A model of automated mold flux feeding into the crystallizer of a continuous casting machine

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This paper describes a model of automatic mold flux (MF) feeding into the crystallizer of a continuous casting machine (CCM). The MF is used to protect metal from secondary oxidation, to lubricate the billet crust and the mold wall, and to fulfill some other functions. Most Russian steel plants use imported MF due to their higher quality and the use of imported CCMs. The effective consumption of MF is essential due to its high cost. Obtaining preliminary data from the model with the introduction of new equipment and expanding the range of steel in steel making shops is an urgent task. Therefore, a model of automated MF feeding has been developed, which can be modified by changing casting parameters. A detailed description of the model developed in Matlab Simulink software is provided. The distinctive features of the model include the relationships between the metal and slag temperature difference, slag layer thickness, and screw feeder flow rate. Mathematical expressions for these relationships are derived and a description of the structural automation diagram and the functional diagram of the model is presented. Model-based equipment settings (electric drive parameters and sensor parameters) and the introduction of the proposed control algorithm reduces flux consumption by up to 13 % while reducing the manufacturing costs of the final product by up to 6 %.

Key words: mold flux, modeling, continuous casting machine, temperature, electric drive, steel, slag.
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Introduction

Continuous casting machines (CCM) are among the main equipment used in steel casting [1–5]. In order to create a layer of slag to prevent the contact of the metal with the air, a mold flux (MF) is applied to the surface of the molten metal [6–8]. The flux assimilates non-metallic inclusions, lubricates the crystallizer walls, and protects against oxidation and metal losses in the tundish ladle and the crystallizer [9, 10]. A three-component system of CaO-SiO_2-Al_2O_3 forms the basis of almost all known MFs [6].

In order to ensure the required properties, fluxing additives containing CaF_2, Na_2O, K_2O, MgO, MnO, B_2O_3, Li_2O, BaO, free carbon, and carbonates are introduced into the flux [6, 7, 9–11].

Maintaining optimum slag layer thickness is important when feeding the MF. If the layer is too thin, the crystallizer movement will create gaps with bare metal on the walls, and the metal will be oxidized. If the layer is too thick, some of the slag will harden and pieces will enter the billet area. As a result, the sliding resistance of the billet and the level of metal damage will increase [6, 8, 10, 11]. An uneven layer leads to excessive consumption of the MF and extra costs. Therefore, the development of devices and methods for introducing MF to the surface of the melt is an urgent issue [12–17]. None of the presented devices have a preliminary evaluation of the flux flow rate, recommendations for selecting the elements of the automatic system, or improving the efficiency of the system.

This work studies a model of automated MF feeding into the crystallizer of a continuous casting machine to improve the efficiency of the system.

Scientific novelty of the work is the development of:

- a method of evaluating the relationships between the metal and slag temperature difference, screw feeder flow rate, and slag layer thickness for the effective distribution of the MF over the crystallizer;
- a model of automated MF feeding into the CCM crystallizer differing from the well-known ones in that it is controlled by varying the temperature of metal and slag, taking into account the changing flux mass fed from the bunker;
- algorithms for automated MF feeding into the crystallizer of CCM which provide the required accuracy of the unit movement due to the flux flow rate.

