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MATHEMATICAL MODELING OF TEMPERATURE FIELD IN THE CONTINUOUS CASTING OF STEEL SLAB (part two)

MATEMATIČKO MODELOVANJE TEMPERATURNOG POLJA KONTINUIRANO LIVENOG ČELIČNOG SLABA (drugi deo)

R. MANOJLOVIĆ, V. JAŠOVSKI

Faculty of Technology and Metallurgy of University "Sv. Kiril and Metodij", R. Boskovic 16, 1000 Skopje, Macedonia

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ABSTRACT

In this paper the temperature field in the solidification area of continuous casting steel slab was determined. The changes of the temperature in the solidification process of the slab was directly followed by the wolfram-rhenium thermocouples inputted into the liquid steel. The liquid, solid and two-phase region in the solidification area of steel slab were performed by the numerical method - finite difference method, and then using the isothermal method. Comparing the temperature field obtained with the numerical method with the one obtained with the isothermal method, it was shown that the isothermal method can be successfuly applied in mathematical modeling of solidification process of steel slabs.

Key words: solidification, temperature field, steel slab, isothermal method

IZVOD

U radu je određeno temperaturno polje u oblasti očvršćavanja kontinuirano livenog čeličnog slaba. Promena temperatura u procesu očvršćavanja slaba direktno je praćena pomoću uronjenih termoelemenata u tečni čelik. Oblasti tečne, čvrste i dvofazne zone u oblasti očvršćavanja čeličnog slaba određene su najpre numeričkim metodom - metodom konačnih razlika, a zatim i izotermalnim metodom. Upoređenje temperaturnog polja dobivenog izotermalnim metodom sa temperaturnim poljem dobivenim numeričkim metodom je pokazalo da se izotermalni metod može uspešno primeniti u procesu matematičkog modelovanja procesa očvršćavanja čeličnih slabova.

Ključne reči: očvršćavanje, temperaturno polje, čelični slab, izotermalni metod

INTRODUCTION

Knowing the temperature field is important because the quality of the steel slab depends, among the rest, from the temperature field in the solidification process. The shape and size of the two-phase region are of great importance in the forming of the primary slab structure.

The mathematical modeling of the temperature field on the steel slab in the solidification process is mostly based on temperatures of the slab surface, rarely based on indirectly measured temperatures and very rarely based on direct measurements of the temperature inside the slab. In this paper the mathematical modeling of the temperature field of the steel slab was performed on the based of directly measured temperature inside the slab in the solidification process [1,2]. Then the temperature field on the longitudinal section on the middle of the wider and on the middle of the tighter side was numerically calculated applying the finite difference method [2]. The existing isothermal method, applied for the mathematical modeling of the cooling process of the cube, was adapted for determining of the isotherms during the steel slab solidification [3,4,5]. Afterwards, the results obtained with the both methods were compared.

ADAPTATION OF THE ISOTHERMAL METHOD FOR DETERMINING OF THE TEMPERATURE FILED DURIN THE STEEL SLAB SOLIDIFICATION

For adaptation of the isothermal method for determining the temperature field in the solidification process of the slab, the temperature during the cube cooling where the solution of the equation should be gained

$$\Delta^2 T = \frac{1}{a}\frac{\partial T}{\partial \tau}, \tag{1}$$

where is Δ - Laplace's operator, a - thermal conductivity and τ - time.

The starting coordinate was set in one of the cube corners. The cube with edge length L is soaked in the liquid medium with temperature $T = T_0$. The initial conditions were: $T = T_0$ for $x = 0, L$; $T = T_0$ for $y = 0, L$; and $T = T_0$ for $z = 0, L$. The general solution have to meet the given boundary conditions, i.e. the temperature on the cube surface is $T = 0$. In this case the temperature T can be determined from the relation [3]

$$T = T_0\left\{1-\frac{64}{\pi^3}\sum_{lmn}\frac{1}{lmn}\sin\frac{l\pi x}{L}\sin\frac{m\pi y}{L}\sin\frac{n\pi z}{L}\exp\left[-(l^2+m^2+n^2)\,a\frac{\pi^2\tau}{L^2}\right]\right\}. \tag{2}$$

When τ » L^2/a, the relation (2) can be rearranged and simplified without decreasing the precision of the calculations, so the temperature T and the shape of the isotherms - $y(\tau, z)$, can be determined from the relations [3, 1]

$$T \approx T_0\,[1-\frac{64}{\pi^3}\sin\frac{\pi x}{L}\sin\frac{\pi y}{L}\sin\frac{\pi z}{L}c_1(\tau)], \tag{3}$$

$$y(\tau=\tau_1, z=z_1) = \frac{L}{\pi}arcsin\left[\frac{1-\frac{T}{T_0}}{\frac{64}{\pi^3}c_1(\tau_1)\,sin\frac{\pi x}{L}sin\frac{\pi z_1}{L}}\right], \tag{3}$$

