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SELECTING EFFICIENT PARAMETERS FOR THE COKE CHARGE OF SHAFT-TYPE MELTING FURNACES

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It is shown based on studies of the changes in the composition of the gases and temperature in the preliminary charge that the performance indices of coke-fired shaft furnaces are determined by the conditions under which the oxidizing zone is formed so as to produce the greatest possible amount of heat. It is shown that the size of this zone increases with an increase in the rate of filtration of the air blast, enrichment of the blast with oxygen, and the use of low-activity coke in the form of lumps of limited size. To maximize the reheating of the melt, it is necessary to increase the average size of the lumps and the flow rate of the air blast in order to increase the height of the preliminary charge.

Keywords: *shaft furnaces, oxidizing zone, melt reheating temperature.*

The most commonly used source of heat in shaft melting furnaces of the cupola type (iron-foundry and mineral-wool cupolas and shaft furnaces used in nonferrous metallurgy) is metallurgical coke. The coke undergoes combustion in a air-blast flow supplied from an outside source. Among the distinguishing features of such furnaces: the furnace is of limited height (no higher than 4.5–5.0 m); the horizontal section of the layer of charge materials is also of limited dimensions (no more than 2.0–3.0 m); the injected gas jets are of low velocity (no higher than 75–80 m/sec); the charge materials do not undergo extensive physicochemical transformations. The quantity and distribution of the solid fuel in the working space of these furnaces depends on the conditions under which the initial components are charged and on the required heating rate. As new portions of coke that enter the furnace with the charge descend in the furnace, they are ignited by a red-hot bed of coarse coke (the preliminary charge) that is introduced into the lower part of furnace beforehand. The upper part of this bed burns in a flow of air that is distributed by tuyeres or an outside source [1]. Thanks to the high strength and porosity of the coke, it also acts as a drainage system that facilitates uniform distribution of the hot gases over the cross section of the furnace. In addition, it collects drops of the melt that filter through the supportive carbon-based packing and removes them from the working space of the furnace.

In accordance with the theoretical postulates in [2], the combustion of solid carbon is an aggregation of complex physicochemical processes that take place in multiple stages: preparation of the fuel (drying and thermal decomposition accompanied by the release of volatile matter); combustion of the gaseous products and the coke residue.

Numerous experimental studies [3, 4] have shown that the layered process of solid-fuel combustion depends both on the hydrodynamic conditions and the thermal conditions that exist. These conditions are interdependent and should be examined in relation to the specific conditions of the given production process.

The most widely used method of feeding an air blast into shaft furnaces – the use of tuyeres – entails the use of high-velocity jets formed by tuyeres that are of a certain size and are evenly distributed about the perimeter of the furnace [5]. Travelling at a high velocity (up to 30–50 m/sec) and having a high kinetic energy (up to 30–35 kW), the air blast propagates

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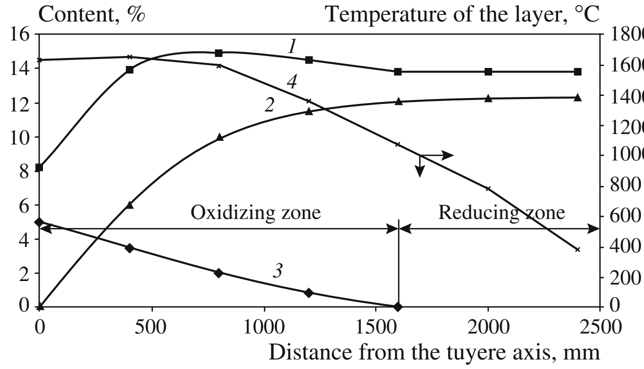

Fig. 1. Change in the composition of the gases at the outlet of the preliminary coke charge over the height of the bed along the axis of the cupola. The changes in composition are shown beginning at the tuyere level: *1*) carbon dioxide; *2*) carbon monoxide; *3*) oxygen; *4*) temperature of the bed.

deep into the hearth. The blast loosens the material in the upper part of the coke charge, and the loosened zone is where the main reactions involving combustion of the solid fuel take place. The gas flow forces the gaseous, liquid, and solid products of these reactions to move toward the center of the furnace.