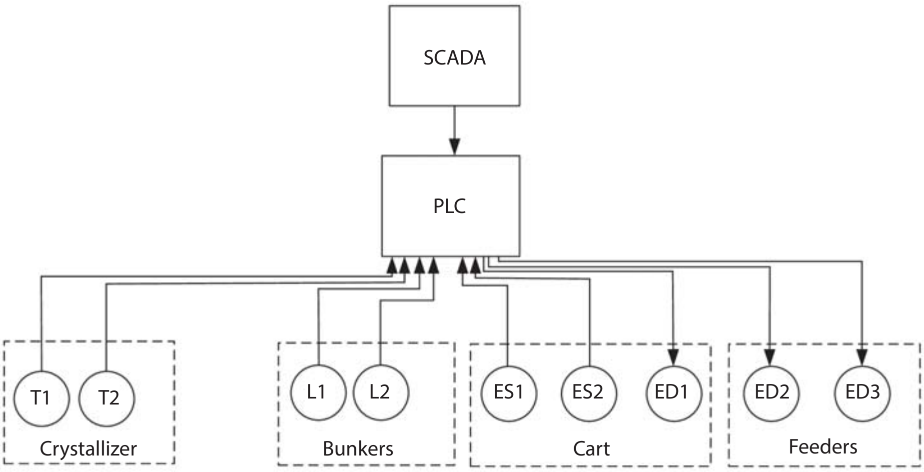

Fig. 1. Block diagram of the automated MF feeding into the crystallizer of the CCM:
T1, T2 are thermocouples to determine the temperature of metal and slag; L1, L2 are level sensors to determine the level of the flux in the bunker; ES1, ES2 are endpoint sensors moving cart; ED1 is the electric drive cart movement; ED2, ED3 are electric drive screw feeders; PLC is the programmable logic controller; SCADA is the system of collection and operational control.

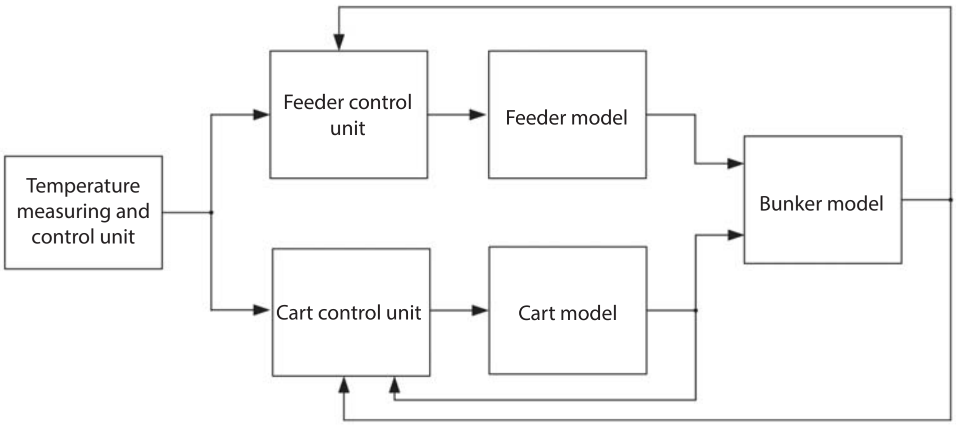

Fig. 2. Functional diagram of the model of the automated mold flux feeding into the crystallizer of a continuous casting machine

Automated mould flux feeding into the crystallizer of a continuous casting machine

Fig. 1 shows the block diagram of the automated MF feeding into the crystallizer of a continuous casting machine.

Slag layer thickness directly depends on the temperature difference between the slag and the metal [18], measured with thermocouples T1 and T2. The movement of the cart is controlled by the variable frequency drive (ED1) and end point sensors (ES1 and ES2). The feeding of MF into the crystallizer is performed by the frequency electric drives of the screw feeding unit (ED2 and ED3). The level of MF is controlled by means of level sensors (L1 and L2). The device is described in detail in [13, 19].

Introducing the device at different enterprises, detecting problems in its operation, the need to modernize equipment, and the digitalization of production processes resulted in conducting a preliminary simulation of the MF feeding process into the CCM crystallizer and using the parameters to optimize steel production.

Development of the model

The functional diagram of the model of the automated MF feeding into the crystallizer of continuous casting machine is shown in **Fig. 2**.

The model was developed in Matlab Simulink software (**Fig. 3**).