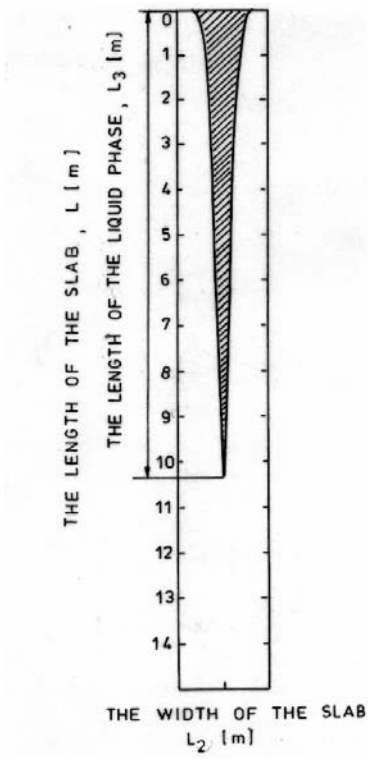
where is τ_1 - time, z_1 - plane where the isothermal curves are determined, and $c_1(\tau_1)$ - so-called time constant.

The adaptation of the existing isothermal method to an isothermal method for determining of the temperatures during the steel slab solidification demands satisfying of some conditions: the solution was in the analytical form which satisfied the starting differential equation - Green's function, the form of the solution was selected depending on the experimental results which give the shape of the isosolidus curve on the longitudinal section on the tighter slab side, the time was determined in the limit of real solidification time, the change interval of the parameter $a(\tau)$ was chosen so that it matched the real values for the given material and conditions etc. However, the solution should meet the initial conditions - the length of the liquid phase, the size of the crystallizator etc. Changing the initial cube shape to the slab's shape, the length of the cube's edge L was substituted with the parameters L_1, L_2 and L_3, which represent the slab's width and thickness and the length of the liquid phase.

DETERMINING THE SHAPE OF THE ISOSOLIDUS SURFACE ON THE LONGITUDINAL SECTION OF THE SLAB

The shape of the isosolidus surface of the steel slab was determined using the Green's function [3, 5].

$$G(x,\tau,0)=T(x,\tau)=\sqrt{\frac{1}{4\pi a\tau}}\,exp\left[\frac{-x^2}{4a\tau}\right]. \qquad (4)$$



The Green's function is usually applied in case when the distribution of the temperature $T(x, \tau)$ in an infinite solid body, given as $T(x, 0) = f(x)$ and when it not depends on y and z. It has Gauss dependence from the parameter x, with the width, proportional to $\sqrt{\tau}$, whose shape successfully describes the real shape of the section of the isosolidus surface. The shape of the isosolidus surface is given in Figure 1.

Figure 1 - Shape and size of the isosolidus surface on the longitudinal slab section

DETERMINING OF THE LIQUIDUS AND SOLIDUS AREA OF THE SLAB CROSS-SECTIONS

The solidus and liquidus areas on the cross-sections of the slab were determined with the next equations:

$$Z_{i,j} = \frac{L_3}{\pi} \arcsin\left[\frac{1 - \frac{T_{sol}}{T_0}}{\frac{64}{\pi^3} \sin\frac{\pi x_i}{L_1} \sin\frac{\pi y_j}{L_2} C_1 C_2} \right] \qquad (5)$$

$$Z_{i,j} = \frac{L_3}{\pi} \arcsin\left[\frac{1 - \frac{T_{lik}}{T_0}}{\frac{64}{\pi^3} \sin\frac{\pi x_i}{L_1} \sin\frac{\pi y_j}{L_2} C_1 C_2} \right] \qquad (6)$$

In the equations (5) and (6) were inputted the geometrical slab parameters - slab width (L_1) and slab length (L_2) as well as the variables x and y (x is ranged from 0 to $L_1/2$, y from 0 to $L_2/2$, which were calculated by the step i = 10^{-9} m with the program package MathCAD), then the temperature of steel casting (T_0 = 1535 ^{o}C) and the liquidus and solidus temperatures (T_{lik} = 1515 ^{o}C, T_{sol} = 1493 ^{o}C) and on the end, the time constants - C_1, with the constant value for all calculations (if the initial conditions are related to the middle of the crystallizator) and C_2, with the various value, calculated for the given conditions using the Green's function [1].

