Real Time Supervising Modeling of a Continuous Casting Mold Using Artificial Intelligence Techniques

Marian Barbu, Emil Ceangă and Constantin Gheorghiu

***Abstract*— The mathematical model used for real time supervising of the primary cooling process combines two types of solidification models: the Hills model used for the range of speed typical of nominal regimes and a model based on an analytical solution of the equation which provides the dynamics of the variation of the solidifying shell thickness. The second model implied some simplifications concerning the limit conditions and is used in the manoeuvre regimes where extremely reduced casting speed values are requested. The Hills solution, which indicates the non-dimensional thickness of the strand, was turned into a neural model. The two methods are combined in a unitary one using a Sugeno type of fuzzy technique, the fuzzification variable being the casting speed.**

***Index Terms*—Continuous casting, Primary cooling, Fuzzy logic, Neural networks.**

I. Introduction

Continuous casting is the process whereby molten metal is solidified into a "semi finished" billet, bloom, slab or beam blank. Nowadays, continuous casting is the predominant way by which steel is produced in the world. Continuous casting is used to solidify most of the 750 million tons of steel, 20 million tons of aluminum, and many tons of other alloys produced in the world every year [1]. Figure 1 presents the typical scheme of the steel continuous casting process. The primary cooling is assured by the mold. This is made of chromium plates that are cooled with water under pressure and have an oscillatory moving, being supplied with powdered flux on the liquid steel surface.

The main role of the mold is to form the solidified steel crust having the thickness that enables a safe secondary cooling system by spraying water along the strand.

In the case of cast charges, the casting speed may vary from values close to 0, when the tundish is replaced without interrupting the process, to superior ones that are limited by the danger of the perforations of the solidified crust at the mold output. Under the circumstances, the estimation, in a dynamic regime and based on a mathematical model, of the solidified shell thickness at the mold output is important in order to monitor the process. Restrictions concerning the data processing resources imposed by the system functioning in real time make impossible the use of complex models integrated through the finite element method [3], [4]. Besides, uncertainties concerning real limit conditions diminish the usefulness of complex models approached through numerical analysis.

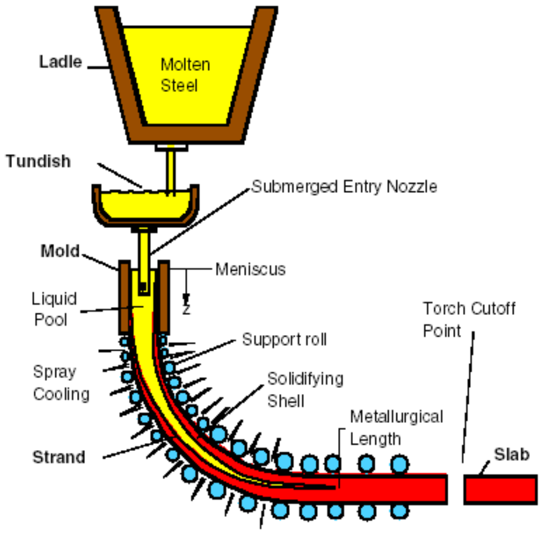

Fig.1. The continuous casting process

The present method of analysis of the mold thermal regime is based on the Hills method of a model where the III-rd type of limit conditions is accepted. This solution is materialized in a nomogram, which allows the identification of the solidified shell thickness at the mold output within the range of current values of speed casting. Nevertheless, when manoeuvring the installation the casting speed may exceed the range of values within which the nomogram of the Hills model can be used. On the other hand, the model based on the I-st type of limit conditions offers a general analytical solution, which can describe the dynamics of the solidification process for any kind of speed casting. [2]

The paper presents a model for real time supervising of the

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mold where the Hills model and the model obtained after correcting the analytical solution are combined using fuzzy techniques of Sugeno type [5], the fuzzification variable being the casting speed.

