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METHOD OF DETERMINING AN EFFICIENT RATE FOR THE SECONDARY COOLING OF A CONTINUOUS-CAST SLAB

A. B. Biryukov[1] and A. A. Ivanova[2]

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This article examines the problem of efficiently determining heat transfer in the secondary cooling zone (SCZ) of a continuous caster. An analytical method is developed to solve this problem. The method is based on the notion that it is necessary for the cooling rate on each longitudinal section of the SCZ to be equal to the sum of the amount of heat released at the solidification front and heat flux corresponding to the prescribed rate of cooling of the metal that has already solidified. The accuracy of the proposed method is checked by using an adapted mathematical model of continuous steel casting that is based on a differential equation which describes nonsteady heat conduction. Results which are presented from numerical experiments show that the temperature field of the solidified part of the ingot, which conforms to the cooling rate established by using the proposed method, is characterized by a uniform decrease in temperature through the entire thickness of the ingot.

Keywords: *continuous casting, secondary cooling, temperature field of an ingot, heat-transfer coefficient, mathematical modeling.*

The use of mathematical modeling methods is playing an increasingly important role in the continuous casting of steel to determine efficient parameters for the temperature-time regimes, predict the parameters of the semifinished product under a wide range of conditions, and solve optimization problems. Despite the wide range of possibilities that mathematical modeling offers for studying the thermal processes which take place during the solidification and cooling of continuous-cast semifinished products, there is still a substantial number of problems that have yet to be resolved in this area.

Determination of the temperature field that will exist for an arbitrarily chosen cooling rate is one such problem, and it has been successfully resolved to a significant extent [1–3]. At the same time, no final resolution has yet been found to the problem of determining the best variant for cooling.

Several different approaches are being taken to improving the cooling system of continuous casters. The first approach employs the method of sorting. Several sets of initial data are specified, these sets being large enough to cover the entire range of possible cooling-parameter combinations. A mathematical model is then used to perform numerical experiments with the sets of values. The resulting characteristics of the temperature field are compared to each other on the basis of selected optimality criteria. The best solution is chosen and the initial data with which that solution was obtained is deemed to be the optimum set of cooling parameters.

[1] Donetsk National Technical University, Donetsk, Ukraine; e-mail: birukov.ttf@gmail.com.
[2] Institute of Applied Mathematics and Mechanics, Ukrainian National Academy of Sciences, Donetsk, Ukraine; e-mail: anna.ivanova@ukr.net.

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A second approach to solving the problem of improving the cooling system of continuous casters is the use of simplified analytic methods. For example, in [4] the problem of optimizing the cooling system of a continuous slab caster was solved by a grapho-analytical method. The essence of the solution was determining the cooling rate at which the decrease in temperature would be the same on the surface of the semifinished product and at the solidification front. This method is somewhat difficult to use for automated determination of efficient secondary-cooling parameters under different casting conditions.

A third variant for optimizing cooling entails the examination of inverse problems: the required characteristics of the temperature field are used as the initial data and the distribution of cooling rate is the quantity that is determined. Solving problems formulated in this manner can be a tedious undertaking from both a mathematical and an algorithmic standpoint. There is little information in the literature on the successful use of this approach to solve specific problems of the type being discussed. One example is [5], where the requirement of achieving the same rate of decrease in temperature on the surface of the semifinished product and at the solidification front was satisfied through the use of a suitable mathematical model. Another example of using the theory of inverse problems is determination of the optimum parameters for a series of nozzles over the cross section of a slab by solving an isoperimetric problem [6].

An effective analytical method was developed in [7] to determine the distribution of cooling rate along the secondary cooling zone (SCZ) of a continuous section caster in which the heat flux removed from the surface of the semifinished product in each section of the SCZ is equal to the sum of the heat given off at the solidification front and the heat flux that corresponds to the cooling of the solidified metal at a prescribed rate. The indices obtained by this approach for the temperature field of the cast section as it being formed were checked with the use of an adapted mathematical model. The same rate of decrease in temperature was realized through the thickness of the semifinished product.

The goal of the present investigation is to create an analytical method of finding the distribution of cooling rate along the SCZ of a continuous slab caster that is efficient from the standpoint of allowing the creation of a uniform temperature field and equalizing the cooling rate through the thickness of the slab's solidified skin.

Creating the analytical method. According to [4], to create a uniform temperature field and equalize cooling rate through the thickness of a slab's solid skin it is necessary that the heat flux removed from the surface of the slab's cross section at each moment of time be equal to the sum of the heat flux at the solidification front and the heat flux corresponding to the prescribed rate of cooling of the metal that has already solidified.

