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Melting of Iron-Ore Pellets in an Arc Furnace

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Abstract—Steel may be produced in an arc furnace from reduced iron-ore pellets that are supplied to the melt through hollow electrodes. Thermoelectric aspects of this process are considered. A method of charging the pellets in accordance with the thermal conditions in the furnace is proposed. The new method of pellet charging intensifies batch melting and reduces metal losses and dust emissions from the furnace.

Keywords: steel production, arc furnaces, furnace electrodes, metal losses, product yield, reduced pellets, melting rate

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It is important to increase the yield of steel from high power arc furnaces [1, 6–9, 12]. Intensification of electrosmelting is found to significantly reduce the yield, primarily because of the increased metal losses. This is especially pronounced when using high-quality batch—specifically, reduced pellets and briquets. The electrosmelting of steel with the continuous supply of reduced iron-ore pellets to the melt was considered in [6–8] (Fig. 1).

Metal losses occur because the heat flux from the arc to the surface of the bath cannot be assimilated by all the steel, which has fairly low thermal conductivity. The surface temperature of the metal batch under the arc remains equal to the boiling point of the steel throughout practically the whole process. In electrosmelting, the steel evaporates, and its vapor is oxidized and entrained from the furnace by the smokestack gases. Most of the steel in the working space of the furnace evaporates from the surface bounded by a circle covering the electrodes—or, more precisely, with the metal surface in contact with the arcs [6].

Hence, to reduce the metal losses in electrosmelting when using reduced iron-ore pellets, we need to reduce the evaporation in the arc-combustion zone. A promising approach is the continuous supply of coolant (pellets, etc.) to the surface of the bath in contact with the arc. That lowers the surface temperature of the steel in that area (Fig. 1) and reduces its evaporation. In other words, it decreases the metal losses and increases the yield of steel in electrosmelting [7, 8].

In the laboratory, we simulate the electrosmelting of reduced iron-ore pellets supplied to the bath through hollow electrodes in a dc system (Fig. 2) [11, 12]. In that case, the operating conditions are determined by the heat generation and heat transfer in the electric arc; and by heating and melting of the pellets within the slag–metal melt under the action of the high-temperature arc [4, 5]. The table summarizes the experimental results.

We find that, when the reduced iron-ore pellets are supplied to the bath through hollow electrodes, the heating and melting of the pellets under the action of the electric arcs at the melt surface is faster, thanks to the additional heating on passing through the arc and also to the higher local temperatures of the melt where the arc acts on the bath surface. This approach is more

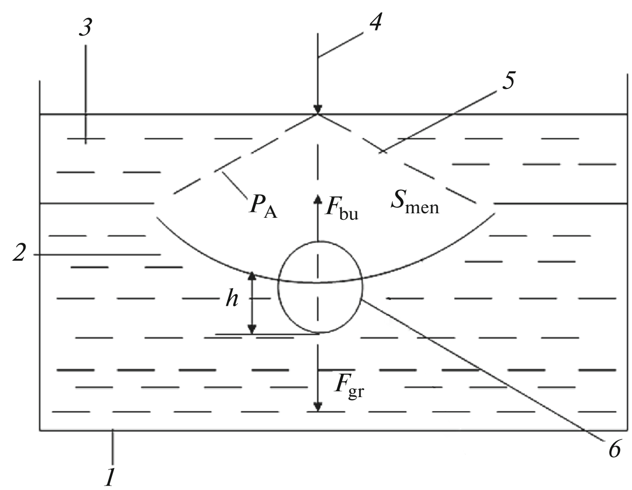

Fig. 1. Pellet immersion in melt after delivery from the hollow electrode: (*1*) furnace vessel; (*2*) evaporation surface (meniscus) of metal; (*3*) slag; (*4*) position of hollow electrode; (*5*) electric arc; (*6*) pellet in liquid steel; h, immersion depth of pellet; F_{bu}, buoyancy force; F_{gr}, gravitational force on pellet; P_A, arc power.