The paper is structured as follows: the second section contains a description of the thermal regime and of the limit conditions in the mold. The third section presents analytical models of the solidification process based on the I-st and III-rd type of limit conditions. The fourth section presents simplified models for the control of the primary cooling process. The fifth section presents the implementation of the estimator of the solidifying shell thickness using a Sugeno type of fuzzy block, and the last section contains the conclusions.

II. The Mold Description

The four plates of the mold have cooling channels with water under pressure. In order to compensate the constriction of the steel in the mold which could lead to a loss of contact: steel crust-mold wall (with important effects on the thermal transfer), the broad surfaces are 0.9%/m conical. In order to have an initial correct formation of the solidifying shell the mold has an oscillatory movement. The magnitude and the frequency of the oscillations influence the period of time necessary to form the first crust. It is therefore necessary that during the descendant movement of the oscillation the medium speed of the mold should be 30% bigger than the strand speed.

During the casting, the molten steel is permanently covered with lubricant powder whose thickness reaches 1…1.5 cm depending on the casting speed. The lubricant is transforming so that it may have -in a static regime- a configuration of the mold-lubricant-steel system similar to the one shown in Figure 2.

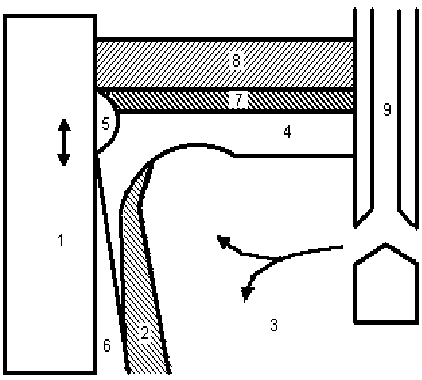

Fig. 2. The configuration of the mold-lubricant-steel system: 1. mold; 2. solidifying shell; 3. , 9. liquid steel; 4. liquid lu bricant; 5., 6. solidified lubricant; 7. burnt lubricant; 8. powdered lubricant.

From the point of view of the thermal regime, the structure presented above determines a complex scheme of the heat transfer as shown in Figure 3. The power density extracted along the mold height is variable and depends on the type of lubricant (its viscosity) as well as the casting speed. The data presented above show that the uncertainties concerning the heat flux density are very important.

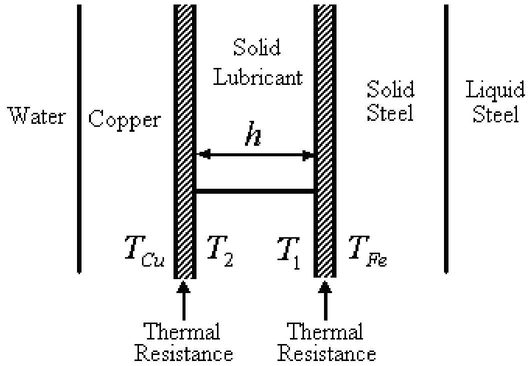

Fig. 3. The scheme of the heat transfer in the primary cooling zone

III. Analytical Modeling of the Solidification Process in the Primary Cooling Zone

A. Estimation of the solidifying shell thickness during the primary cooling in the I-st type of limit condition

In order to analyze the solidification process in the mold, it is considered a quantity of molten steel whose initial uniform temperature is known, $T_{li.}$ At an initial moment t=0 the temperature x=0 becomes T_{s0} below the solidification temperature T_{sold} as a result of the thermal transfer to the mold. At a certain moment t the distribution of the temperature is similar to the one shown in Figure 4 and the solidifying shell thickness is $X(t)$.

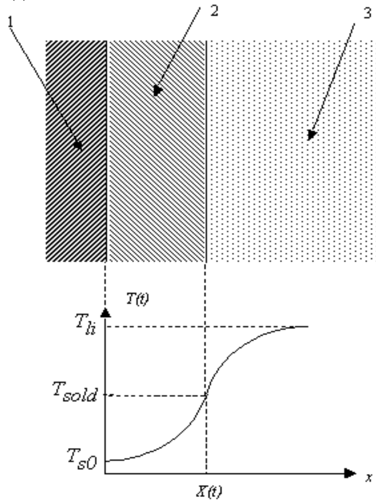

Fig. 4. The temperature distribution during the solidification process in the mold: 1. copper mold cooled with water; 2. solidifying shell; 3. liquid.