In accordance with the data that have been obtained from probing an operating iron-foundry cupola with a rated productivity of 5 tons/h (Fig.1), as the gas jets move deeper into the coke charge the oxygen content continuously decreases due to oxidation of the coke carbon and the gaseous products. Both primary and secondary solid-fuel combustion reactions can take place in the bed under these conditions.

The decrease in oxygen content of the air blast is accompanied by an increase in its content of CO_2, with the concentration of carbon dioxide reaching a maximum at a certain distance from the end of the tuyeres. The carbon dioxide content of the gas subsequently decreases with an increase in the content of CO. Further development of fuel gasification processes is curtailed as a result of a reduction in the temperature of the bed and the absence of oxygen. An oxidizing zone is formed in the region of the hearth in which coke undergoes combustion and gasification, and the outer boundary of this zone is where the concentration of CO_2 changes. The zone can be further broken down into an inner part in which the gases contain free oxygen and an outer part in which carbon is oxidized by previously formed carbonic acid [2].

Due to the above features of the propagation of gases in the bed, the oxidizing zone in the tuyere region expands toward the center of the furnace from above and below it. The part of the bed in which the concentration of carbon dioxide reaches its maximum value is called the combustion focus, and it has the highest temperature as well.

The region from the point of entry of the blast to the combustion focus is dominated by primary exothermic reactions that involve the oxidation of carbon in the fuel and form CO_2, both of which help raise the temperature in the bed. The development of this region determines the conditions for preheating of the initial charge and the reheating of the melt. Past the focus and farther toward the center of the furnace, the conditions that are created facilitate the occurrence of secondary endothermic reactions and processes which result in thermal decomposition of the fuel (this part of the furnace is referred to as the reducing zone).

When analyzing the laws that govern the development of the oxidizing zone in the coke bed, allowance should be made for certain aspects of the change in the oxygen content of the tuyere region over its length *x*. This change can be described by the expression [4]

$$\frac{dO_2}{dx} = -\frac{d(wFO_2)}{dx} = k'SFO_2, \qquad (1)$$

where F is the cross-sectional area of the flow of blast air at the distance x from the tip of the tuyeres, m^2; O_2 is the average concentration of oxygen in this section, %; k' is the overall value of the rate constant for the fuel oxidation reaction; S is the average reaction area of the surface per unit volume of the bed of coke lumps in the combustion zone, m^2; and w is the average velocity of the gases in the cross section x, m/sec.

Allowing for the continuity of the gas flow moving at the velocity w_0 at the outlet of tuyeres having the area F_0 and considering that $w_0F_0 = wF$ in a certain section of the oxidizing zone, we can assume that

$$\frac{dO_2}{O_2} = \frac{k'S}{w_0F_0}dV, \tag{2}$$

where V is the volume of the oxidizing zone, m^3.

Integration of this equation within the limits of the oxidizing zone inside the coke bed makes it possible to determine the total volume of the solid-fuel combustion zone in the bed:

$$V = \frac{w_0F_0}{k'S}\ln\frac{O_2^0}{O_2}, \ m^3, \tag{3}$$

where O_2^0 is the initial concentration of oxygen in the blast, %.

An analysis of this relation shows that for a constant tuyere cross section and constant blast flow rate, an increase in the average velocity of the blast w_0 is accompanied by an increase in the volume of the combustion zone. Most of this increase in volume takes place in the radial direction. These circumstances make it possible to bring the layers of fuel that are closer to the center of the furnace into the combustion process, which in turn reduces the volume of the region of materials not exposed to the blast and makes more complete use of the fuel.

At the same time, when less active coke (k') with a reduced granulometric composition is used and the blast air is enriched with oxygen (O_2), the oxidizing zone becomes larger and the melt is reheated to a higher final temperature.