The signals used in the digital twin are as follows:

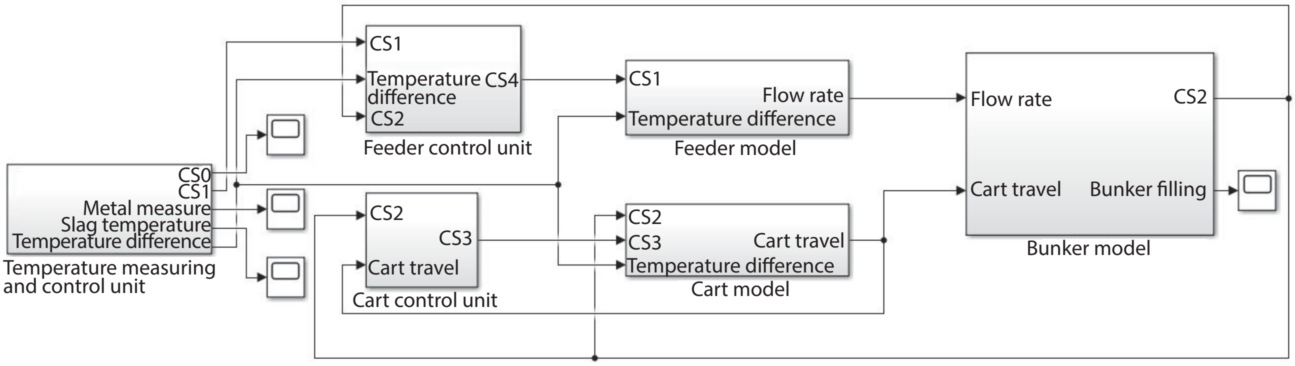

Fig. 3. Model of the automatic mold flux feeding into the crystallizer of a CCM in Matlab Simulink

1. Temperature measurement and control unit:

• CS0 (control signal 0) is an alarm when the temperature difference exceeds the threshold value, True/False or 0 or 1;

• CS1 (control signal 1) is the signal voltage difference between the metal and slag thermocouples, V;

• Metal temperature, °C;

• Slag temperature, °C;

• Temperature differences the temperature difference between the metal and the slag surface, °C.

2. Cart control unit:

• CS2 (control signal 2) is availability of MF in the bunker, True/False or, 0 or 1);

• Cart travel is a current position of the cart on the guide frame (distance from the initial position), m;

• CS3 (control signal 3) is the signal that sets the cart travel, V.

3. Feeder control unit:

• CS1 (control signal 1) is the signal voltage difference between the metal and slag thermocouples, V;

• Temperature difference is the temperature difference between the metal and the slag surface, °C;

• CS2 (control signal 2) is the availability of MF in the bunker, True/False or, 0 or 1;

• CS4 (control signal 4) is a release signal of the feeder operation, True/False or, 0 or 1.

4. Feeder model:

• CS4 (control signal 4) is a release signal of the feeder operation, True/False or, 0 or 1.

• Temperature difference is the temperature difference between the metal and the slag surface, °C;

• Flow rate is the MF flow rate by the feeder, m^3/s.

5. Cart model:

• CS2 (control signal 2) is presence of MF in the bunker, True/False or, 0 or 1;

• CS3 (control signal 3) is the signal that sets the cart travel, V;

• Temperature difference is the temperature difference between the metal and the slag surface, °C;

• Cart travel is the current position of the cart on the guide frame (the distance from the initial position), m;

6. Feeder model:

• Flow rate is the flow rate of MF by the feeder, m^3/s;

• Cart travel is the current position of the cart on the guide frame (distance from the initial position), m;

• CS2 (control signal 2) is availability of MF in the bunker, True/False or, 0 or 1;

• Bunker filling is a share of the filled part from the total volume of the bunker.

The temperature values are recorded in the Temperature Measurement and Control Unit. This unit in the model (Fig. 3) provides the ability to simulate the temperature values of the metal and the slag when specifying the initial values of the flux, the type of steel, and the thermocouples.

The control units of the feeder and the cart are based on logical control systems [13, 18, 20, 21].