Taking into consideration that in the mold the solidifying shell thickness is small when compared to the thickness of the molten metal zone, the unstationary dynamic regime of the solidifying shell thickness can be treated making the hypothesis that the molten metal medium is semi-infinite (for $x>X(t)$).

The unidirectional heat transfer is described in two different equations characteristic to the liquid and solid states. For the solidified zone the equation is:

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

where α_s stands for the thermal diffusivity of the solid material.

For the liquid zone the equation is similar:

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

where α_l stands for the thermal diffusivity of the liquid material.

The equations (1) and (2) have the following limit conditions:

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

$$T_l(x)|_{x\to\infty} = T_{li}\,;\ t>0 \tag{4}$$

The limit condition characteristic to the solid-liquid interface is:

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

The initial conditions are:

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

The equation of the advance speed of the solidifying shell thickness that results from the equation of the thermal balance in the metal is:

$$r_S.\Delta H.\frac{dX(t)}{dt} = l_l.\frac{\partial T_l}{\partial x} - l_S.\frac{\partial T_S}{\partial x} \tag{7}$$

The analytical solutions of (1) and (2) are:

$$T_s = A_1 + B_1\mathrm{erfc}\left(\frac{x}{2\sqrt{a_s t}}\right) \quad \text{for } 0 \le x \le X(t) \tag{8}$$

$$T_l = A_2 + B_2\mathrm{erfc}\left(\frac{x}{2\sqrt{a_l t}}\right) \quad \text{for } X(t) \le x < \infty \tag{9}$$

where $A1$, $B1$, $A2$, $B2$ are integration constants which are obtained from the limit conditions and erfc(·) is the function complementary to the error.

As T_{sold}=const, it implies that the sum of terms that contain the functions erf(·) and erfc(·) must be constant. It only happens when $X(t)$ is proportional to $\sqrt{t}$:

$$X(t) = 2.K.\sqrt{a_s.t} \tag{10}$$

The equation used to identify the parameter K is the following:

$$\left(\frac{l_l}{l_s}\right).\sqrt{\frac{a_s}{a_l}}\,\frac{T_{li}-T_{sold}}{K.\exp\left(K^2\frac{a_s}{a_l}\right).\mathrm{erfc}\left(\sqrt{\frac{a_s}{a_l}}K\right)} - \frac{1}{K.\exp(K^2).\mathrm{erf}(K)} = \frac{\sqrt{p}.\Delta H_s}{C_{ps}.(T_{sold}-T_{s0})} \tag{11}$$

where $C_{ps} = \frac{l_s}{r.a_s}$ stands for the heat capacity to the solid state.

When the liquid reaches the melting point $T_{li} = T_{sold}$, (11) becomes:

$$K.\exp(K^2).\mathrm{erf}(K) = \frac{C_{ps}.(T_{sold}-T_{s0})}{\sqrt{p}.\Delta H_s} \tag{12}$$

The solution K of the non-lineal (11) equation is replaced in (10) and allows the identification in time of the variation of the solidifying shell thickness. Figure 5 shows the special distribution of the temperature in the solid state at different moments in time, obtained due to the model presented above.

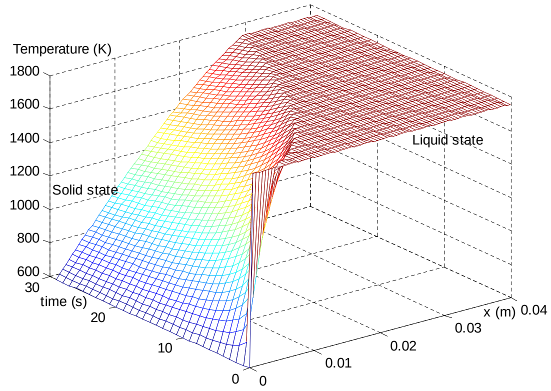

Fig. 5. The temperature in the solid state at different moments in time

B. The estimation of the solidifying shell thickness dynamics during the primary cooling process in the III-rd type of limit conditions

