehensive description of these processes can be found in (Oprea, F., *et al*, 1994).

Automation control for continuous casting machine is a very complex problem and involve development of adequate mathematical models (Thomas, B.G., 2001), (De Keyser, R., 1977), X. (Huang, X., *et al.* 1992), (Simon F, *et al,*1997).

An important goal in continuous casting automation process is represented by steel layer solidification thickness obtained at the exit from mould. This solid steel layer thickness must have enough width to support the mechanical efforts which are applied to the strand in the following production steps. To achieve this is necessary to establish an estimation solution using models for solid steel thickness at the mould exit, as base for process automation, known that there is no method for direct measurement of this thickness. Research in this field was published by (Thomas,B.G., 2001). In essence, there are monitored cases when solidified thickness layer at the exit from the mould is thin and possibility of cracking is real. These situations occurred mainly in dynamic regime caused by set point changing (casting speed modification) but also due to bad operation with the whole machine.

To solve this problem a series of solutions were generated, materialized in two types of models:

– analytical model, resulted from applying of idealized boundary conditions and
– Hills model, in which are considered second order boundary conditions, but this model is realistic only in permanent regime.

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Both methods presents important inconvenient due to approximation involved. A series of proposal for reducing these errors induced by these approximations are presented in (Barbu, B., *et al* 2002); Barbu, B. , *et al*, 2003). Present paper proposes a new method for steel solidified layer thickness estimation, which allows approximation for solidification dynamics on different casting speeds.

Paper is organized in the following manner: in next two sections are presented analytical model and Hills model including modifications proposed in (Barbu, B., *et al*, 2002; Barbu, B., *et al,* 2003). Section 4 contains corrected model proposed in this paper and in section 5 are presented results obtained by numerical simulation, which shown the properties of proposed model. One conclusions section ends the paper.

2. ANALYTICAL MODEL

For solidification process on the mould level is considered a molten with uniform initial temperature, considered known, T_{li}. In initial moment, t=0, temperature at coordinate x=0 is reduced to T_{s0} value, below the solidification temperature, T_{sold}, due to heat transfer from steel to mould wall. At a certain moment t, temperature distribution becomes shaped as is presented in fig. 1 and solidified layer has thickness $X(t)$.

Due to the fact that solidified thickness is reduced on the mould level comparing with molten thickness non-permanent regime, can be considered, as hypothesis, that molten steel medium is semi-infinite (for $x>X(t)$). Unidirectional heat transfer is described by two equations corresponding both solid state and molten state.

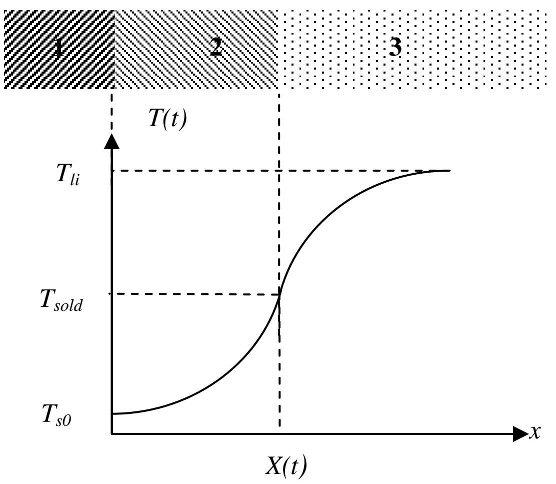


Fig. 1 Temperature distribution in mould solidification.
1. water cooled mould;
2. solidified layer;
3. molten layer.

For solidified layer, status equation is:

$$(1)\ \frac{\partial T_s}{\partial t}=\alpha_s\frac{\partial^2 T_s}{\partial x^2} \qquad \text{for } 0 \le x \le X(t)$$

where α_s is thermal diffusivity for solid steel.
For molten layer, status equation is similar:

$$(2)\ \frac{\partial T_l}{\partial t}=\alpha_l\frac{\partial^2 T_l}{\partial x^2} \quad \text{for } X(t) \le x < \infty$$

where α_l is thermal diffusivity for molten steel.
Equations (1) and (2) have the following limitation conditions:

$$(3) T_s(x)|_{x=0} = T_{s0}\ ;\ t>0$$

$$(4) Tl(x)|x\rightarrow\infty = Tli\ ; \qquad t>0$$

Limitation condition related to solid-molten interface is:

$$(5) T_l = T_s = T_{sold} \ \text{ at } \ x=X(t)$$

Initial conditions are:

$$(6) T_s(x)|_{x=0,\ t=0} = T_{s0}\ ; \qquad T_l(x)|_{x>0,\ t=0} = T_{li}\ ;$$

In order to calculate solidification boundary speed, will be used energetic equilibrium equation in metal.