To make the most efficient possible use of the coke, it is necessary to create conditions such that the coke also undergoes complete combustion in the vertical direction within the fuel-combustion zone. This is done by making the preliminary coke charge a certain height. The conditions for complete combustion of the carbon of the fuel in the vertical direction within the top part of this zone – starting at the tuyere level – can be expressed approximately in the form

$$-\gamma_m u_0 \frac{dr}{dz} = Mk'O_2, \tag{4}$$

where u_0 is the initial average velocity of the fuel in the vertical direction, m/sec; r is the radius of a lump of the fuel, m; γ_m is the density of the fuel, kg/m^3; and M is the stoichiometric coefficient.

Changing over to the relative size of the lump r_0 compared to its initial size ($\vartheta = r/r_0$), we can determine the law that governs the combustion of the fuel over the height of the fuel bed:

$$-\gamma_m u_0 r_0 \vartheta^3 \frac{d\vartheta}{dz} = Mk'O_2. \tag{5}$$

In the case of complete combustion of the lumps of fuel ($\vartheta = 0$) and a constant concentration of oxygen in the bed (O_2 = const), the height of the oxidizing zone will be

$$z = \frac{\gamma_m u_0 r_0}{Mk'O_2}, \ m. \tag{6}$$

Analysis of this expression shows that the greater the reactivity of the solid fuel k' and the concentration of oxygen O_2 and the smaller the initial size of the coke lumps r_0, the smaller the size of the oxidation zone in the vertical direction. The temperature to which the drops of melt within the bed are reheated will be correspondingly lower, assuming that their velocity remains unchanged. However, an increase in the size of the lumps of coke reduces the area of its reaction surface.

That in turn helps expand the combustion zone in the vertical direction, and the accompanying decrease in the hydraulic resistance of the bed lengthens the time that the drops remain in the oxidizing zone and increases their final temperature. If the height of the preliminary charge is inconsistent with the size of the lumps of fuel and their reactivity in the oxidizing zone, then a reducing zone may be formed again inside the upper part of the oxidizing zone and facilitate reduction of the carbon of the coke by carbonic acid. The outgoing gases will have a higher concentration of carbon monoxide in this case, the exact concentration depending on the excess height of the preliminary charge. When the oxidizing zone in the coke bed expands, the new portions of fuel that enter the furnace with the charge are heated to higher temperatures (above 700°C) and undergo endothermic reactions involving the decomposition of carbon in the fuel and the reduction of carbonic acid by previously formed combustion products. The yield of carbon monoxide increases in this case and the efficiency of fuel use decreases while fuel consumption increases. Thus, for shaft furnaces operating on solid fuel, it is necessary to attempt to reduce the height of the high-temperature zone. This can be done by using fuel which has a low reactivity in relation to carbon dioxide (such as a fuel based on petroleum coke) or is of reduced coarseness, which ensures an efficient distribution of the air blast. Another measure that can be used is to operate the furnace with a small amount of excess air ($\alpha = 1.05$–1.1 [6]). The performance indices of shaft furnaces are improved by technical measures that help concentrate heat in the focus region. Among the most effective such measures are proper ignition of the preliminary charge during the initial period of the heat, the use of an oxygen-enriched blast, preheating of the blast, an increase in pressure j working space, and optimization of the volume of the working charges.

The height of the focus region in the bed is the main factor that determines the conditions created for reheating of the melt: the higher this region, the higher the temperature of the finished product at the tap hole.

Dispersed introduction of the air blast with the use of a second or even a third row of tuyeres helps expand the high-temperature zone. In this case, the preliminary charge needs to be 150–200 mm above the last row of tuyeres.