Classical approaches of the solidifying process modeling in the mold adopt the following hypotheses:

I1 - The molten metal is homogeneous thermally speaking, so it is not considered a thermal gradient in the liquid;

I2 - The heat transfer through thermal conductibility is negligible in the direction of the strand movement and it is produced only on the normal direction at the mold surface;

I3 - The thermal transfer coefficient between the outer face of the solidifying shell and the mold wall is considered to be known and constant on the strand moving direction y.

These hypotheses being considered, the thermal transfer model through conductibility in the solidifying shell is:

$$\frac{\partial T_s}{\partial t} = a_s.\frac{\partial^2 T_s}{\partial x^2} = V_t.\frac{\partial T_s}{\partial y} \quad \text{for } 0 \le x \le X(y) \tag{13}$$

where $V_t = \frac{dy}{dt}$ stands for the casting speed and $X(y)$ represents the solidifying shell thickness at distance y from the metal output in the mold.

The limit condition of the solidifying shell is

$$T_s = T_{sold} \ \text{ at } x = X(y) \tag{14}$$

The thermal balance equation at the solid-liquid interface is:

$$-l_S\frac{\partial T_s}{\partial x} = r.\Delta H_t.\frac{dX(y)}{dy}.V_t \ \text{ at } x = X(y) \tag{15}$$

where ΔH_t stands for the latent heat of solidification plus the heat excess due to the fact that the molten metal temperature is superior to T_{sold}.

The limit condition x=0, i.e. the contact between the outer surface of the solidifying shell and the mold surface is:

$$l_s \cdot \frac{\partial T_s}{\partial x} = h_c.(T_s - T_c) \text{ at } x=0 \quad (16)$$

where T_c stands for the mold temperature and h_c is the thermal transfer coefficient between the outer face of the solidifying shell and the mold wall.

The equations (13)-(16) form the mathematical model used by the Hills solution to calculate the solidifying shell thickness at the mold output. The Hills solution of the (13)-(16) model involves the use of process engineering information concerning the thermal transfer coefficient h_c and is materialized in the function:

$$\bar{Y} = F(x, \overline{\Delta H_T}) \quad (17)$$

given in a tabular form or on a graph (Figure 6). In keeping with this solution, the following can be measured:

- the non-dimensional distance in the moving direction: $x = \dfrac{y.h_c^2}{V_t.r.C_{ps}.l_s}$;
- the non-dimensional thickness of the solidifying strand: $\bar{Y} = \dfrac{h_c.Y(y)}{l_s}$;
- the latent heat plus the non-dimensional overheat: $\Delta\bar{H}_T = -\dfrac{\Delta H_T}{C_{ps}.T_{sold}}$;

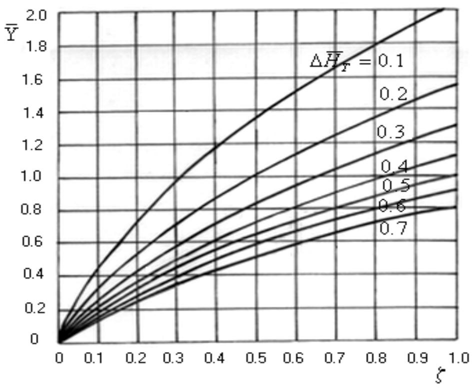

Fig. 6. The non-dimensional thickness dependence on the non-dimensional distance

IV. Simplified Models for the Control of the Primary Cooling Process

A. *Estimator Based on the Hills Solution*

The purpose is to approximate the Hills nomogram using a function.

Two methods have been used:

- polynomial regression;
- the use of neural networks.

