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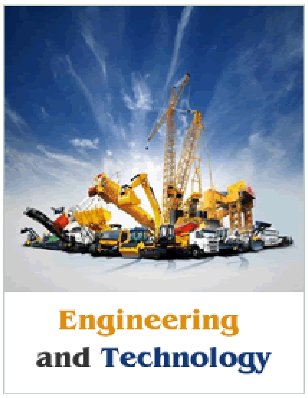

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Determination of Energy Performance for Sinter Charge Ignition

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Abstract
The work offers a method of calculating of the energy performance of sinter charge ignition, such as the consumption of gaseous fuel, intensity and time of ignition, total amount of heat obtained from external sources and specific energy consumption of this process. The method takes into account the main features of sinter charge, sintering machine and gaseous fuels used in the ignition furnace. The connection of energy consumption for sinter ignition with fuel particle size has been established. It has been demonstrated that the energy consumption grows as particles dispersion decreases. Using numerical study of obtained dependencies the work reveals the causes of increased consumption of gaseous fuel in sintering plants of CIS countries. The main cause is increased humidity of fine Krivoy Rog iron ore concentrate, which is used at the number of sinter plants. Another reason is an old design of sintering machines that does not let to prevent uncontrolled air leaks, ensure recirculation of flue gases in sintering and cooling zones, as well as the impossibility of sintering of high layers of the charge.

1. Introduction

The process of sinter charge ignition can be considered as the process of heating of fuel particles located in the upper layers of agglomerated layer to the ignition temperature. After ignition the heat wave directed into deeper layer, where sintering of dispersed charge takes place, and providing appearance of fuel in combustion zone is generated. Sintering charge ignition process is carried out by an external source, as a rule, due to the heat of flue gases from the combustion of gaseous fuel at the burners of ignition furnace located above the agglomerated layer. Heating the charge to the ignition temperature is commonly characterized by the following energy parameters: flow rate of gaseous fuel used for the charge ignition, ignition intensity, i.e. the amount of heat per unit area of the layer in a unit of time, duration of ignition, the total amount of heat produced per unit area of the layer from the external heat source and specific heat consumption for the ignition process [1]. The last parameter, i.e. specific heat consumption for the charge ignition or power consumption of the ignition is the main environmental indicator, as it gives an opportunity to assess the effectiveness of the ignition technology in comparison with other known techniques and find ways to improve it. Comparison of sinter production in the CIS and the EU shows that the energy intensity of sinter production at the enterprises of Eastern Europe is higher than one in Western Europe by 20% [2]. Increased energy consumption takes place both during sinter ignition and in the process of agglomeration. The main energy carriers in the process of agglomeration are solid and gaseous fuels, in this connection high energy intensity of sinter production raises the product self-cost and environmental load, as the number of emissions of oxides of carbon, sulfur and nitrogen is proportional to the amount of fuel burned. At present, the energy performance of the charge ignition is determined empirically, that does not allow identifying the factors influencing the ignition process of the sintered layer and reducing energy consumption for its implementation.

The aim of this work is to develop methods of calculating consumption of gaseous fuel to ignite sinter charge and specific energy consumption of the process, as well as to determine the main parameters affecting this value.

2. Mathematical Dependencies for Energy Performance of Charge Ignition

Numerous studies have shown that the energy intensity of the charge ignition process depends on the charge humidity, temperature of preliminary heating and heating temperature of the air supplied to the ignition furnace. However, any estimates establishing the interconnection of power indicators of the ignition process and main characteristics of the charge ignition, sinter machine and characteristics of the fuel and oxidant supplied to the ignition furnace are missing in the special literature. An exception makes proposed by the author method of calculation of flow of gaseous fuel supplied to the ignition of charge based on drawing up of the heat balance for the upper burning layer of the fuel particles [3]. This method provides determination of the gas flow spent on ignition of charge through introduction of the concept of the burning bed and provision of dependence for calculation of the estimated height of the layer.