This way the solidus and liquidus curves on the slab cross-section were obtained (with the dimensions 1550x250 mm), on every meter following the slab length, starting from the steel "mirror" in the crystallizator, to the end of the two-phase region area. The solidus and liquidus curve on the quarter of the slab cross-section on the end of the crystallizator are shown in Figure 2.

The liquidus curves obtained for all slab cross-sections from the "mirror" to the fourth meter of the slab length are shown in Figure 3. The solidus curves obtained for all slab cross-sections are shown in Figure 4. As shown in Figure 3 and Figure 4, the isotherms are inscribing one into another, on certain distance, which depends on the value of the parameter C_2.

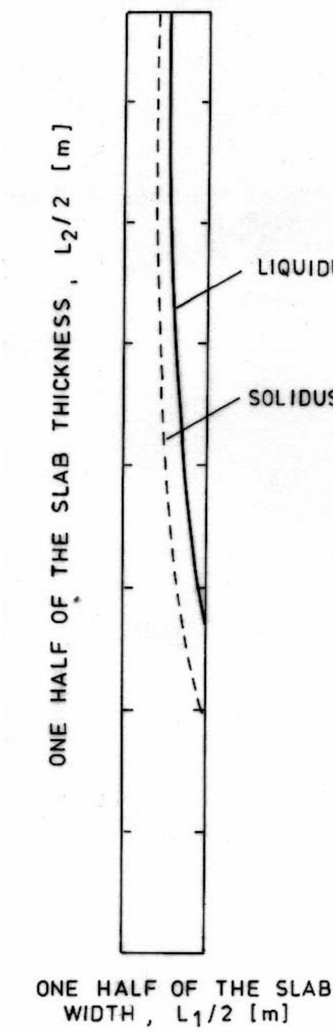


Figure 2 - Solidus and liquidus curve on quarter of the slab cross-section on the end of the crystallizator

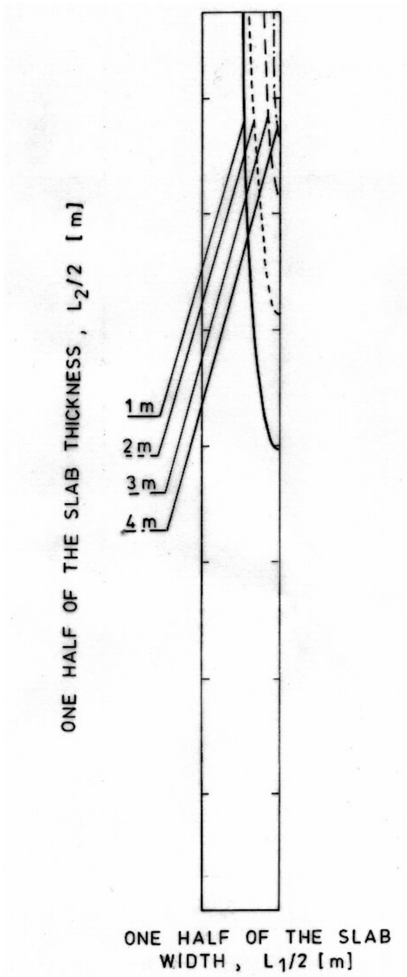


Figure 3 - Liquidus curves shown toge together of the slab cross-section (1÷4 m)

With the isothermal method was determined the liquid phase length, which reaches to 11,65, as well as the values of the shell thickness on the wider and tighter slab side. The values of the shell thickness obtained with the isothermal method and with the numerical method (based on directly measured temperatures during the slab solidification) were compared. These values were given parallel in Table I.

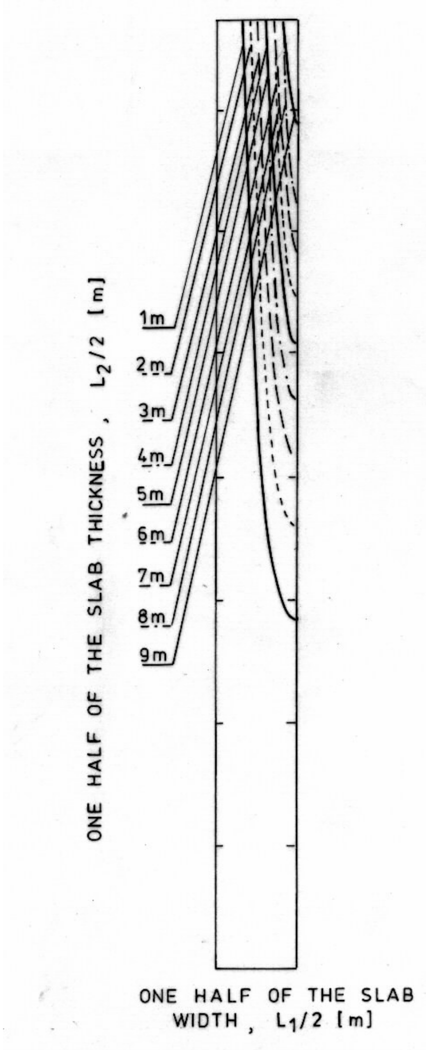


Figure 4 - Solidus curves shown together on quarter of the slab cross-section (1÷9 m)