In the case of the first method a polynomial expression of four degree has been used. Figure 7 shows the results of this model. The continuous line indicates the thickness dependence on the curve dimension from Figure 6, and the dotted line indicates the other kinds of dependence on the values of the $\overline{\Delta H_T}$ parameter. The graph shows that the function that has been identified, though it makes a good approximation of the range of values used in the identification, does not make a satisfactory extrapolation beside the [0,1 0,7] domain of the $\overline{\Delta H_T}$ variable (it can be remarked the tendency of a descendant evolution which contradicts the physical reality).

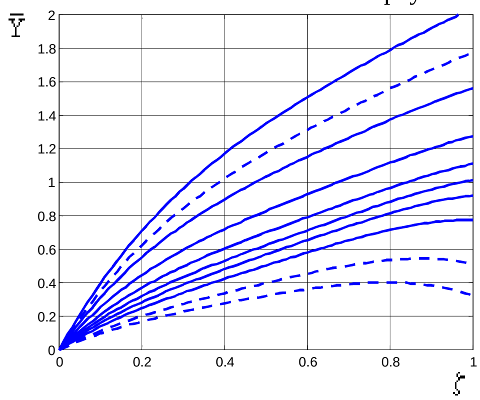

Fig. 7. The result of the Hills nomogram approximation using a polynomial expression

The second method used to approximate function (17) is a non-parametric method that uses neural networks. A two-layered neural network has been used, the input layer consisting of 7 neurons, the output layer of 1 neuron. The activation functions are ***tansig*** and respectively ***purelin***. The structure of the network is given in Figure 8.

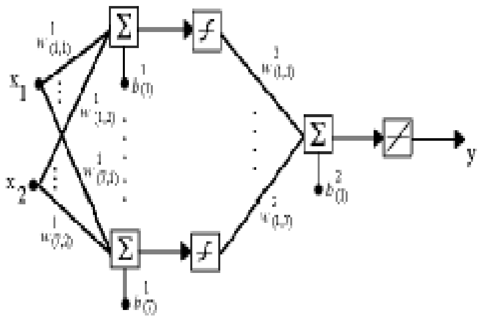

Fig. 8. The structure of the neural network

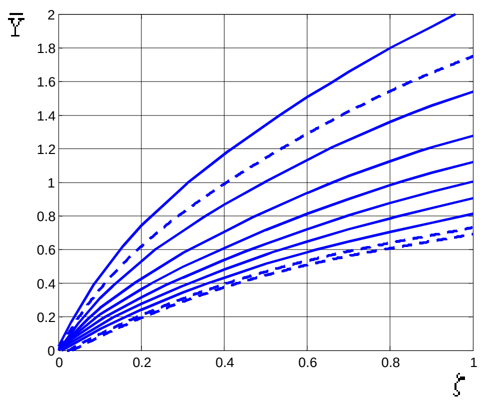

Fig. 9. The result of the Hills nomogram approximation using a neural network

Figure 9 shows the results obtained after using this method. It is to be noticed from the figure that the neural approximation method makes a good extrapolation beside the values used for training. The small errors that occur around the origin constitute its disadvantage. It is a small error as it is less important to estimate the thickness in the superior surface of the mold when compared to the thickness estimation in the middle area and especially at the output. Consequently, when using the Hills solution the estimator implementation will be based on the neural model.

B. Estimator Based on the Analytical Solution of the Solidification Equation

Figure 10 depicts the solidifying shell evolution according to the analytical model (10), (11) (the curves 1 correspond to three values of the T_{li} temperature) and according to the Hills model (curve 2). It is to be noticed that between the analytical model and the Hills one there are sensible differences during the stage of the solidifying shell formation, i.e. the analytical model leads to an overestimation of the initial solidification speed. It can be explained due to the simplifying hypotheses concerning the limit conditions that are accepted in the analytical model. Except for the initial area, it is to be noticed that in the middle and end areas of the mold the bending of the curves that describe the solidifying shell evolution are almost similar.