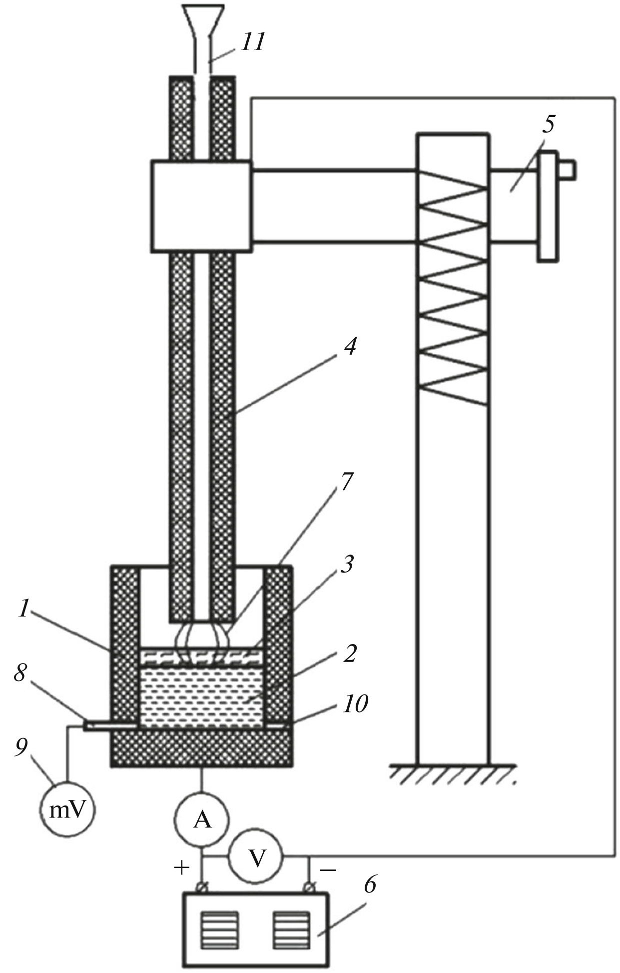

Fig. 2. Experimental electrofurnace: (*1*) crucible; (*2*) steel; (*3*) slag; (*4*) electrode with axial hole; (*5*) mechanism for moving electrode; (*6*) welding rectifier; (*7*) electric arc; (*8*) thermocouple; (*9*) millivoltmeter; (*10*) tap hole for metal discharge; (*11*) charging funnel.

effective than other methods of supplying the reduced pellets to the melt. The total time of pellet melting is reduced by 10%, on average. Thus, when the reduced iron-ore pellets are supplied to the bath through hollow electrodes, we observe not only fast and economical heating of the pellets but also their subsequent melting within the area affected by the arc.

Since the surface of the reduced pellets reaches the melting point within an infinitesimally short time, whereas the initial temperature is retained within the pellets, the total heating and melting time of a single pellet τ_{Σ}^{pe} (s) may be calculated from the formula

$$\tau_{\Sigma}^{pe} = \frac{\rho_{pe}[c_{pe}(T_{pe}^{me} - T_{pe}^{in}) + r_{me}]r_{pe}}{\int_{T_{pe}^{in}}^{T_{pe}^{me}} \alpha_{ef}(T_{melt} - T_{pe})dT_{pe}}. \quad (1)$$

Here r_{me} is the unit heat of fusion (melting) of the pellet, J/kg ; c_{pe} is the specific heat of the pellet, J/kg K; T_{pe}^{in} is the initial pellet temperature on charging in the furnace, K; T_{pe}^{me} is the melting point of the pellet, K; α_{ef} is the effective heat-transfer coefficient, W/m^2 K; T_{melt} is the temperature of the melt, K.

Pellet melting during continuous charging with intense boiling of the steel maintains the corresponding level of slag oxidation. The effective heat-transfer coefficient $\alpha = 1–10$ kW/m^2 K, depending on the bath hydrodynamics [10].

As we see from Eq. (1), the total melting time τ_{Σ}^{pe} and the melting rate v_{me} of the pellets in the furnace bath depend on the bath temperature T_b, the initial pellet temperature T_{pe}^{in}, and the effective pellet–melt heat-transfer coefficient α_{ef}, if the thermophysical properties (ρ_{pe}, c_{pe}, r_{me}) and pellet dimensions (r_{pe}) are constant. The calculations show that the melting time of the pellet declines sharply with increase in α_{ef} and T_b. Statistical analysis yields the following regression equations for the total pellet-melting time (s) in a 150-t high-power arc furnace

$$\left.\begin{aligned} \tau_{\Sigma}^{pe} &= 22.604\alpha_{ef}^{-0.9996} \text{ when } r_{pe} = 6 \text{ mm} \\ \tau_{\Sigma}^{pe} &= 30.033\alpha_{ef}^{-1.0024} \text{ when } r_{pe} = 8 \text{ mm} \\ \tau_{\Sigma}^{pe} &= 37.862\alpha_{ef}^{-1.0061} \text{ when } r_{pe} = 10 \text{ mm} \end{aligned}\right\} T = 1873 \text{ K};$$