The feeder and cart models include subsystems of electric drives for the cart (EP1, Fig. 1) of the feeder (EP2 and EP3, Fig. 1), which is implemented on the basis of the system of equations (1) [19]:

$$\begin{cases} u_{s\alpha} = i_{s\alpha}R_s + \dfrac{d\psi_{s\alpha}}{dt}; \\ u_{s\beta} = i_{s\beta}R_s + \dfrac{d\psi_{s\beta}}{dt}; \\ u_{r\alpha} = i_{r\alpha}R_r + \dfrac{d\psi_{r\alpha}}{dt} + \psi_{r\beta} \cdot w; \\ u_{r\beta} = i_{r\beta}R_r + \dfrac{d\psi_{r\beta}}{dt} + \psi_{r\alpha} \cdot w; \\ \psi_{s\alpha} = L_s i_{s\alpha} + L_m i_{r\alpha}; \\ \psi_{s\beta} = L_s i_{s\beta} + L_m i_{r\beta}; \\ \psi_{r\alpha} = L_r i_{r\alpha} + L_m i_{s\alpha}; \\ \psi_{r\beta} = L_r i_{r\beta} + L_m i_{s\beta}; \\ M = \dfrac{3L_m}{2L_r} \cdot \rho \cdot (\psi_{r\alpha} i_{s\beta} - \psi_{r\beta} i_{s\alpha}); \\ \dfrac{dw}{dt} = \dfrac{M - M_C}{J}; \end{cases} \quad (1)$$