Depending from the parameters of the casting and solidification process, the shell thickness on the tighter slab's side on the end of the crystallizator was ranged from 23 to 37 mm, experimentally measured was 32 mm, calculated with the numerical method was 34 mm and calculated with the isothermal method - 39 mm [1,6,7]. The shell thickness estimated by the isothermal method deviates from the shell thickness obtained by the other methods, especially on the wider slab side and on the slab beginning. Figure 5 illustrates the graphical comparison of the shell thickness obtained with the numerical (curve 1) and with the isothermal method (curve 2).

Table I. Shell thickness obtained with the isothermal and the numerical method

Slab length [m]	Shell thickness [m]			
	tighter slab side		wider slab side	
	numerical	analitical	numerical	analitical
"mirror"	0	0	0	0
1	0,034	0,039	0,044	0,078
2	0,057	0,063	0,132	0,149
3	0,070	0,072	0,232	0,246
4	0,079	0,078	0,329	0,334
5	0,084	0,084	0,396	0,412
6	0,094	0,089	0,461	0,458
7	0,103	0,099	0,513	0,523
8	0,111	0,102	0,571	0,578
9	0,116	0,109	0,639	0,643
10	0,120	0,116	0,702	0,699
11	0,123	0,122	0,741	0,731
11,65	0,125	125	0,775	0,775

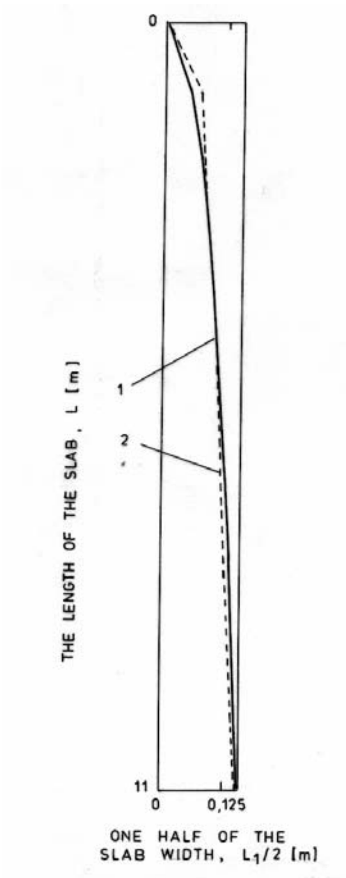


Figure 5 - Shell thickness on the tighter slab side obtained with the numerical (curve 1) and the isothermal method (curve 2)

In the mathematical modeling of solidification steel slab using the numerical method physical essence of the solidification process is expressed through the thermophysical parameters and through the steel casting parameters which are inputted in the mathematical model [2]. In the isothermal method the parameters C_1 and C_2 have that role. Even slight variation of the value of the parameter C_2 influences on the shape of the isotherms a lot. In fact, the successfulness of the application of the isothermal method can be increased with:

- Entering various values for the parameters C_1 and C_2 for the tighter and for the wider slab side in the mathematical model. In that case, the entire three-dimensional show of the solidus and the liuidus and the two-phase region would be obtained with sum of separated calculations for the shell thickness for both slab sides.

- Adapting the values of the parameter C_1 and C_2 to known (previously estimated) values for the shell thickness.

CONCLUSION

In this paper the temperature field in the solidification area of the continuous steel casting using the isothermal method was determined.

With the application of this method were estimated the shape of the isosolidus and isoliquidus areas on the longitudinal slab sections, the liquid phase length, the shell thickness on the tighter and on the wider slab side, as well as the liquidus, solidus and two-phase region on the slab cross-sections.

The significant advantage of the isothermal method compared with the other methods are it's graphical possibilities. With merging the solidus and liquidus curves on every slab cross-section a three-dimensional representation of these areas during the slab solidification can be obtained.

The obtained knowledge can be applied in future research directed at understanding the complex mechanisms for temperature defects and also for improving the slabs quality and for enlarging the quantity of the continuous steel casting process.

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