$$\tau_{\Sigma}^{pe} = 1 \times 10^7 T_{melt}^{-1.7409} \text{ when } r_{pe} = 6 \text{ mm}, \alpha_{ef} = 1 \text{ kW/m}^2\text{ K},$$
$$\tau_{\Sigma}^{pe} = 5 \times 10^6 T_{melt}^{-1.7808} \text{ when } r_{pe} = 8 \text{ mm}, \alpha_{ef} = 4 \text{ kW/m}^2\text{ K},$$
$$\tau_{\Sigma}^{pe} = 1 \times 10^6 T_{melt}^{-1.698} \text{ when } r_{pe} = 10 \text{ mm}, \alpha_{ef} = 10 \text{ kW/m}^2\text{ K},$$

$$\tau_{\Sigma}^{pe} = 20.6429 - 0.0020\alpha_{ef} + 1285.214r_{pe} - 0.0055T_{melt}, \; R^2 = 0.68.$$

In smelting steel from reduced iron-ore pellets in an arc furnace (Fig. 3), including the case where the pellets are supplied continuously through hollow electrodes to the evaporation zone formed by arc–melt

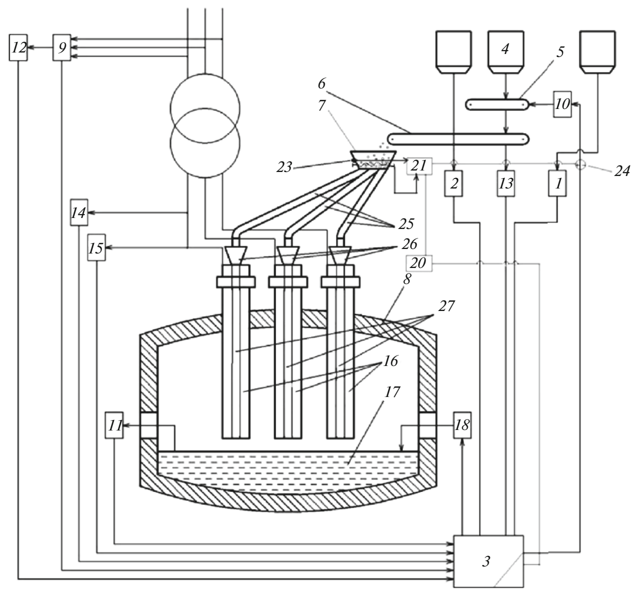

Fig. 3. Arc furnace with hollow electrodes: (*1*) system for calculating the supply of metal batch to the furnace; (*2*) sensor for measuring the flow rate of friable materials lime, etc.); (*3*) control computer; (*4–6*) pellet-supply units; (*4*) bunker for metallic pellets; (*5*, *6*) containers for charging pellets and other friable materials; (*7*) intake funnel; (*8*) electrofurnace; (*9*) sensor for consumed active power; (*10*) executive mechanism for charging pellets and friable materials; (*11*) monitoring system for the metal temperature in the furnace; (*12*) signals from active-power sensors; (*13*) signals from pellet-flow sensors; (*14*) current sensors; (*15*) voltage sensors; (*16*) hollow electrodes; (*17*) bath with metal and slag; (*18*) system for calculating the heat assimilation in the furnace bath; (*20*) specification unit; (*21*) rate controller for pellet charging; (*22*) executive mechanism for pellet supply to axial holes of the furnace electrodes; (*23*) photosensor for recording the charging level of the pellets in the intake funnel; (*24*) switching block for executive mechanism *10* supplying pellets to the funnel *7*; (*25*) flexible rods for pellet supply to the electrodes; (*26*) conical funnels in electrode holes.

contact, the metal losses may be maintained at the optimal level by regulating the pellet consumption in that zone [8]. To that end, a new method of cyclic supply of pellet portions to the melt may be used (Fig. 4). The method permits the supply of portions of pellets corresponding to the thermal power of the melt under

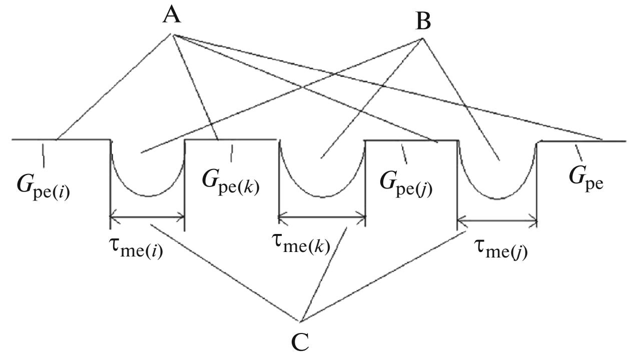

Fig. 4. Cycles characterized by charging of pellet portions (A) and intervals with no charging (B), with variation in the pellet flow rate $G_{pe}(i, k, j)$ under the arcs in the pellet–meniscus contact zone, for different melting times of each pellet portion (C), taking account of the corresponding values for the voltage stages (*i*, *k*, *j*, etc.) in the arc furnace.

the arcs [8]. The calculation of the thermophysical processes in the heating and melting of each pellet portion and the calculation of the metal losses in the supply of pellet portions to the furnace is described by Eq. (1).