Proceeding on this basis, the heat flux which must be removed from the surface of the slab depends on time in the following manner:

$$q(\tau) = \frac{k_{\mathrm{w}}}{b\sqrt{\tau}}\left(b - 2k_{\mathrm{n}}\sqrt{\tau}\right)\rho_{\mathrm{lm}} q_{\mathrm{cr}} + \rho_{\mathrm{sm}} c_{\mathrm{m}} \Delta t k_{\mathrm{w}} \sqrt{\tau}, \tag{1}$$

where k_{w} and k_{n} respectively are the solidification coefficients for the wide and narrow faces of the slab, m·sec$^{-1/2}$; b is the width of the slab, m; q_{cr} is the heat of crystallization of the steel, J/kg; ρ_{lm} and ρ_{sm} are the densities of the liquid metal and solid metal, respectively, kg/m^3; c_{m} is the average specific heat capacity of the solid metal, J/(kg·K); and Δt is the prescribed rate of decrease in the weighted-mean temperature of the metal in the SCZ, °C/sec.

We will illustrate the use of the proposed method for the following initial data: b = 1200 mm; q_{cr} = 260 kJ/kg; ρ_{lm} = 6800 kg/m^3; ρ_{sm} = 7600 kg/m^3; c_{m} = 680 J/(kg·K); casting speed v = 1 m/min. Here, k_{w} = 2.4 cm·min$^{-1/2}$ and k_{n} = 2.2 cm·min$^{-1/2}$ were taken as the solidification coefficients for the wide and narrow faces of the slab based on well-known empirical data. The rate of decrease in the weighted-mean temperature of the slab was chosen as 0.28°C/sec based on the condition of obtaining a temperature on the order of 900°C at the end of the SCZ (the coordinate located 20 m from the meniscus when reckoned along the longitudinal axis of the slab).

In the general case, the metal's solidification coefficient k depends on the rate of cooling of the solid metal Δt. This relationship is not accounted for mathematically in the model we are proposing; judging from practical experience, it should be reflected in the values assigned to k and Δt in the initial data,

Figure 1 shows the change in the heat flux removed from the surface of the slab according to Eq. (1).

The descending character of curve *2* is due to the fact that the linear rate of advance of the solidification front changes over time in accordance with a quadratic law. Here, the weight of the solidified metal increases over time, so that the

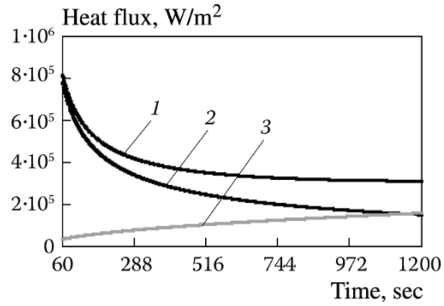

Fig. 1. Use of the proposed method to determine the change in the rate of heat transfer from the surface of a semifinished slab over time: *1*) total heat flux that needs to be removed to achieve equilibrium cooling through the thickness of the solid skin; *2*) heat-flux component corresponding to heat release at the solidification front; *3*) heat-flux component corresponding to cooling of the solid skin at a prescribed rate.

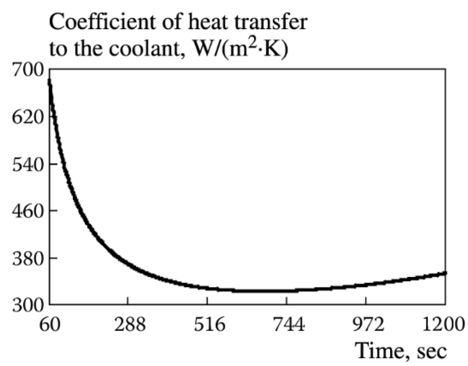

Fig. 2. Use of the proposed method to find an efficient value for the change in the coefficients of heat transfer from the surface of the slab to the coolant in the SCZ.

heat-flux component *3* associated with the cooling of the solid skin at a prescribed rate should also increase. We thus obtain cumulative curve *1*, which descends over time. The curve's rate of descent slows appreciably on the final sections of the SCZ.

In accordance with the above-mentioned time dependences of the heat fluxes, the change in the heat-transfer coefficients over time is determined with the use of the Newton–Richmann law (Fig. 2).

Here, we assumed the existence of a linear law of temperature distribution through the thickness of the semifinished product. That made it possible to assume that the rate of the change in temperature on the surface of the slab is the same as the rate of change in the weighted-mean temperature. A value on the order of 1200°C was chosen for the temperature on the surface of the slab at the moment it leaves the mold.