Considering that sinter machine refers to through-type furnaces because sintering belt moves continuously under the stationary ignition furnace, let us record the heat balance for the mass flow of the charge into the ignited layer defined by the equation

$$m_i = F_i h \rho_c,\ \text{kg/sec} \qquad (1)$$

where ρ_c is the bulk density of the charge, kg/m^3; h is the height of the ignited layer, m.

F_i is the area of layer ignited per unit of time that is evaluated using formula:

$$F_i = wS\ ,\ \text{m}^2/\text{sec} \qquad (2)$$

where w is the speed of sinter belt movement, m/sec; S is the width of the sinter belt, m.

The heat balance equation for this mass of charge will be the following:

$$Q_{cb} = Q_{ih} + Q_p + Q_a,\ \text{J/sec} \qquad (3)$$

where Q_{cb} is the credit balance, it accounts the amount of heat transferred from the flue gases to the ignited layer, J/sec; Q_{ih} is the heat required for heating the surface layer of the charge to the ignition temperature, J/sec; Q_p is the amount of heat spent on the implementation of the physical and chemical processes in the ignited layer, J/sec; Q_a is the amount of air sucked through the ignited layer to sustain the process of fuel combustion, J/sec.

The amount of heat transferred from the flue gases to the ignited layer of the sinter charge is determined with the following equation:

$$Q_{fg} = BV_{fg}c_{fg}(t_{fg}^0 - t_{fg}^f),\quad \text{J/sec} \qquad (4)$$

where B is the consumption of the gaseous fuel, m^3/sec; V_{fg} is the volume of flue gases generated by combustion of one cubic meter of gaseous fuel, m^3/m^3; c_{fg} is the flue gases thermal capacity, J/(m^3·°C); t_{fg}^0 and t_{fg}^f are the initial and final temperatures of flue gases at the inlet and outlet respectively, °C.

The initial temperature of flue gases entering the ignited layer of charge usually equals to t_{fg}^0= 1150 – 1300 °C and the temperature of flue gases leaving the ignition furnace equals to the temperature of ignition $t_{fg}^f = t_i$ = 700 ^{0}C [4].

The amount of heat required for heating the air filtered through the layer is determined as follows:

$$Q_в = w_f F_i \tau c_a(t_a^f - t_a^0)\ \ ,\ \text{J/sec} \qquad (5)$$

where w_f is the rate of air filtration through the layer, m/sec; c_a is the air thermal capacity, J/(m^3·°C); t_a^0 and t_a^f are the air initial and final temperatures, °C; τ is the time during which the ignited layer stays in the furnace, sec.

The time τ is defined by:

$$\tau = \frac{l}{w}\ \ ,\ \text{sec} \qquad (6)$$

where l is the width of the ignition furnace, m.

The value of air filtration rate through the sinter layer depends on the value of dispersion under the sinter belt, the dispersive size of sinter charge particles and the height of the sintered layer. It could be determined using Ramzin formula [1]:

$$w_f = (2r_p\,\Delta p/AH)^{1/n},\ \text{m/sec} \qquad (7)$$

where Δp is the dispersion in vacuum chambers, Pa; H is the height of the sintered layer, m; r_p is the modal diameter of sinter charge particles, mm; A and n are the factors depending on the form and size of particles, determined by reference data [1]. In this case they can be accepted equal to A=1300 and n=0,5.

As the weight ratio of fuel in the sinter charge is not large and it is no greater than 5% from sinter charge weight, it is necessary to heat not only fuel particles but also the non-combustible sinter charge to the temperature of ignition. Considering that, the heat consumption for sinter charge heating up to the temperature of ignition will be as follows:

$$Q_{il} = m_{il}c_c(t_i - t_c^0),\quad \text{J/sec} \qquad (8)$$

where m_{il} is the weight of ignited sinter charge layer per a unit of time, kg/sec; c_c is the sinter charge thermal capacity, J/(kg·°C); t_c^0 is the initial temperature of charge (°C).

