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Temperature Differences in the Mold of a Continuous-Casting Machine with a New Cooling System

V. V. Stulov
Bauman Moscow State Technical University, Moscow, Russia
e-mail: stuvv@inbox.ru
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Abstract—Attention focuses on the processes in the mold of a continuous-casting machine when using a patented new cooling system. In particular, the temperature differences in the steel billet and in the wall over the mold height are of interest in modeling the casting processes, because those differences affect the quality of the billet produced. A literature review covers research on the slag-forming mixture, which affects the heat flux from the billet to the mold. Non-Russian authors highlight mild cooling of the mold in selecting the slag-forming mixture. Improvement of billet cooling in the mold permits improvement in the surface quality of the slab, extension of mold life, and increase in productivity. According to numerous authors, that may be accomplished by mathematical modeling of the process. The mold cooling depends directly on the convective motion of liquid steel in the mold, a topic addressed by many non-Russian authors. Researchers have considered systems in which the heat pipes in the cooling system of the mold are based on porous material, with water and air as the working fluid, and those in which liquid droplets on nanostructured superhydrophilic surfaces are evaporated. Mold cooling at steel casting rates higher than 7 m/min, accompanied by increase in the heat-flux density, is of great importance, as reflected by the number of studies published. The relations between the basic process parameters are determined by means of Rayleigh dimensionality theory. The basic parameter selected is the temperature difference in the metal mold wall, which depends on the casting rate (the time that the billet is in the mold), the properties of the steel (specific heat, thermal diffusivity), the thermal conductivity of the mold wall, and the temperature difference in the cast steel. In determining the exponents in the dimensionless relations, the available experimental data regarding the dependence of the heat-flux density on the casting rate and the parameter of the steel are taken into account. On the basis of the ratio $\Delta t_{me}/t_{me}$ obtained (where Δt_{me} is the mean temperature difference over the wall thickness and t_{me} is the mean wall temperature) for molds with the existing and new (patented) cooling systems, the temperature difference in the steel billet may be determined. For the two cooling systems compared, Δt_{me1} = 450°C and Δt_{me2} = 231°C. Consequently, $\Delta t_{me1}/\Delta t_{me2}$ = 1.95. The smaller temperature difference Δt_{me2} indicates milder cooling of the mold with the new cooling system.

Keywords: modeling, mold, continuous-casting machine, cooling systems, steel casting, casting rate, wall thickness

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It is important to study the formation of continuous-cast billet in the mold of the casting machine in order to increase the productivity (the casting rate), expand the range of steels cast, and improve their quality [1].

Physical modeling of continuous casting expands the scope for mathematical modeling to predict billet quality [1].

Existing research on billet formation in the mold addresses a wide range of topics: the hydrodynamics of the melt; the properties and behavior of the slag-forming mixture; heat transfer; billet solidification; and cooling of the steel and the walls of the mold [2–12].

Cooling of the metal in continuous casting and heat transfer in the mold—in particular, at casting rates above 7 m/min—were considered in [2, 3].

Mathematical modeling of steel casting on continuous slab-casting machines permits prediction of the billet quality, as is evident from [13]. Improvement in billet cooling in the mold improves the surface quality of the slab, extends mold life, and increases productivity, as noted in [13]. The billet hardening in a slab machine may be analyzed on the basis of the mathematical model and computer program developed in [13]. On that basis, the linear shrinkage of the billet over the mold height may be monitored.

The influence of the slag-forming mixture on the thermophysical parameters in billet solidification was investigated in [5, 6, 14].

One of the main reasons for longitudinal cracks at the surface of continuous-cast billet is nonuniform hardening in the mold, as noted in [5, 6]. To prevent such cracks, it is important to ensure mild cooling of the solidifying crust at the meniscus over a section measuring tens of mm. This may be accomplished by selection of the slag-forming mixture, according to [5, 6]. Means of ensuring high surface quality of the continuous-cast billet formed in the mold in the presence of slag-forming mixture were considered in [14]. It was found that solidification of the crust on a continuous-cast billet depends greatly on the grade of steel being cast. Therefore, for different steels, slag-forming mixtures with different properties (in particular, different viscosity, initial hardening temperature, and degree of slag solidification) must be chosen.