$$(7)\left(\begin{matrix}\textit{heat generated}\\ \textit{solidification derivate}\end{matrix}\right)=\left(\begin{matrix}\textit{absolute heat flow}\\ \textit{at molten - solid interface}\end{matrix}\right)$$

Heat generated per volume, due to solidification, is $\rho_s\Delta H$, where ρ_s is solid phase density and ΔH is latent solidification heat. In these conditions energetic equilibrium equation in metal is:

$$(8)\ \rho_S.\Delta H.\frac{dX(t)}{dt}=\lambda_l.\frac{\partial T_l}{\partial x}-\lambda_S.\frac{\partial T_S}{\partial x}$$

where λ_l and λ_s are thermal conductibility coefficients for both solid phase and molten phase. According with the previous, process model for primary cooling will consist in:

Initial data: physical and material constants: α_s, α_l, T_{sold}, λ_l, λ_s, ρ_s, ΔH, mould length.

Measured variables: T_{s0} (mould temperature), T_{li} (tundish current measured steel temperature).

Mathematical model:

$$\frac{\partial T_s}{\partial t}=\alpha_s\frac{\partial^2 T_s}{\partial x^2}$$

$$\frac{\partial T_l}{\partial t}=\alpha_l\frac{\partial^2 T_l}{\partial x^2}$$

$$T_s(x)|_{x=0} = T_{s0}\ ;\ T_l(x)|_{x\rightarrow\infty} = T_{li}$$

$$T_l = T_s = T_{sold}$$

$$T_s(x)|_{x=0,\ t=0} = T_{s0}\ ;\ T_l(x)|_{x>0,\ t=0} = T_{li}$$

$$\rho_S \Delta H \frac{dX(t)}{dt} = \lambda_l \frac{\partial T_l}{\partial x} - \lambda_S \frac{\partial T_S}{\partial x}$$

Output variables: solidified layer thickness at the mould exit/ solidification boundary speed.

Analytic solutions for this mathematical model conduct to a solidification boundary dynamic having the following form

$$(9)\ X(t) = 2.K.\sqrt{\alpha_s.t}$$

where calculation method for K coefficient is presented in (Oprea,F., *et al.*1994). Analytical solution (9) generates an overestimation for solidified layer thickness, which is unacceptable. A series of modifications for this model were accomplished by (Barbu, M., *et al,* 2002; Barbu, M., *et al*, 2003) in order to obtain a model improvement. The model proposed in these papers contains two exponential correction terms which becomes zero very fast with time incrementation. Relation for solidified layer thickness becomes:

$$(10)\ X(t) = 2.K.(\sqrt{\alpha_s.(q.\exp(-q_1.t)+t)} - \sqrt{\alpha_s.q.\exp(-q_1.t)}\ )$$

where q=4.2; q_1=0.013.

3. HILLS MODEL

A different model used for solidification process on the mould level is Hills model (Thomas,B.G., 2001) for which explanation, Hills hypothesis will be adopted as follows:

I1 – molten steel is homogenous from thermal point of view so no thermal gradient in molten will be considered;

I2 – heat transfer by thermal conductibility is ignorable in strand movement direction and is considered only in rectangular direction regarding mould wall;

I3 – thermal transfer coefficient between outer solidified surface and mould wall is considered known and constant on y strand moving direction.

Using these hypotheses thermal transfer model through convection in solidified layer can be written:

$$(11)\ \frac{\partial T_s}{\partial t} = \alpha_s.\frac{\partial^2 T_s}{\partial x^2} = V_t.\frac{\partial T_s}{\partial y},\ 0 \le x \le X(y)$$

where $V_t = \dfrac{dy}{dt}$ represents casting speed; $X(y)$ is solidified layer thickness at y distance from upper surface of the mould.