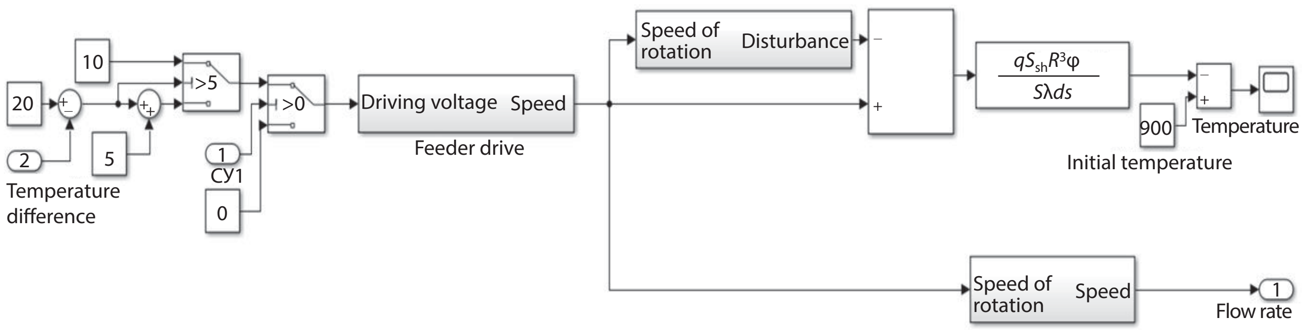

Fig. 4. Mathematical model of the feeder

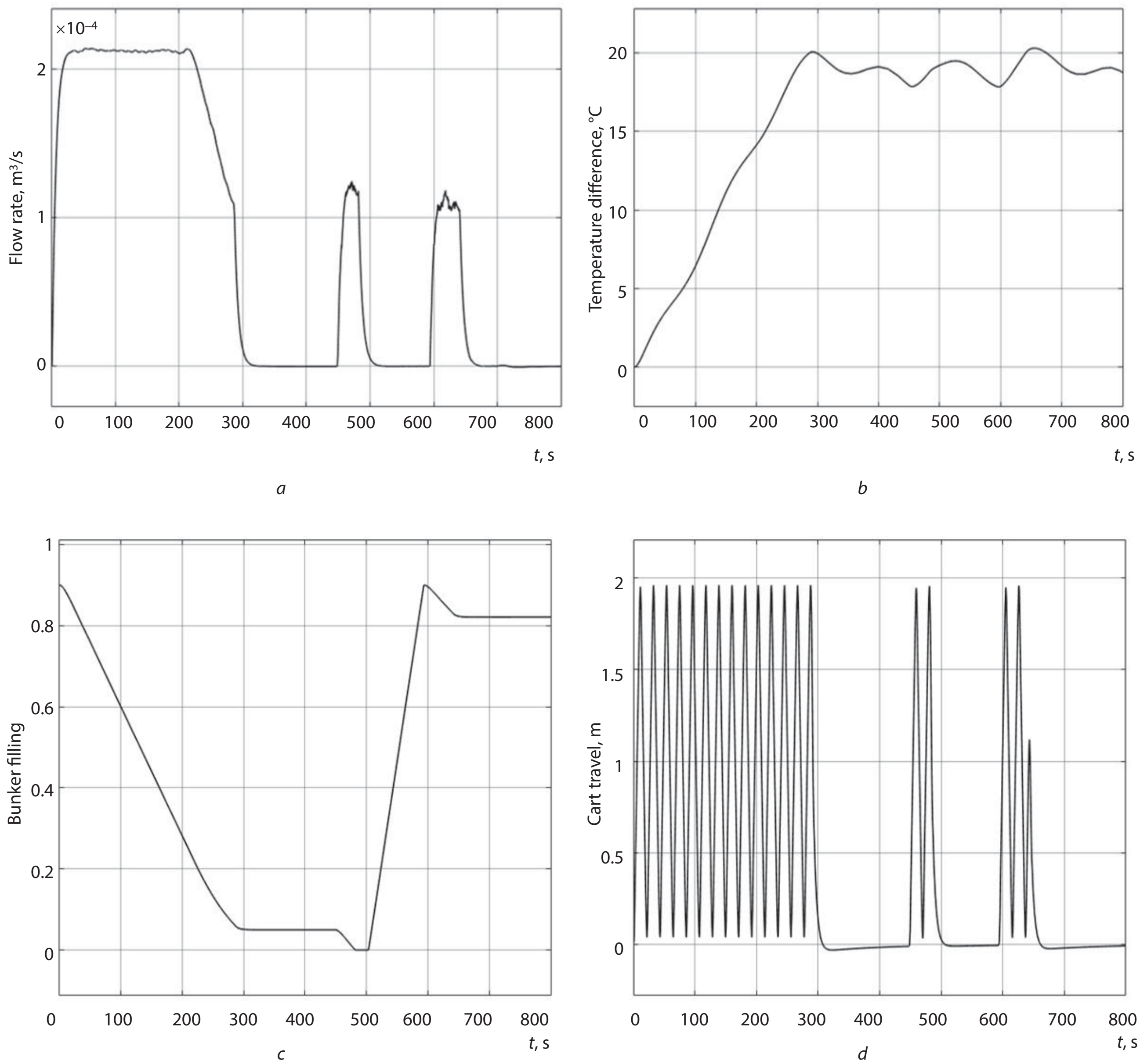

Fig. 5. Transient processes of the model:
a) MF flow rate; *b*) temperature differences; *c*) bunker filling; *d*) cart travel

where $u_{s\alpha}$, $u_{s\beta}$, $i_{s\alpha}$, $i_{s\beta}$, $\psi_{s\alpha}$, $\psi_{s\beta}$, are the voltage, current, and magnetic linkage values of the stator (s) and the rotor (r) in the fixed axes α, β; R_r is rotor resistance, Ohm; L_m is the main coefficient of inductance of an induction motor (magnetization inductance), Ohm; L_s is stator inductance, Ohm; L_r is rotor inductance, Ohm; J is a moment of inertia of the electric drive, kg·m²; M, M_r are a motor torque and a moment of resistance, Nm; ρ is a number of motor pole pairs; w is motor speed, rad/s.