In recent years, optimization of the liquid steel flux in the mold has taken on great importance in continuous casting. Very useful modeling results were presented in [7–10].

In this context, modeling of the cooling of mold walls by means of heat pipes [15] is of great interest [11, 12].

Numerical results regarding the influence of the thermal conductivity of porous material on the heat transfer in the pipe were presented in [11]. The working media employed were air and water. The porosity of the material was 90%, and the effective thermal conductivity was 0.1–200 W/(m K). The modeling results show the relation between the Reynolds number and Nusselt number of the medium and the effective thermal conductivity, as well as their influence on the heat transfer.

Experimental data for the Leidenfrost temperature of droplets evaporating on nanostructured superhydrophilic surfaces were obtained in [12]. The nanostructure has great influence on the Leidenfrost point; specifically, it rises.

Physical modeling of the solidification of model materials with cooling by heat pipes was undertaken in [16–19]. The solidification parameters were presented for the casting of steel billet.

One of the main reasons for longitudinal cracks at the surface of continuous-cast billet is nonuniform hardening in the mold, as noted in [20]. In steels with 0.08–0.016% C, peritectic reactions are involved in shrinkage of the solidifying crust and the formation of longitudinal cracks. To prevent such cracks, mild cooling of the solidifying crust is important.

In the present work, we determine the parameters of steel casting in the mold, for the case of replacement of the wall material, change in the temperature difference in the steel, and a modified cooling system [21].

The goal is to improve the casting conditions of steel with low carbon content (0.08–0.15% C) in the mold: in particular, to prevent cracking in mild (slow) cooling of the solidifying crust (thickness no more than 1 mm) in a section of length a few tens of mm at the meniscus. This may be accomplished by changing the mold design and the cooling system.

The following steels are among those with low carbon content: 12XH (0.09–0.15% C), 15X5 (0.15% C), 12X8BΦ (0.08–0.15% C), P6M5 (0.82–0.90% C); and P9 (0.85–0.95% C).

The existing method of mold cooling includes the supply of cold water (30°C or less) to the cooling channels of the walls or the slot gap [15]. In the new method, the mold has a two-loop cooling system; water at 150–180°C circulating in the first cooling loop is supplied to the slot gap of the mold [21]. That permits more effective mild cooling of the walls [22].

In Fig. 1, we show the cooling systems of a cylindrical mold *1* heated by water circulating through slot channel *2* under the action of pump *5* and cooled in heat exchanger *6* [21]. Before casting the steel in mold *1*, heater *17* is turned on. That heats the water in slot gap *2* and also the walls of the mold to the specified temperature. Then heater *17* is turned off. At the same time, pump *5*, which circulates the hot water, is turned on; the liquid metal is poured in the mold; and the supply of cold water to heat exchanger *6* through pipe *11* is turned on. The temperature of the water entering and leaving the mold is recorded by thermocouples *13* and *14*, respectively, which are connected to the automatic control system.

A nickel mold (height $H = 0.5$ m, wall thickness $\delta_w = 0.005$ m) was described in [22]; the wall temperature was calculated for cylindrical billet of diameter $d = 0.15$ m. The temperature of the wall's working surface $t_1 = 297$–303°C when the temperature of the wall's internal surface $t_2 = 198$–204°C and the mean heat-flux density $q = 1.5$ MW/m^2.

The relatively large number of parameters affecting billet formation in the mold requires the adoption of the most important and convenient variables.

The process variables are determined on the basis of Rayleigh dimensionality theory [16, 23].

We undertake dimensional analysis for the example of the temperature difference in the mold wall.

The temperature difference Δt_w (K) in the mold wall depends on the thermal diffusivity of the steel a_m (m^2/s); the specific heat C_m of the metal (J/(kg K)); the latent heat of phase transition r_m (J/kg); the billet's residence time in the mold τ_m (s); the wall height H_w (m); the temperature difference in the steel billet Δt_m (K); and the thermal conductivity of the wall λ_w (J/s m K). As a result, we have $n = 8$ dimensional parameters of the process.