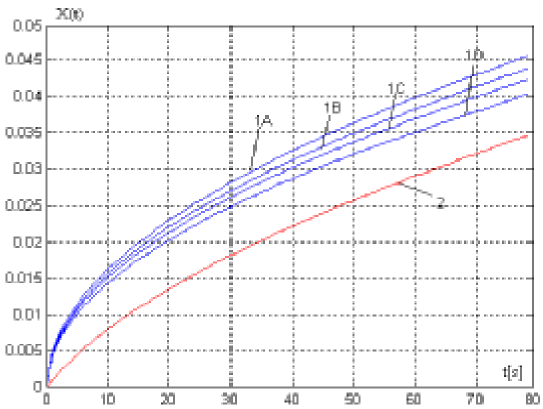

Fig. 10. The solidifying shell evolution according to the analytical method (1A,1B, 1C, 1D curves) and the Hills model (Curve 2)

Under the circumstances *a revised analytical model* has been created which allows the adjustment of solidification process initial dynamics so that the results might be identical to the ones given by the Hills model. The revised model contains an exponential term that is quickly annulated as time passes: $q\exp(-q_1.t)$. Introducing two parameters makes the correction: q that establishes the correction weight and q1 that determines the period of time within which the correction operates. Consequently in the revised model equation (10) is replaced by the equation:

$$X(t)=2K.(\sqrt{a_s.(q.\exp(-q_1.t)+t)}-\sqrt{a_s.q.\exp(-q_1.t)}\,) \tag{18}$$

The values of the parameters q and q_1 have been identified through adjustments. The revised analytical model results are similar to the Hills model (Figure 11) but it has the advantage that it enables the analysis of the system dynamics in the manoeuvre regimes when the casting speed has different values than the ones of the usual permanent regimes. Therefore, the dynamics of the variation of the solidifying shell thickness is described using a model similar to $K\sqrt{t}$ law adding the corrections made to the initial regime.

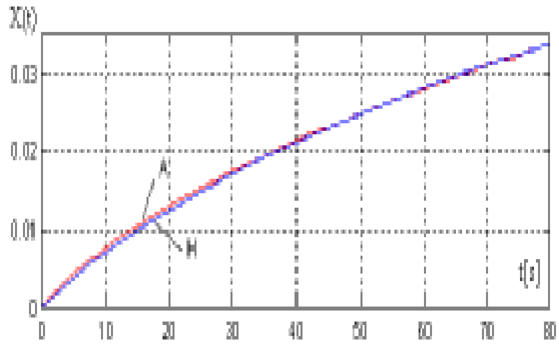

Fig. 11. The solidifying shell evolution according to the Hills model (curve H) and the revised analytical model (curve A).

V. The Implementation of the Estimator of the Solidifying Shell Thickness Using a Fuzzy Block of Sugeno Type

The fuzzy block used to combine the Hills and revised analytical model takes into consideration the characteristics of the two models described in the previous section. Thus the Hills model is used for the range of speed typical of nominal regimes, when high speed is preferred in order to obtain superior qualities; the analytical model is used in the case of manoeuvre regimes where extremely reduced casting speed is required.

The fuzzy block has only one fuzzed variable, the casting speed, containing two linguistic terms *Small* and *Big*. The membership function for the casting speed is shown in Figure 12.

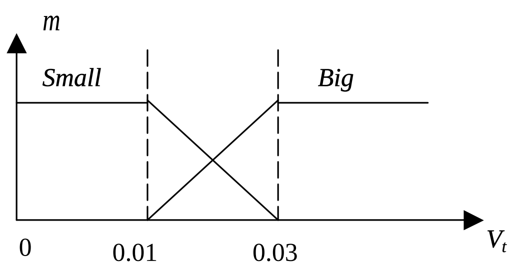

Fig. 12. The membership functions of the Sugeno type of fuzzy block

The output of the fuzzy block is represented by the solidifying shell thickness at the mold output:

$$X = K_1 \cdot X_1 + K_2 \cdot X_2 \tag{19}$$

where K_1 and K_2 are the membership degrees of the casting speed to the two linguistic expressions, and X_1 and X_2 stand for the thickness estimated using the analytical model and the

Hills one.