The main feature of the model is the method of evaluating the relationship between the metal and the slag temperature difference, the screw feeder flow rate, and the thickness of the slag layer.

The screw feeder flow rate (Q, m³/s) can be calculated as follows: (2):

$$Q = \frac{s_p}{d} R^3 w\varphi, \quad (2)$$

where S is the screw conveyor pitch, mm; d is the external diameter of the screw, mm; R is the screw radius, mm; w is the screw speed, mm; φ is the coefficient of efficiency.

The temperature value of the slag surface can be calculated on the basis of Fourier's law:

$$t_2 = t_1 - \frac{ql}{\lambda}, \quad (3)$$

where t_2 is the slag surface temperature, °C; t_1 is the temperature of the molten metal, °C; q is the heat flux density, W/m²; l is the thickness of slag layer, m; λ is the heat conductivity coefficient, W/(m²·K).

The slag layer thickness can be calculated by the ratio of the integral of the feeder flow rate to the working area of the crystallizer:

$$l = \frac{\int Q(t)}{S}, \quad (4)$$

If we paste (4) into formula (3), we obtain:

$$t_2 = t_1 - \frac{q\int Q(t)}{S}, \quad (5)$$

At zero initial parameters, taking into account the expressions (2) and (5), we obtain:

$$t_2 = -\frac{qS_pR^3\varphi}{Sd\lambda}\int w(t), \quad (6)$$

The transfer function of the feeder subsystem responsible for the flow rate correction during changes in the slag temperature (7) can be derived from expression (6) using the direct Laplace transform:

$$W(p) = \frac{t_2(p)}{\omega(p)} = -\frac{qS_pR^3\varphi}{pS\lambda d}, \quad (7)$$

where p is the Laplace operator.

The feeder model is shown in **Fig. 4**.

The availability of MF in the feeder system is defined in the Bunker model. When the system is running, the bunker is regularly filled and emptied. When the feeder is emptied, it runs at the flow rate produced by the screw feeder. After emptying, the cart returns to its initial position and the bunker unit switches to filling.

Testing the model

The model was tested on the basis of experimental data obtained at the company "Ural Steel" (Novotroitsk, Orenburg region). In the modeling, the bunker is initially full, and the desired temperature difference is 20 ºC.

Fig. 5*b* shows the temperature differences, indicating that the screw feeder flow rate is maximum until the temperature difference reaches 15 ºC (Fig. 5*a*). Once the temperature difference exceeds 15 ºC (t = 210 s), the screw feeder flow rate gradually begins to decrease, thus increasing the accuracy of the flux feed. The cart with the screw feeder is moving (Fig. 5*d*).

At t = 280 s, when the temperature difference has reached the required value of 20 ºC, according to the obtained empirical values at the enterprise, the screw feeder stops and the cart returns to its initial position.

When the system stops, the graph of the temperature difference shows that the temperature difference gradually decreases, thus indicating a reduction in the slag layer on the surface of the liquid metal. At t = 450 seconds, when the temperature difference reaches the lower boundary of acceptable values (in our case it is 18 ºC), the system starts operating again until the temperature difference reaches the desired value.

The graph of the bunker filling (Fig. 5*c*) shows that the bunker is completely emptied at t = 500 s, after receiving the signal "SU2", the cart returns to the initial position (Fig. 5*d*). The bunker receives the command for filling only after returning the cart to the initial position.

Conclusion

The model of automated MF feeding into the CCM crystallizer enables the system to be virtually tested when using a new flux composition, expanding the product range or introducing a new system of MF feeding.

The experiments show the efficiency of the feed, compliance with the real parameters of the flux flow rate, and the metal and slag temperatures, thus enabling a preliminary simulation before the introduction of new elements of the system.

The equipment settings (electric drive parameters, required sensor parameters) obtained on the basis of the model and the implementation of the proposed control algorithm will reduce the flux flow rate down to 13 % while reducing the financial costs of the final product production by about 6 %.

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