To validate the adequacy of the analytical method proposed here, the heat-transfer coefficients obtained by this method were used as the initial data in an adapted mathematical model of the solidification and cooling of a continuous-cast semifinished product. The model is deemed to be adequate if numerical experiments performed using the heat-transfer coefficients obtained by the analytical method yield results (the metal solidification coefficient k and the rate of cooling of the solid metal Δt) that are equal or close to the values used as the initial data to determine the heat-transfer coefficients.

Mathematical model of the temperature field of the ingot in a continuous slab caster. The mathematical model chosen to describe the temperature field of a continuous-cast slab is based on a continuous caster at the Azovstal plant. This model is described in greater detail in [8].

The coordinate system is linked to the continuous caster. The origin of the system is at the level of the meniscus. For the sake of simplification, we assumed that the thermophysical characteristics of the metal inside one of the phases (the liquid phase or solid phase) are constant (are independent of temperature). Given this assumption, the equation that describes convective heat transfer in the ingot appears as follows:

$$\frac{\partial T}{\partial \tau} + v(\tau)\frac{\partial T}{\partial z} = \frac{\lambda}{c\rho}\left\{\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right\}, \tag{2}$$

where τ is time; $T = T(\tau, x, y, z)$ is temperature; $v(\tau)$ is the velocity of the ingot; c is specific heat capacity; ρ is density; and λ is the thermal conductivity of the metal.

The boundary conditions assigned for the part of the ingot inside the mold correspond to the character of heat transfer during casting under a slag when a gap filled partly with slag crust and partly with gas is located between the surface of the ingot and the wall of the mold. The appropriate initial and boundary conditions were assigned for all the differential equations.

The position of the unknown interface $x = \xi(z)$ is determined based on the condition of temperature equality and the Stefan condition:

$$T(x, z)\big|_{\xi_+} = T(x, z)\big|_{\xi_-} = T_{\mathrm{cr}}, \tag{3}$$

$$\lambda(T)\frac{\partial T}{\partial \bar{n}}\bigg|_{\xi_-} - \lambda(T)\frac{\partial T}{\partial \bar{n}}\bigg|_{\xi_+} = \mu\rho_{\mathrm{cr}}\left(v(\tau)\frac{\partial \xi}{\partial z} + \frac{\partial \xi}{\partial \tau}\right), \tag{4}$$

where $\bar{n}$ is a normal to the interface; T_{cr} is the crystallization temperature (the average from the liquidus-solidus interval); μ is the latent heat of crystallization; ρ_{cr} is density at the crystallization temperature; and ξ is the phase boundary.

The boundary conditions in the SCZ have the form:

$$-\lambda\frac{\partial T}{\partial x}\bigg|_{x=l} = \alpha(\tau, z)\left(T_A - T\big|_{x=l}\right), \tag{5}$$

where $\alpha(\tau, z)$ is the heat-transfer coefficient on the surface of the ingot; T_A is the ambient temperature in the SCZ; l is half the thickness of the ingot; and $x = l$ represents points on the surface of the ingot. Initial conditions are assigned for the temperature field and the positions of the phase boundaries. The resulting boundary-value problem is solved by the finite-differences method. The position of the phase boundary is determined by the method described in [9].

As $\alpha(\tau, z)$, we use the distribution of cooling rate determined by means of the proposed analytical method over the length of the SCZ (see Fig. 2). Here, the transition from time to the coordinates of a chosen moving cross section is made by multiplying time by the casting speed.

The following was used for the base calculations: slab thickness 0.2 m; rate of ingot withdrawal 1 m/min; the thermodynamic parameters of steel 40Kh; temperature of the incoming melt 1550°C. The chemical composition of steel 40Kh (GOST 4543–71) is as follows, wt. %: C 0.36–0.44; Si 0.17–0.37; Mn 0.5–0.8; Ni to 0.3; S to 0.035; P to 0.035; Cr 0.8–1.1; Cu to 0.3.

An analysis of temperature in the longitudinal section of the slab passing through the middle of the wide faces (Fig. 3) showed that the average rate of cooling of the solidified metal during the time (1140 sec) that it passed through a specified length of the SCZ was 0.26°C/sec. The solidification coefficient was 2.4 cm·min$^{-1/2}$. It is apparent from an analysis of the top curve in Fig. 3 that the middle of the semifinished product solidified at the 17-m mark, i.e., after 17 min. This finding was subsequently used to determine the solidification coefficient. In addition, the temperature curves through the thickness of the semifinished product are straight lines inclined at the same angle, which indicates that the cooling rate was the same through