When heating the surface layer of the sinter charge to the temperature of ignition, there is actually only one physical and chemical process in the ignited layer – moisture evaporation. The amount of heat necessary for moisture evaporation is determined with the following equation:

$$Q_p = q_m m_{il} Q_e \text{ , J/sec} \tag{9}$$

where qm is the ratio of moisture in the sinter charge; Qe is the latent heat of evaporation, J/kg.

Let us determine the height of the ignited layer, making the following assumptions:

- there is only one surface layer of fuel particles in the ignited layer;
- all fuel particles are spherical and are of equal size;
- fuel particles are evenly distributed throughout the sinter charge layer.

Using the assumption of even distribution of particles in the layer, let us divide the sintered layer of the charge into elementary cubic volumes of ΔV, each of them containing one fuel particle:

$$\Delta V = \frac{V}{N} = \frac{FH}{N} \text{, m}^3 \tag{10}$$

where V is the volume of sinter charge layer, m^3; F and H are its area and height, respectively, m^2 and m; N is the number of particles in the layer, psc.

Let us determine the number of fuel particles in the sinter charge layer as a correlation of weight of fuel in the layer to the weight of one fuel particle:

$$N = \frac{M_f}{m_p} \text{ , pcs} \tag{11}$$

where M_f is the weight of fuel in the sinter charge, kg; m_p is the weight of one fuel particle, kg.

The weight of fuel in the sinter charge is determined using the equation:

$$M_f = q_f \rho_c FH, \text{ kg} \tag{12}$$

where q_f is the share of fuel in the sinter charge.

The weight of a fuel particle is determined with the formula:

$$m_p = \frac{4}{3}\pi r_f^3 \rho_f, \text{ kg} \tag{13}$$

where r_f is the fuel radius, m; ρ_f is the density of fuel particles, kg/m^3.

Inputting (12) and (13) into (11), we obtain a formula to determine the number of fuel particles in the layer:

$$N = \frac{3q_f FH\rho_c}{4\pi r_f^3 \rho_f}, \text{ pcs} \tag{14}$$

Considering formula (14), the elementary volume of sinter charge containing only one fuel particle is determined as follows:

$$\Delta V = \frac{4\pi r_f^3 \rho_c}{3q_f \rho_f} \text{ , m}^3 \tag{15}$$

Let us assume that the upper ignited layer of sinter charge consists of the layer of elementary volumes ΔV with the height of h, then the height of the ignited layer is determined with the following equation:

$$h = r_f \sqrt[3]{\frac{4\pi\rho_c}{3q_f\rho_f}}, \text{ m} \tag{16}$$

Now all the components of equation (3) are determined. Let us input formulae (4) and (5), (8) and (9) into this equation, then we will obtain:

$$BV_{fg}c_{fg}\left(t_{fg}^i - t_{fg}^f\right) = m_{il}[c_c(t_i - t_c^0) + q_m Q_e] + w_f F_i \tau c_a(t_a^f - t_a^0) \tag{17}$$

Resolving it with respect to "B", inputting the weight of the ignited layer into it, we will obtain the equation to calculate the consumption of gaseous fuel for the ignition furnace of the sinter machine.

$$B = \frac{wS\rho_c r_f[c_c(t_i - t_c^0) + q_m Q_e]}{V_{fg}c_{fg}\left(t_{fg}^0 - t_{fg}^f\right)} * \sqrt[3]{\frac{4\pi r_f \rho_c}{3q_f\rho_f}} + \frac{w_f Slc_a(t_a^f - t_a^0)}{V_{fg}c_{fg}\left(t_{fg}^0 - t_{fg}^f\right)}, \text{ m}^3\text{/sec} \tag{18}$$

This formula sets the connection of fuel consumption to ignite sinter charge with the main parameters of the sinter machine, type of used fuel and physical characteristics of sintered charge. This formula correlates to the experimental data on increasing of fuel consumption at the increase of charge humidity, decrease of fuel consumption at the initial heating of charge and air supplied to the burners of the ignition furnace. It evidently shows that the consumption of the gaseous fuel increases not only as the moisture of sinter burden rises, but also as the size of fuel particles increases as well as the width of the sinter belt, the speed of its movement and the dispersion under it increase. Besides, this formula sets the relation of gaseous fuel consumption with the charge particle size describing that the consumption of gaseous fuel decreases at increase of dispersed composition of the fuel.