To evaluate the height of the oxygen zone in the case of layer-by-layer combustion of the coke, we assume that combustion takes place by means of the following reactions [7] (the thermal effect is given in kJ/mole):

$$C + O_2 = CO_2 + 394.63, \tag{7}$$

$$CO_2 + C = 2CO - 176.65. \tag{8}$$

In accordance with the channel mechanism of solid-fuel combustion, we also assume that the kinetics of the change in the content of oxygen in a given layer of coke is described by a first-order differential equation [8]:

$$\frac{dO_2}{dz} = \phi(z) F_k O_2 \left(\frac{1}{1+\mathrm{Sm}} \right) + \frac{O_2^0}{B} \frac{dB}{dz}, \tag{9}$$

where $\phi(z)$ is the transfer function and is determined from the expression $\phi(z) = 0.28\mathrm{Re}^{0.2}$ (the Reynolds criterion $\mathrm{Re} = wr/\nu$; ν is the coefficient of kinematic viscosity, m^2/sec); F_k is the specific surface of one lump of coke, m^2/m^3; $\mathrm{Sm} = \beta/k'$ is the Semenov criterion (β is the mass-transfer coefficient, kg/(m^2·sec); k' is the average value of the rate constant for the coke combustion reaction); and B is the unit consumption of blast, m^3/(m^2·sec).

With the boundary conditions $z = 0$, $O_2 = O_2^0$, the solution of Eq. (9) has the form [9]

$$O_2(z) = O_2^0 e^{-\int_0^z P(S)dS} + \frac{O_2^0}{B_1} e^{-\int_0^z P(S)dS} \int_0^z e^{\int_0^z P(S)dS} \frac{\partial B}{\partial z} dz, \tag{10}$$

where

$$P_1 = \phi_0 F_k \frac{1}{1+\mathrm{Sm}};$$

S is the running value of the vertical coordinate z.

The amount of oxygen that has reacted with carbon is determined from the difference between its initial concentration O_2^0 and its residual concentration $O_2(z)$:

$$\Delta O_2 = O_2^0 - O_2(z). \tag{11}$$

We determine the gas temperature $T(z)$ in the oxygen zone and the reducing zone based on the heat-balance equation for the solid-fuel combustion zone:

$$G_{ox}Q_7 + G_{red}Q_8 = k_1' V_a C_g (T(z) - T_0), \tag{12}$$

where $k_1' = 2.0$ is a coefficient that expresses the increase in the yield of gas due to reaction (7); T_0 is the initial temperature of the blast air, K; G_{ox} is the amount of carbon that has undergone reaction (7); G_{red} is the amount of carbon that has undergone reaction (8); Q_7 and Q_8 are the thermal effects of reactions (7) and (8), respectively; and C_g is the average heat capacity of the gas, kJ/(m^3·K).

In accordance with the data in [10], we take

$$G_{ox} = 0.00537\Delta O_2(z)w_0; \quad G_{red} = 0.537\Delta CO_2(z)w_0, \tag{13}$$

where ΔO_2 and ΔCO_2 are, respectively, the changes in the concentrations of oxygen and carbon dioxide in the oxidizing zone, %; w_0 is the nominal rate of filtration of the gases, m/sec.

With allowance for Eq. (10), we can establish that

$$T(z) = T_0 + A_1 O_2^0 \left[\left(1 - e^{-\int_0^z P(S)dz} \right) - \frac{1}{B} e^{-\int_0^z P(S)dz} \int_0^z \frac{\partial B}{\partial z} dz \cdot e^{-\int_0^z P(S)dz} \right] - A_2 CO_2^0 (1 - e^{-Pz}). \tag{14}$$

Here, $A_1 = 0.00537Q_7/C_g$; $A_2 = 0.00537Q_8/C_g$; CO_2^0 is the maximum content of CO_2 in the outgoing gases, %;

$$P = \phi_0 F_k \left(\frac{1}{1 + Sm_2} \right); \tag{15}$$

$$Sm_2 = \phi V_a / k_2', \tag{16}$$

where k_2' is the rate constant of reaction (8).