Condition for solidified layer limitation is:

$$(12)\ T_s = T_{sold} \text{ at } x = X(y)$$

Thermal equilibrium equation at solid molten interface is:

$$(13)\ -\lambda_S \frac{\partial T_s}{\partial x} = \rho.\Delta H_T.\frac{dX(y)}{dy}.V_t,\ x = X(y)$$

where ΔH_t is solidification heat plus heat overplus due to the fact that molten steel temperature is superior to T_{sold}:

$$(14)\ \Delta H_T = \Delta H_s + C_{ps}.(T_{sold} - T_{li})$$

Boundary condition on x=0, to wit on contact between solidified outer surface and mould wall is:

$$(15)\ \lambda_s.\frac{\partial T_s}{\partial x} = h_c.(T_s - T_c) \quad \text{at } x=0$$

where T_c is mould wall temperature, h_c thermal transfer constant between solidified outer layer and mould wall.

Equations (11) – (15) forms based model from which Hills calculated solution for solidified layer thickness at the mould exit is obtained. According with this solution a series of constants are defined as follows:

- dimensionless distance on movement direction:

$$(16)\ \varsigma = \frac{y.h_c^2}{V_t.\rho.C_{ps}.\lambda_s}$$

- dimensionless thickness for solidified layer:

$$(17)\ \bar{X} = \frac{h_c.X(y)}{\lambda_s}$$

- latency heat plus dimensionless overheating:

$$(18)\ \overline{\Delta H_T} = -\frac{\Delta H_T}{C_{ps}.T_{sold}}$$

Hills solution for (11) – (15) equations model is materialized in function:

$$(19)\ \bar{X} = F(\varsigma, \overline{\Delta H_T})$$

displayed as chart or table in (Oprea, F. et all 1994). In fig. 2 was displayed the dependence between dimensionless thickness and dimensionless distance using as parameter latency heat plus dimensionless overheating.

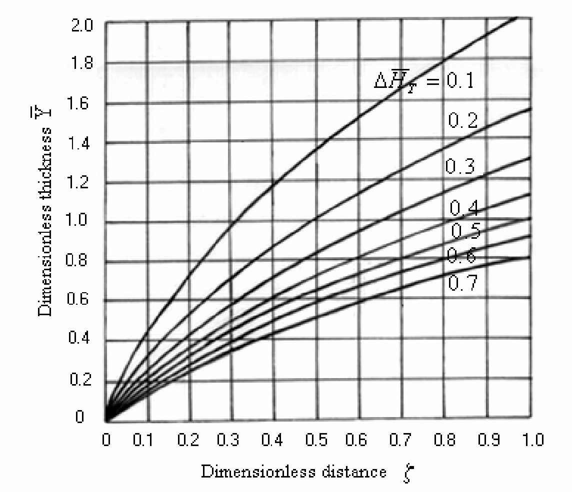


Fig. 2 Dependence between dimensionless thickness and dimensionless distance (Oprea, F., *et al*, 1994)

4. CORECTED ANALYTICAL MODEL

The following preliminary conclusions were generated analyzing presented methods:

1. analytical model conducts on a $X(t)=K.\sqrt{t}$ relation, which is considered as a classical model in solidification processes. Anyway, this analytical model is based on nonrealistic boundary first order condition. Even in this hypothesis $T_s(x)|_{x=0}=T_{s0}$ temperature is non measurable (is known with a very high level of imprecision);
2. analytical model describes solidification process dynamics not using casting speed as independent input variable;
3. Hills model uses realistic second order boundary conditions, but thermal coefficient transfer between outer solidified layer and mould wall, h_c, can be evaluated with a very high level of imprecision, due to complex structure (and unpredictable) of contact between solidification skin and mould wall.
4. Hills model includes casting speed as independent input variable but there is no explicit dependence between $\sqrt{t}$ and solidified layer thickness. In dimensionless form the model is used for obtaining solidified layer thickness in stationary regime.

Considering all these aspects is proposed a much simple solution for analytic model, in such a way that to obtain an approximate solidification dynamics on different casting speeds. Information provided by this model is used in primary cooling monitoring and refers to an estimation of solidified layer thickness. From safety reasons it was considered that estimated thickness must be smaller than the one obtained from Hills model.

Solidified layer thickness depends upon two independent variables: casting speed and tundish steel temperature. Correction takes into consideration differences between two previous models, to wit:

- Analytical model (which will be corrected), with boundary first order conditions;
- Hills model (the one used by operators in permanent regime), with boundary second order conditions.