Using (17) it is possible to determine other energy parameters of the process of charge ignition. The intensity of ignition, i.e. the amount of heat obtained from the unit of layer area per unit of time, is defined as:

$$I = \frac{BV_{fg}c_{fg}(t_{fg}^i - t_{fg}^f)}{Sl} \text{ , J/sec} \tag{19}$$

According to obtained formula, the intensity of charge ignition at the sinter belt will be increasing at the increase of fuel consumption and decrease of the area of ignition.

The time of sinter ignition is supposed to determine [5] as a sum of time spent for the heating of fuel particles to the temperature of ignition (τ_h) and time of burning of single fuel particle (τ_b).

$$\tau_f = \tau_h + \tau_b \text{ , sec} \quad (20)$$

The time of layer heating to the temperature of ignition can be determined assuming that the amount of heat transferred with the intensity I during the time of ignition τ_i will be spent for the heating of the upper ignited layer having an area of 1 m^2 till the temperature of ignition.

$$I\tau_i = h\rho_c[c_c(t_i - t_c^0) + q_m Q_e] \quad (21)$$

Taking into account (19) the time of heating will be determined as

$$\tau_h = \frac{Slh\rho_c[c_c(t_i - t_c^0) + q_m Q_e]}{BV_{fg}c_{fg}(t_{fg}^0 - t_{fg}^f)}, \text{ sec} \quad (22)$$

An obtained formula shows that the time of ignition decreases with the decrease of dispersed composition of the fuel, linear sizes of ignition furnace and increase of gaseous fuel consumption.

The time of fuel particle burning can be determined using formula [5]:

$$\tau_b = \frac{q_f r_f \rho_f}{0{,}75 k_f C_{O2}}, \text{sec} \quad (23)$$

where CO_2 is the oxygen concentration in the zone of burning; k_f is the constant of rate of burning for the solid fuel; q_f is a share of carbon in the fuel.

From this formula, it follows that the rate of burning of fuel particles depends on the size of particles. The smaller the fuel particles, the less time of combustion is. Oxygen concentration in the combustion zone greatly influences the time of burning of particles. The flue gases from the furnace, in which the proportion of oxygen is not great, constantly wash the ignition zone. Accounting that to reduce the burning time it is necessary to ensure supply of fresh portions of the oxidant with high oxygen content into this area.

The formula for the calculation of such power parameter as the total amount of heat generated per unit area of the layer from an external heat source, (J/m^2) can be defined as

$$Q^I = I\tau_b \text{ , J/m}^2 \quad (24)$$

According to the formula the total amount of heat generated per unit area of the burning layer from an external source, which is herein ignition furnace, depends on all the factors that affect the intensity and time of ignition.

The specific amount of heat energy that is required for combusting the amount of sinter charge necessary for the production of one ton of sinter is determined with the following equation:

$$q_f = \frac{BQ_l}{\propto \rho_c wSH}, \text{ GJ/т} \quad (25)$$

where q_f is the specific heat input, GJ/t; Q_l is the lowest fuel combustion heat, MJ/m^3; α is the output factor of suitable agglomerate.

It follows from equation (25) that energy intensity of the charge ignition depends on the flow of gaseous fuel to the ignition furnace and on the parameters of the layer: width, height and speed of its movement in the ignition furnace. An important factor is the output ratio of suitable agglomerate.