By Rayleigh's algebraic method, we may determine the dimensionless variables on the basis of the expression

$$\Delta t_w = A a_m^{\alpha} \tau_m^{\beta} C_m^{\gamma} r_m^{\delta} H_w^{\varepsilon} \Delta t_m^{\zeta} \lambda_w^{\eta}, \qquad (1)$$

where A is a constant.

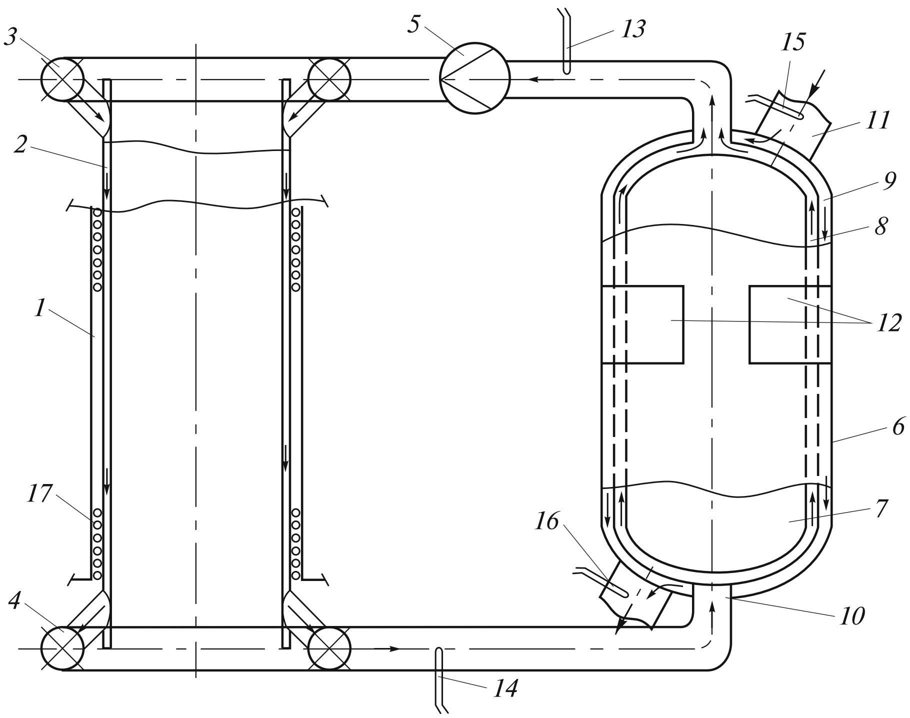

Fig. 1. Cooling system of a cylindrical nickel mold: (*1*) mold; (*2*, *8*, *9*) slot channels; (*3*, *4*) input and output lines for superheated water, respectively; (*5*) water pump; (*6*) heat exchanger; (*7*) hollow body; (*10*, *11*) inputs for superheated and cold water, respectively; (*12*) doors; (*13–16*) thermocouples; (*17*) electric heater.

Rewriting Eq. (1) in terms of the dimensions of the parameters, we obtain

$$K = A\left(\frac{m^2}{s}\right)^{\alpha} s^{\beta}\left(\frac{J}{kg\ K}\right)^{\gamma}\left(\frac{J}{kg}\right)^{\delta} m^{\varepsilon}K^{\zeta}\left(\frac{J}{s\ m\ K}\right)^{\eta}. \quad (2)$$

Summing the exponents for the same basic units, we obtain a system of five equations

$$\text{for K: } 1 = -\beta - \eta + \zeta; \quad (3)$$

$$\text{for J: } 0 = \beta + \delta + \eta; \quad (4)$$

$$\text{for s: } 0 = -\alpha + \beta - \eta; \quad (5)$$

$$\text{for m: } 0 = 2\alpha + \varepsilon - \eta; \quad (6)$$

$$\text{for kg: } 0 = -\beta - \delta. \quad (7)$$

Solution of Eqs. (3)–(7) yields $\zeta = -\delta$; $\eta = 0$; $\alpha = \beta$; $\varepsilon = -2\alpha$; and $\gamma = -\delta$.