Such pellet delivery to the high-temperature zone (Fig. 4) intensifies melting and reduces the dust liberation from the liquid meniscus. It increases the furnace productivity, decreases the power consumption, decreases dust entrainment, and increases the final yield of steel. The metal losses are regulated by adjusting the flow rate of the reduced iron-ore pellets in accordance with the monitoring data for the arc's thermal operation or by adjusting the power consumption in the process. The pellets are charged to the arc-combustion zone continuously or periodically in portions [8].

The specified electrosmelting characteristics are attained by matching the supply rate and melting rate of the pellets ($v_{pe} = v_{me}$) according to the mathematical model, which we now outline [6]. We suppose that

$$\begin{cases} G_{lo} = f(P_A, \Delta q_b, q_{pe}); \\ \Delta q_b = f(v_t); \\ q_{pe} = f(t_m, v_{pe}). \end{cases} \quad (2)$$

Melting time of reduced pellets supplied through hollow/regular electrodes

Arc power P_A, kW	Unit pellet-charging rate V_{pe}^{un}	Total melting time* of pellet in bath τ_Σ, s	
		with supply through hollow electrodes	at a distance of 3 cm from the arc
12.0/12.0	0.3/0.3	47/–	54/56
14.0/14.0	0.4/0.4	58/–	66/68
16.0/16.0	0.5/0.5	70/–	79/80

* Mean of measurements for three melts.

The metal losses are calculated from the expression

$$G_{\text{lo}} = (3P_{\text{A}} \times \eta_{\text{A}} - \Delta q_{\text{b}} - K \times q_{\text{pe}})/L_j, \quad (3)$$

where P_A is the heat generated in the arc, W; η_A is its efficiency; K is the proportion of pellets that melt at the surface layer of metal in the evaporation zone; Δq_b is the heat assimilation by the bath, W; q_{pe} is the heat flux in pellet heating and melting in the liquid layer under the arc, W/m^3; L_j is the unit heat of vaporization of the iron, J/kg.

The heat generated in the arc is determined from the familiar expression $P_A = U_A I_A$, where U_A and I_A are, respectively, the arc voltage (V) and current (A). The heat assimilation by the bath is

$$\Delta q_{\text{b}} = (M_{\text{m}}c_{\text{m}} + M_{\text{sl}}c_{\text{sl}})v_t, \quad (4)$$

where M_m, M_{sl} are, respectively, the mass of metal and the mass of slag, kg; c_m, c_{sl} are, respectively, the specific heats of then metal and slag, J/kg K; v_t is the heating rate of the metal, °C/s.

The heat flux in pellet heating and melting in the melt under the arc is

$$q_{\text{pe}} = [c_{\text{pe}}(t_{\text{me}} - t_{\text{pe}}) + L_{\text{me}} + c_{\text{melt}}(t_{\text{m}} - t_{\text{me}})v_{\text{pe}}, \quad (5)$$

where L_{me} is the heat of evaporation of the iron and melting of the pellets, J/kg; c_{pe} and c_{melt} are, respectively, the specific heats of the pellet and the melt obtained from the pellet, J/kg K; t_{pe}, t_{me}, and t_m are the initial temperature of the pellet, its melting point, and the temperature of the molten metal in the furnace bath, respectively, °C; v_{pe} is the consumption rate of the iron-ore pellets in the zone of metal evaporation within the furnace, kg/s [1, 2].

The rate of pellet supply through the hollow electrodes to the bath (kg/s) is determined from the expression [6–8]

$$v_{\text{pe}} = \left(\frac{\Delta q_{\text{b}}}{\bar{c}v_t} - G_0\right)\bigg/\tau_{\text{pe}}, \quad (6)$$

where G_0 is the initial mass of metal in the furnace, kg; $\bar{c}$ is the mean specific heat of the metal in the furnace, J/kg K; τ_{pe} is the charging time of the pellets in the furnace, s. The current pellet mass (kg) in continuous or discrete delivery may be calculated from the formula

$$G_{\text{pe}}(i,k,j \text{ and so on}) = v_{\text{pe}}\tau_{\text{me}}(i,k,j \text{ and so on}). \quad (7)$$

Here i, k, j, and so on denote the voltage stages in the arc furnace; $\tau_{me}(i, k, j$, and so on) is the melting time of the pellet portions in the furnace bath.