The temperature of the gas over the height of the oxygen zone will be determined not only by the rate of exothermic reaction (8) but also the superimposed effect of the delivery of blast air to the bed and the conditions under which reaction (7) proceeds. Thus, with allowance for the variability of the heat capacity of the gas flow, the change in gas temperature over the height of the oxygen zone during layer-by-layer combustion of the solid fuel can be determined from the equation

$$\Delta T(z) = (T_g' - T_m'') e^{-\int_0^z P_1(s)dz} + e^{-\int_0^z P_1(s)dz} - \int_0^z e^{-\int_0^z P(s)dz} \frac{\partial T}{\partial z} dz, \tag{17}$$

where $P_1(s) = A(1/(W_g(s) + 1/W_m))$; $W_g(s)$ and W_m are the heat capacities of the gas flow and the flow of materials, kJ/K; and A is a constant coefficient.

To determine the average change in gas temperature inside the oxidizing zone, this function must be integrated over the height of the upper part of the preliminary charge above the tuyere level z_0:

$$\Delta \overline{T} = \frac{1}{z_0} \int_0^{z_0} \Delta T(z) dz. \tag{18}$$

The solution of system (14)–(18) is the average temperature gradient between the gas and the materials in the upper part of the preliminary charge. With the use of a simplified version of Eq. (14) that contains its first two terms, the solution has the form

$$\frac{\partial T}{\partial z} = AO_2^0 P e^{-P_1 z}\left(1 - \frac{a}{B_1 P}\right), \tag{19}$$

where P is a constant coefficient; $B_1 = \int_0^z \frac{\partial B}{\partial z} dz$; $a = 1/B$.

Then the average change in gas temperature in the upper part of the preliminary charge will be

$$\Delta \bar{T} = \frac{1}{z_0}\int_0^{z_0}\left[(T_g' - T_m'')S^{-\frac{A}{a}} e^{\frac{AS}{W_m}} + S^{-\frac{A}{a}} e^{\frac{AS}{W_m}}\left[\int_0^{AS/a} z^{\frac{AS}{a}} e^{-\frac{AS}{W_m}} AO_2^0 P\left(1 - \frac{a}{B_1 P}\right)dz\right]\right]ds, \tag{20}$$

where T_g' and T_m'' are, respectively, the maximum gas temperature in the combustion zone and the temperature of the melt at the outlet of the upper part of the preliminary charge.

To ensure that the temperature head between the gas and the materials in the oxidizing zone is constant, it is necessary to ensure satisfaction of the condition $\partial \Delta T / \partial z = 0$. Then the second term of Eq. (17) will be equal to zero and we can obtain the following condition from Eq. (20):

$$1 - \frac{a}{B_1 P} = 0. \tag{21}$$

In the course of determining the integral (18), with allowance for $a = B_1 P$ we can establish that $z_0 = 1/P$.

Here,

$$P = \frac{0.28}{\mathrm{Re}^{0.2}} \frac{6(1-\varepsilon)}{r} \frac{k_1}{k_1' + \phi W_m}, \tag{22}$$

where ε is the porosity of the bed.

Based on the features of the development of the oxidizing zone in the preliminary charge, we take $\phi W_m \ll k_1'$. Then $k_1'/(k_1' + \phi W_m) \approx 1$. For the actual conditions that characterize the thermal performance of the preliminary charge in cupola-type coke-fired shaft furnaces, we can take $\varepsilon = 0.4$–0.6; Re = 1000–10000, and $r = 0.05$–0.1 m. In this case, the change in the size of the oxidizing zone over the height of the bed can be seen from the data in Fig. 2.

Analysis of these data shows that an increase in the porosity of the coke bed helps expand the oxidizing zone and thus improves the conditions for reheating of the melt that is formed. This result is seen when coarse lumps of coke are used. However, each 10-mm change in the average diameter of the coke lumps increases the average total height of the preliminary charge by 30 mm.