Faster solidification dynamics of analytical model is determined by the fact that $T_s(x)|_{x=0}=T_{s0}$ temperature, considered known in analytical model has a direct influence – by system status equations – on temperature spatial distribution. In case of second order boundary condition, thermal flow modification $\lambda_s.\dfrac{\partial T_s}{\partial x}=h_c.(T_s-T_c)$ on outer solidified layer determines through a dynamic process $T_s(x)|_{x=0}=T_{s0}$ temperature. This temperature dynamics is slower than thermal flow dynamics. In these conditions changing in analytical model structure must include also a dynamic subsystem, having parameters dependant upon casting speed so that, solidified layer thickness modification speed to be approximately equal with the one generated by Hills model. Basic diagram for this correction is given in Fig. 3.

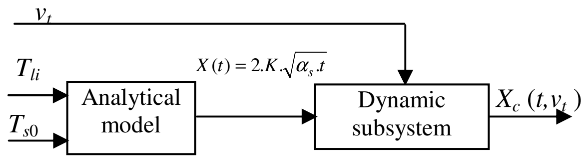


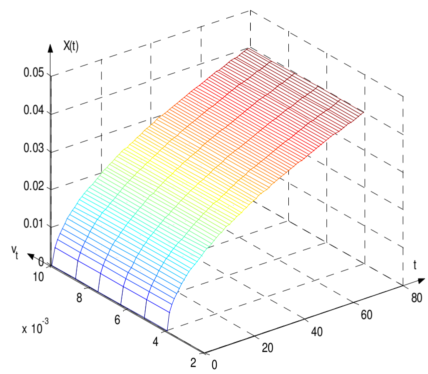
Fig. 3 Analytical model correction

Dynamic subsystem model using for analytical model solution filtration is a second order model and has parameters dependant upon casting speed:

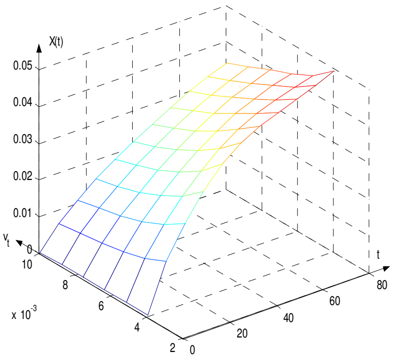
$$X_{c1}(k)=aX_{c1}(k-1)+(1-a)X(k);$$
$$X_c(k)=(a+d)X_c(k-1)+(b-c.v_t(k))X_{c1}(k);$$

where k is discrete current time, $v_t(k)$ represents casting speed, and subsystem parameters are:

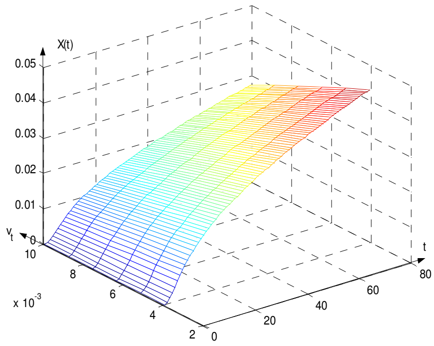
$$a=0.65;\ b=0.475,\ c=25 \text{ and } d=3.$$



a



b



c

Fig. 4 Solidified skin dynamics on different casting speeds: (a) –analytical model case; (b) – Hills model case; (c) – analytical model corrected case

5. RESULTS OBTAINED USING NUMERICAL SIMULATION

In Fig. 4 is presented the dynamics of solidified skin on different casting speeds in the following conditions:

– Analytical model case (Fig. 4.a), when casting speed did not influence the dynamics of solidified skin;

– Hills model case (Fig. 4.b);

– Analytical model corrected case (Fig. 4.c).

In analytical model corrected case, the solidification layer thickness evolution is similar with situation generated by Hills model. For an easier comparing in Fig. 5 are displayed solidification layer thickness estimation based upon Hills model (dashed line) and based upon corrected analytical model (solid line) for different casting speeds. It was considered useful that on high casting speeds and on relatively higher time values (t > 50s), when position of solidified layer corresponding with exit mould zone, estimation obtained from corrected analytical model to be inferior to the one gave by Hills model. This estimation is useful for achieving protection functionalities; in this context a reasonable negative tolerance is recommended.