The calculations in the control computer permit determination of the time τ_{sw} (s) at which the speed regulator and executive mechanism for pellet charging in the axial channel of the electrodes are switched off

$$\tau_{\text{sw}}(i,k,j \text{ and so on}) = \tau_{\text{me}}(i,k,j \text{ and so on}) = (3S_{\text{men}}k/S_{\text{pe}})m_{\text{pe}}/v_{\text{pe}}, \quad (8)$$

where $S_{men} = 2\pi(L_A + r_e)h_{men}$ is the surface area of the meniscus, m^3; $S_{pe} = \pi r_{pe}^2$ is the surface area occupied by the pellets at the meniscus, m^2; $h_{men} = 3 \times 10^{-3} I_A$ is the depth of the meniscus, m; L_A is the arc length, m; r_{pe} is the pellet radius, m; r_{el} is the electrode radius, m; m_{pe} is the pellet mass, kg; $k = 0.9069$ characterizes the coverage of the meniscus surface S_{men} (m^2) by the pellets in the case of the best surface filling.

The proposed system for calculations in the control computer permits determination of the melting time (s) of the pellet portions from the formula $\tau^{me}(i, k, j$, and so on) = Nm_{pe}/v_{me}, where N is the number of pellets in the given portion and v_{me} is the melting rate of the pellets, kg/s (Fig. 3) [6]. In the first approximation, the melting rate of the pellets at the meniscus may be calculated from the formula

$$v_{\text{me}} = m_{\text{pe}}N/\tau_{\text{me}}, \quad (9)$$

where N is the number of pellets at the evaporation surface under the three electrical arcs

$$N = (3S_{\text{men}}/S_{\text{pe}}) \times 0.9069. \quad (10)$$

The dependence of the melting time on the convective heat-transfer coefficient of the pellets on heating in the furnace bath is

$$\tau_{\text{me}} = \chi_1\alpha^{\chi_2}, \quad (11)$$

where the convective heat-transfer coefficient in the pellet–melt system $\alpha = 10$ kW/m^2 K; $\chi_1 = 10.64$ and $\chi_2 = -0.798$ for the given conditions of pellet melting in the furnace.

The pellet consumption v_{pe} (kg/s) is related to the melting rate v_{me} (kg/s) of the pellets as follows

$$v_{\text{pe}} \le v_{\text{me}} = m_{\text{pe}}N/\tau_{\text{me}}. \quad (12)$$

Together, Eqs. (2)–(11) constitute the mathematical model of the thermophysical processes in the melting of reduced iron-ore pellets in an arc furnace.

On the basis of the metal losses calculated for different thermal conditions of a metallic bath of variable mass, we obtain the following regression equations

$$g_{\text{lo}} = -0.0465v_{\text{pe}} + 1.5621 \text{ when } P_{\text{A}} = 105 \text{ MV A},$$
$$g_{\text{lo}} = -0.0457v_{\text{pe}} + 1.4877 \text{ when } P_{\text{A}} = 100 \text{ MV A},$$
$$g_{\text{lo}} = -0.0449v_{\text{pe}} + 1.4133 \text{ when } P_{\text{A}} = 95 \text{ MV A},$$
$$g_{\text{lo}} = -0.0441v_{\text{pe}} + 1.3348 \text{ when } P_{\text{A}} = 90 \text{ MV A},$$
$$g_{\text{lo}} = -0.3160 - 0.0453v_{\text{pe}} + 1.0116P_{\text{A}}, \; R^2 = 0.99.$$

Thus, with known thermal power of the bath, it is possible to regulate the metal losses by adjusting the supply of reduced iron-ore pellets to the furnace bath.

CONCLUSIONS

Steel may be produced in an arc furnace from reduced iron-ore pellets that are supplied continuously to the melt through hollow electrodes. After thermoelectric analysis of this process, we propose a method for cyclic supply of portions of reduced iron-ore pellets to the arc furnace, as well as a mathematical model and an algorithm for calculating the thermal parameters of the furnace. The algorithm permits determination of the furnace productivity, the yield of steel, the power consumption, and other factors. The metal losses and the dust entrainment may be regulated by adjusting the supply of reduced iron-ore pellets and the thermal parameters of the furnace.

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