In keeping with the data obtained here, it can be concluded that increasing the melting rate by increasing the consumption of the air blast enlarges the oxidizing zone in the coke bed by an average of 30 mm for each 1000-unit change in the Reynolds criterion and requires a corresponding correction of the height of the preliminary charge. Otherwise, combustion of the coke in the bed will be slowed and the temperature in the focus region will be reduced, which will in turn reduce the temperature to which the melt is reheated.

Conclusions

1. The operating conditions of furnaces used with layers of coke as the fuel depend on the development of the oxidizing zone above the tuyere level inside the preliminary charge, since the rate of heat generation is highest in that part of the zone.

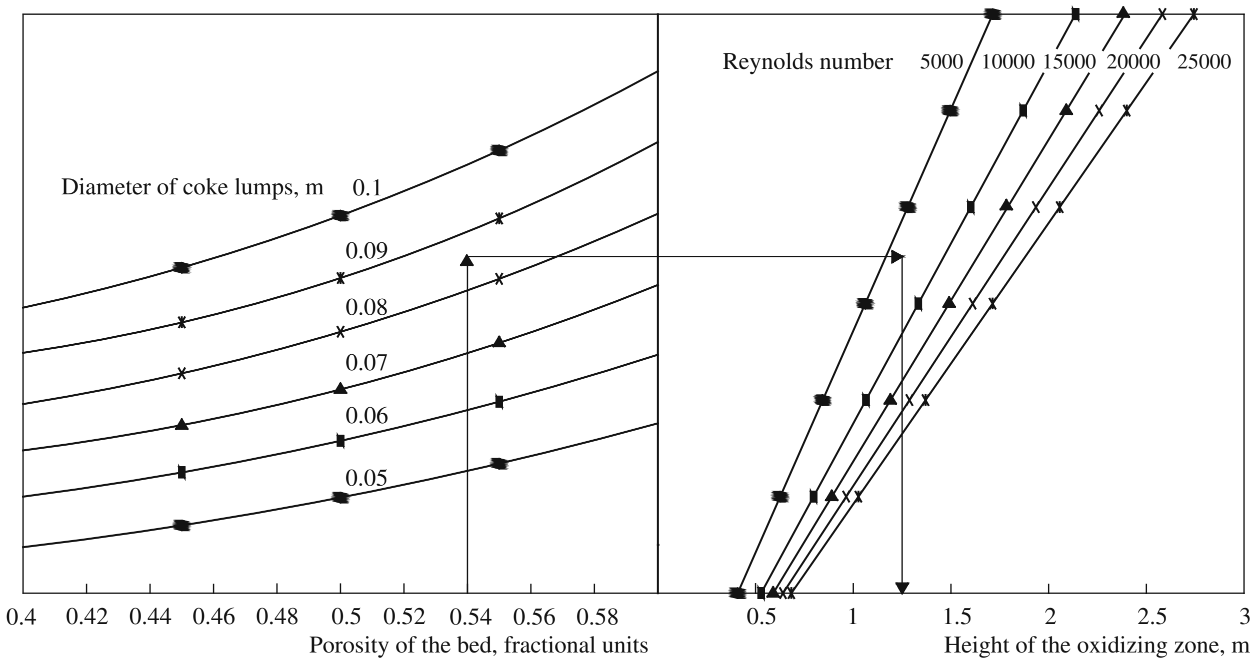

Fig. 2. Dependence of the height of the oxidizing zone in the coke bed on its porosity, the diameter of the coke lumps, and the Reynolds number.

2. To maximize the volume of the oxidizing zone and the energy efficiency of shaft furnaces (cupolas), it is best to increase the velocity of the air blast and maximize its oxygen content while using low-activity coke with lumps of limited size.

3. The use of coarse coke in the preliminary charge helps increase the temperature to which the resulting melt is preheated.

4. The height of the preliminary charge should be consistent with the size of the coke lumps that are used and the gasdynamic regime of the gases. For maximal reheating of the melt, the average height of the preliminary charge will need to be increased 30 mm for each 10-mm increase in the average diameter of the coke lumps and each 1000-unit increase made in the Reynolds number to increase blast consumption.

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