As it was mentioned also in fig. 3, solidification layer thickness estimation is influenced by T_{s0} temperature and molten steel temperature measured in the tundish, T_{li}. Considering uncertainties in obtaining these parameters, it was analyzed the impact of them in X(t) estimation.

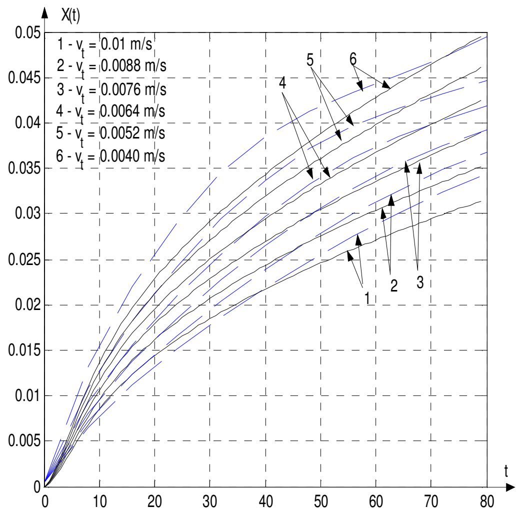


Fig. 5 Solidified layer thickness estimation, on different casting speeds, obtained from Hills model (dashed line) and from corrected analytical model (solid line)

In Fig. 6 are plotted the evolution of X(t) thickness estimation, on T_{s0} temperature equals with: 400K, 450K, 500K and 550K, both in corrected analytical model (I curve), and in analytical model (II curve). In this case, is easier to observe that, effect of T_{s0} temperature variation is reduced. Also usual variations for tundish molten steel temperature over solidification rate are reduced, as can be observed in Fig. 6. In this picture are plotted also with dashed line, results obtained with Hills model.

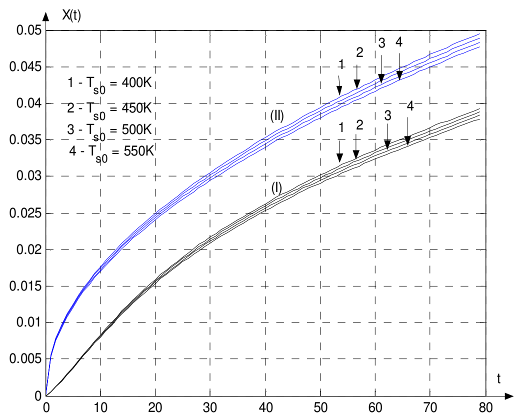


Fig. 6 T_{s0} temperature influence on $X(t)$ thickness evolution

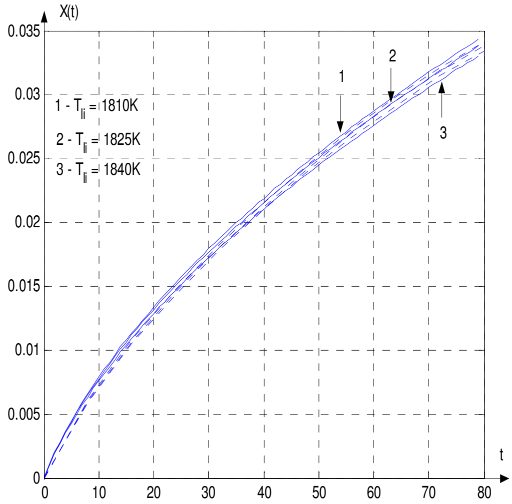


Fig. 7 T_{li} temperature influence on $X(t)$ thickness evolution

6. CONCLUSIONS

Results plotted in fig. 6 and 7 states that are possible to work with values considered "rated", constants, for T_{s0} and T_{li} temperatures. Anyway, T_{li} temperature can be calculated with enough precision from global model for ladle-tundish assembly. This model is initialized using effective measured temperature of molten steel in the tundish (this temperature is measured 4 times per heat in tundish). Also mould wall temperature is measured constantly during the heat in such a way that temperature T_{s0} variations can be considered approximately as variations of measured temperatures.

Concluding, even if solidified model sensibilities in relation to T_{s0} and T_{li} variables are reduced, automation system can use data from measurements and from ladle-tundish assembly model in order to obtain reducing estimation error.

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