Figure 13 presents the two working regimes. The graph allows noticing that in the case of small speed the Hills model does not permit a correct estimation (the non-dimensional distance x goes out of the nomogram, see Figure 7) whereas in the case of large speeds, the results of the two models coincide. Figure 14 shows the evolution of the solidifying shell thickness at the mold output when the tundish is replaced (the casting speed is close to 0).

The estimation algorithm of the solidifying shell thickness evolution along the mold height implies the following operations:

- for each charge the variable T_{sold} can be calculated on the basis of the information concerning the steel composition;

- for any attempt to determine the steel temperature in the tundish (the temperature is identified 4 times for each charge), the value of the K coefficient is actualized in the fundamental formula that provides the solidification dynamics. For this purpose, the equation (12) is solved in relation with K;

- the model (18) is used in order to estimate the solidifying shell thickness at the mold output. The same variable can be calculated using the neural network given in the Figure 9. The fuzzy block gives the solidifying shell thickness at the mold output.

The calculations are made at any moment of the sampling step of the real time supervising system.

VI. CONCLUSIONS

The revised analytical system and the Hills one have identical results; there are differences only in the initial zone that is in the superior part of the mold. As the variable we are interested in is the solidifying shell thickness at the mold output, equality between the results of the two methods is obtained. The Hills model, implemented by a neural network is used in the case of the permanent functioning regime when V_t=const. In the case of the manoeuvre regimes, when the casting speed has great variations the non-dimensional distance going out of the Hills nomogram (Figure 7) the revised analytical model results are used.

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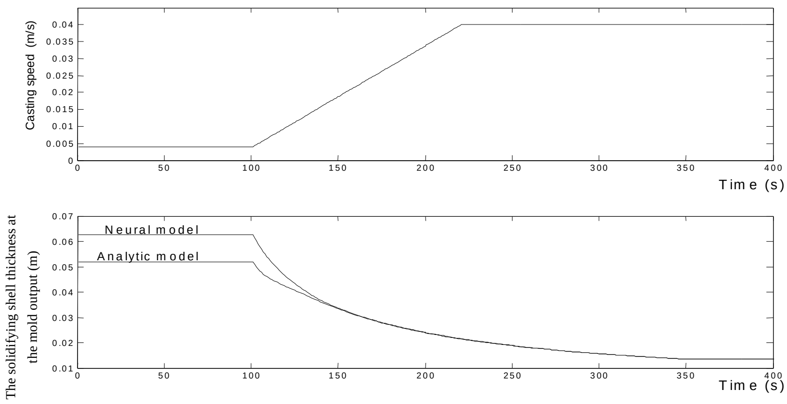

Fig. 13. The solidifying shell thickness at the mold output in two workings regimes

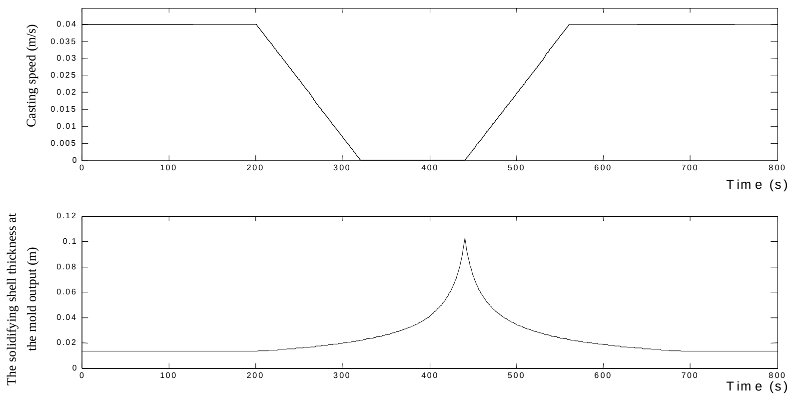

Fig. 14. The solidifying shell thickness at the mold output when the tundish is replaced