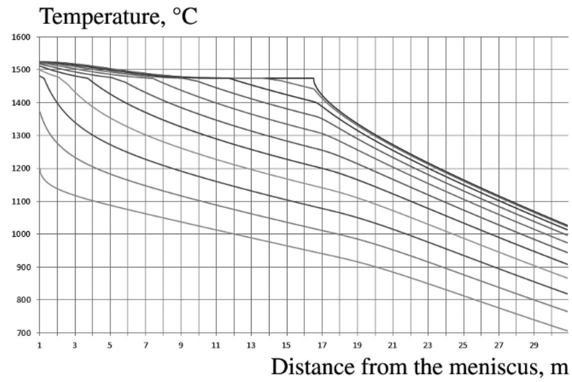

Fig. 3. Change in temperature with the heat-transfer coefficient determined from Eq. (1); top line – temperature on the axis; bottom line – temperature on the surface; intervening lines – temperature between the surface and the axis every 1 cm.

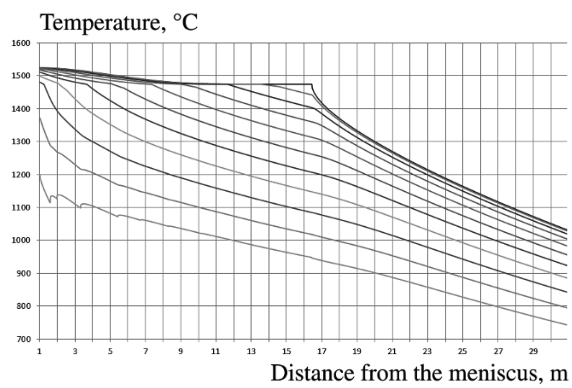

Fig. 4. Temperature distribution with a piecewise-constant heat-transfer coefficient; top line – temperature on the axis; bottom line – temperature on the surface; intervening lines – temperature between the axis and the surface every 1 cm.

the entire thickness of the slab solidified skin. A check of the proposed analytical method with the use of an adapted mathematical model demonstrated the adequacy of the method.

Since a continuous change in the heat-transfer coefficient along the different sectors of the SCZ (see Fig. 2) is not possible under production conditions, efficient choices for the values of these coefficients and, thus, the type of nozzle and water flow rate in each sector should be made by averaging the data shown in Fig. 2. We were able to obtain specific information (Fig. 4) by following the procedure for the given initial data and assigning the boundary conditions in the adapted mathematical model based on the distribution obtained for cooling rate in the SCZ.

Conclusions. An analytical method has been developed to find an efficient distribution for the rate of secondary cooling of a continuous-cast slab. The method is based on having the heat flux removed from the surface of the semifinished product in each section of the SCZ be equal to the sum of the heat given off at the solidification front and the heat flux that corresponds to the cooling of the solidified metal at a prescribed rate.

Checking of the proposed method by means of an adapted mathematical model of continuous steel casting demonstrated the method's adequacy and showed that the temperature field of the slabs obtained by using the cooling system recommended here is characterized by a uniform decrease in temperature through the thickness of the ingot.

REFERENCES

1. V. A. Emel'yanov, *Thermal Performance of Continuous-Casting Machines: Textbook*, Metallurgiya, Moscow (1988).
2. A. N. Smirnov, S. V. Kuberskii, and E. V. Shtepan, *Continuous Casting of Steel: Textbok*, DonNTU, Donetsk (2011).
3. A. B. Biryukov, *Improving the Heat-Engineering Parameters of Continuous Casters and Their Thermal Performance*, Knowledge, Donetsk (2013).
4. V. S. Rutes, V. I. Askol'dov, D. P. Evteev, et al., *Theory of Continuous Casting*, Metallurgiya, Moscow (1971).
5. V. I. Sheludchenko, V. V. Kravtsov, and A. B. Biryukov, "Optimization of secondary cooling regimes on continuous casters," *Proc. 10th Anniv. Int. Conf. Conserving Resources in a Market Economy*, NDTs Navtokhim, Kiev (2003), pp. 50–51.
6. A. A. Ivanova, V. A. Kapitanov, and A. V. Kuklev, "Method of calculating the optimum parameters for the air-mist cooling of a continuous-cast slab," *Metallurg*, No. 3, 45–49 (2012).
7. A. B. Biryukov, V. V. Kravtsov, I. P. Oleksyuk, and N. A. Ostapenko, "Effective control of the secondary cooling zone of high-speed continuous section casters," *Metall i Lit'e Ukrainy*, No. 7, 21–23 (2010).
8. A. A. Ivanova, "3D mathematical model of the temperature field of a continuous-cast ingot," *Tr. IPMM NAN Ukrainy*, **23**, 100–109 (2011).
9. A. A. Ivanova, "Calculation of phase-change boundary position in continuous casting," *Arch. Foundry Eng.*, **13**, No. 4, 57–62 (2013).