3. Numerical Study of Obtained Formulae

For numerical study of obtained calculated dependences, with their help we have calculated the energy performance for ignition of agglomerated layer. The calculation is made for the following range of input data: charge humidity is 7-12%, the share of fuel in the mixture is 3,6-6%, the initial temperature of the charge and air is 20°C, the coefficient of the output sinter $\alpha = 0{,}61$, the ignition temperature of the solid fuel is t_i = 700°C, the bulk density of the charge ρ_c = 1800 kg/m^3, the density of fuel ρ_f = 1200 kg/m^3, the value of density in the vacuum chambers is 6000-14000 Pa, the height of sintered layer is 0,15-0,4 m, the diameter of fuel particles is 0,0005-0,003 m, the speed of movement of sinter belt is w = 0,05 m/sec and the width of the ignition furnace is 500 mm.

Figure 1 demonstrates the dependence of specific heat spent for sinter charge ignition on the size of fuel particles, intended for the heights of sinter charge layer H=150 mm and H=400 mm. It is known from literature data [2,6] that the value of specific energy consumption of sinter layer varies in the range from 0,068 to 0,2 GJ. The graph presented in Figure 1 demonstrates that calculated data are well coordinated with experimental data, that indicates the adequacy of the calculated dependencies obtained and the possibility of using the formula (25) for calculating the consumption of gaseous fuel to the ignition furnace and formula (18) for determining the specific fuel consumption for these purposes. The calculation of the intensity of the ignition of sinter charge have also showed good agreement between calculated and experimental data. As stated in [4] in the enterprises of the Russian Federation, the intensity of the heat supply for the ignition charge is I=33-42 MJ/m^2min. According to the calculated data, it varies between I=17-65 MJ/m^2min. Estimated time of heating the layer to the ignition temperature, calculated by the formula (22), ranges τ_h = 7-8 sec, i.e. according to the formula (6) it is almost equal to the time of stay of the burning layer in the ignition furnace τ = 10 sec. Estimated time of burning of fuel particles defined by equation (23) is τ_b = 67-194 sec. It gives us a reason to believe that to take into account the time of the particle burning in the calculation of the time of ignition is incorrect, since the layer does not stay under the ignition furnace for a long time. Just considering the time of burning of particles the time of ignition may reach 1,5-1,8 minutes as specified in [4]. However, in this period, the burned layer stays outside ignition furnace and an external supply of heat into it will not be implemented. Thus, the ignition time of layer can be determined by formula (23), and it should be used to adjust the width of the ignition furnace. With this in mind, the estimated total amount of heat supplied to the ignited layer from an external source, i.e. ignition furnace, is in the settlement within $Q^I = 45$ MJ/m^2.

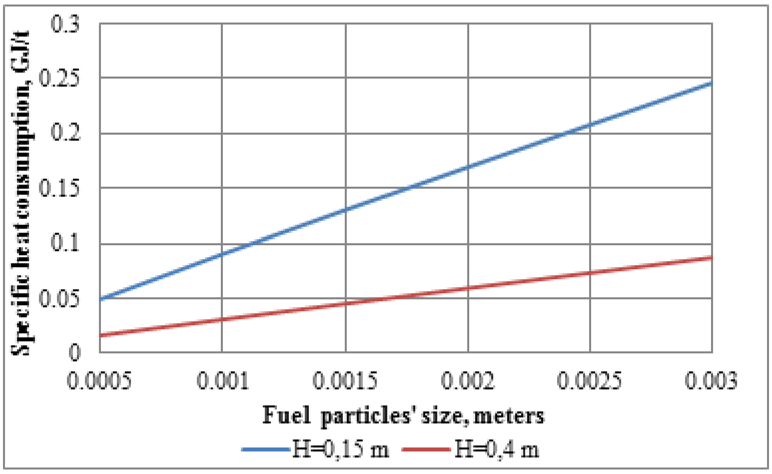

Figure 1. *Dependence of energy consumption for charge ignition on fuel particles' size.*