Substitution of these results converts Eq. (1) to the form

$$\Delta t_w = A a_m^{\alpha} \tau_m^{\alpha} C_m^{-\delta} r_m^{\delta} H_w^{-2\alpha} \Delta t_m^{-\delta} \lambda_w^{0}. \quad (8)$$

In Eq. (8), we set

$$\left(\frac{a_m \tau_m}{H_w^2}\right)^{\alpha} = \mathrm{Fo}^{\alpha}, \quad \left(\frac{r_m}{C_m \Delta t_m}\right)^{\delta} \mathrm{Ku}^{\delta},$$

where Fo is the Fourier number and Ku is the Kutateladze number.

Substituting Fo and Ku into Eq. (8), we obtain

$$\Delta t_w = A\mathrm{Fo}^{\alpha}\mathrm{Ku}^{\delta}. \quad (9)$$

We now divide the right and left sides of Eq. (9) by A. On the right side, we obtain a dimensionless complex. Then the ratio $\Delta t_w/A$ on the left must also be dimensionless. Setting $A = t_w$, we write Eq. (9) in the form

$$\frac{\Delta t_w}{t_w} = \mathrm{Fo}^{\alpha}\mathrm{Ku}^{\delta}, \quad (10)$$

where t_w is the mean wall temperature of the mold.

For comparison, $A = -1/H$ in [16].

The ratio $\Delta t_w/t_w$ depends on the cooling system and the material used for the mold walls [15, 21, 22, 24]. For the existing mold cooling system, with $\Delta t_w \leq 50$ and $t_w \leq 250$°C, we find that $\Delta t_w/t_w \leq 0.2$ [24].

For the new wall-cooling system, with coolant temperature $t_{co} > 100$°C, $\lambda_w \leq 70$ W/(m K), $\Delta t_w \geq 100$, and $t_w \geq 250$°C, we find that $\Delta t_w/t_w \geq 0.4$ [21, 22].

We now determine the exponents α and δ for Fo and Ku when the steel parameters are as follows [24]:

$$a_m = 0.5 \times 10^{-5}\ \mathrm{m^2/s},\ r_m = 287 \times 10^3\ \mathrm{J/kg},$$
$$C_m = 622\ \mathrm{J/(kg\ K)}.$$

If $H_w = 1.2$ m and the casting rate $v = 1.2$ m/min, then $\tau = H/v = 72$ s and Fo = 25.

When $q = 1.3$–1.5 MW/m^2, for the existing cooling system (with $\Delta t_w/t_w \leq 0.2$), we substitute the initial data into Eq. (10), with $\Delta t_{m1} = 450°C$ [24]. We find that $\alpha = -0.5$ and $\delta = 1$. Then Eq. (10) takes the following form

$$\frac{\Delta t_w}{t_w} = -Fo^{-0.5}Ku. \quad (11)$$

After substituting the initial data into Eq. (11), we obtain $\Delta t_{m2} = 231°C$ for the new cooling system (with $\Delta t_w/t_w \geq 0.4$) [21, 22]. The ratio $\Delta t_{m1}/\Delta t_{m2}$ is 1.95.

The new cooling system is not intended primarily to increase the casting rate of the steel (alloys) with low carbon content (0.08–0.15% C) but rather to expand the range of steel that may be produced by continuous casting. Therefore, higher casting rates ($v > 1.2$ m/min) have not yet been considered.

CONCLUSIONS

When the heat-flux density in the mold is no more than 1.3–1.5 MW/m^2, we obtain an expression in terms of dimensionless variables that include the main process parameters. On the basis of that expression, we may determine the temperature difference in the metal when modeling the casting of steel with low carbon content (0.08–0.15% C). The quality of the billet produced depends on that temperature difference.

The ratio of the mean temperatures t_{me1} of the metal for nickel molds with the existing cooling system (with coolant temperature 30°C or less) and t_{me2} for the new cooling system (with coolant above 100°C) is 1.95.

The results of mathematical modeling may be used in casting steel in models of molds with the existing and new cooling systems.

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