Furthermore, the dependence obtained enables us to determine the causes of gaseous fuel overconsumption in sinter production in CIS countries. First of all, these facilities commonly practice sintering of lower layers of charge (280 mm), that increases the specific energy consumption for its ignition in comparison with the layer of the height of 400 mm. Fuel consumption could also be influenced with failure to meet the requirements to moisture content in sinter charge and to the size of fuel particles. In CIS sinter plants, many of which working on fine-grained concentrate of Krivoy Rog ore, the consumption of water for wetting the surface of the particles prior to pelletizing, due to the large specific surface area, will be greater than when wetting coarser concentrates. In this connection, sintering plants, in particular in Ukraine, often work with moisture of sinter charge equaled to 12%, taking into account that the standard moisture contentment is 7% that significantly increases the consumption of gas for ignition furnace [2]. According to the calculations carried out according to the equation (25) with increasing moisture content of the charge in this range the energy intensity of the ignition process is increased by 8 to 10%.

The resulting equations for calculating the energy performance of ignition of sinter layer show that particle size distribution of sinter charge has a significant impact on energy consumption of the ignition process. The finer the fuel, so they are lower. According to the existing guidelines, the size of fuel particles in sinter charge should be at the level from 0,5 to 3 mm, that lets to avoid emitting of fuel particles from the sintered layer, to decrease the fuel underburning and decrease CO emissions [7]. To provide reduction of fuel consumption by reducing the size of the fuel particles is possible by bedding the surface of sinter charge with dry fine fuel powder as the burning layer. This will eliminate the consumption of energy for evaporation and heating of the other components of the charge in the ignited layer.

Reducing the energy characteristics of the process of sinter charge ignition can be achieved by preheating of the charge with gases exhaust from the cooling zone of sinter [4,8 -10]. For this purpose, it is necessary to provide the recirculation of flue gas between cooling zone and sintering zone [4]. Most effectively, this process will be carried out at lower volume of sinter gases, by preventing uncontrolled air leaks to sinter gases. This can be achieved by covering the sinter belt [6]. This arrangement not only reduces energy consumption for the layer ignition, but also improves the other environmental performance of sintering process. Filtration of gas through a layer of charge reduces dust emission from sinter machine, allows to burn the CO contained in sinter gas, reduces its output and enables the use of a chemical heat generated in the oxidation of carbon monoxide.

Preheating of the air supplied to the burners of ignition furnace improves the energy characteristics of the ignition process of agglomerated layer. This process can be executed by supplying of the burner with the air heated by the exhaust gases from the sintering machines [11] and using the heat accumulated by refractory brickwork of the furnace having a special structure [12].

CIS sintering enterprises use natural gas in the ignition furnace. In the EU ignition furnaces are supplied with a mixture of coke oven and blast furnace gases [2,6]. Calculations show that the replacement of natural gas with coke and blast mixture triples the gas flow, but reduces the energy consumption for the charge ignition by 6%. The other energy parameters remain almost the same.

4. Conclusions

1. The dependencies for determining the energy efficiency of the process of ignition of sinter charge such as flow of gaseous fuel, ignition time, intensity of ignition, the total amount of heat supplied to the layer from external sources and energy intensity of the process were obtained. These equations enable us to determine the energy characteristics of the charge ignition process depending on the basic parameters of the sintered charge, fuel combusted in furnace and design of sintering machine.
2. The comparison of the calculated data with published experimental data has shown the adequacy of the

obtained dependencies.

3. Numerical study of the calculated dependencies showed the influence of different technological characteristics of the sintering process on the energy performance of the charge ignition. It was shown that significant reduction of their values could be achieved by the use of fine fuel, reducing the moisture content of the charge and preheating of the charge and air supplied to the burners with flue gases. With the increase of the height of the sintered layer, the energy consumption for the charge ignition is reduced proportionally.
4. Causes of gaseous fuel overconsumption at sintering plants of CIS countries were analyzed. It was shown that the increased power consumption of charge ignition process is due to the increased moisture content of the charge, usage of fine iron concentrate, sintering of low layers and lack of the system of gas recirculation in the sintering machine.

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