Mathematical modelling of thermal and physical-chemical processes during sintering

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Considered is an approach to simulation of sintering processes having regard to almost all the significant processes typical for such kind of physical-chemical effects on raw materials. Mathematical formulation of a sintering process includes the relations which allow describing the time history of fractional void volume based on rheological models of moisture evaporation from the surface of particles. There are also taken into consideration the gas pressure changes throughout the height of fractional void volume, which appear on decarbonization, coke burning, strengthening during agglomeration, heat exchange between the solid and gas phases. Analysis of the sinter green ignition modes which allow cutting down the fuel consumption has been carried out. Obtained was the behaviour of the fuel combustion front at an initial agglomeration stage until the steady coke brining conditions. The parameters of a layer relevant to the stable passing of the sintering process have been revealed. Mathematical model permits the influence of difference parameters on thermalphysic processes passing in a layer during the course of agglomeration to be qualitatively assessed. According to the results of calculations of the ignition process, the coke burning front formation occurs at a certain depth, when the combustion becomes stable. Thus, heating of the upper charge layer with finite thickness is necessary during the ignition, which agrees with practical results. Removal of moisture and dissociation of carbonates proceed almost simultaneously with coke burning and represent a narrow area throughout the height of the layer. The model provides qualitative dependences of thermal parameters of the process and permits analyzing an impact of any parameter on the behaviour of the system. The dependence of the ignition time on the gas flow rate is investigated. Reliable ignition is achieved owing to the intensification of the charge heating, while reducing the heat consumption in the furnace of a sintering machine. The model and the results of its implementation may be used both in ferrous and non-ferrous metallurgy.

Key words: sintering, heat exchange, gas dynamics, drying, ignition, decarbonization, agglomeration, mathematical model, ignition modes.

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Introduction

Urgency of applying the ore fines sintering processes is increasing with the time passing, since waste treatment during aluminium, lead and other non-ferrous metals production gains more and more importance. Depletion of bauxite deposits, availability of multiple dumps of lead sulfide ore fines, which pollute the landscape and affects regional ecological situation, bring an exigency of wastes recycling for main production process.

The problem of equipment adaptation to changes of an operating mode according to variations of the raw material properties belongs to a class of the resource-saving and ecological ones, since the unforeseen changing of aggregates functioning in power-consuming industries usually leads to the growth of energy inputs per a product unit and variation of emissions. The issues of resource economy and ecology are of great importance in metallurgy [1–5].

In a sintering process, air is fed into a layer for coke combustion and heat transfer from the heated upper charge layers to the lower ones. Heat exchange has a regeneration nature, that is, the gases sucked through the layer transmit the heat from upper layers to the lower ones. Zone of sinter formation moves down at a rate, which is specified by the heat exchange conditions and the rate of physical-chemical conversions.

The layer sintering is one of the most perfect technological processes with reference to the heat. At a fuel rate of 3–7%, the charge is brought to softening and partial burn-off with attainment temperatures in the neighborhood of 1500 °C in a sinter formation zone. High heat utilization efficiency is achieved on the fuel combustion within the sintered layer with a large specific surface area of charge particles, providing high intensity of heat exchange between gases and sintering mixture. Design of sintering machines and energy exchange processes possess certain technology features in each individual case, and influence of circuitries is sometimes very efficient [6–8]. The sintering process is accompanied by compacting of material which is connected with the fractional void volume changes and corresponding hydraulic friction increase in the sintering zone. Both solid-phase and liquid-phase sintering may be fulfilled with predominance of different mechanisms subject to the raw material composition and agglomeration conditions. The processes which accompany and determine thermophysical pattern of sintering are interrelated and non-linear, yet an experimental analysis of the equipment behaviour is connected with considerable expenses, therefore mathematical modelling is a universal approach to assessment of such a complicated system as sintering [9–12].

Mathematical model of a sintering layer

It is supposed that the layer is uniform with uniformly distributed coke particles. Heat exchange between the particles is realized by means of gaseous heat carrier, in other words, by convection.

Heat balance of an elementary *dy* thick layer allows noting down necessary equations for sintering mixture and gases as follows:

$$(1-\varepsilon) r_m c_{pm}\, \partial t_m/\partial\tau = \alpha_v (t_g - t_m) + \Sigma_i \rho_i \omega_i Q_i; \qquad (1)$$

$$-\varepsilon\rho_g W_g c_{pg}\, \partial t_g/\partial y = \alpha_v (t_g - t_m)\ ; \qquad (2)$$

$$\partial c_{O_2}/\partial y = K_S^{O_2} c_c (\rho_m/\rho_c)(c_{CO}/c_c)^{1/3}(6/d_{CO})\times \times(c_{O_2}/W_g)\ ; \qquad (3)$$

$$\partial P/\partial y = 3/2[(1-\varepsilon)/\varepsilon\psi](1 + 422/R_{em})(\rho_g W_g^2/d_m)\times \times(Pr_c/Pr_g)^{0.33}\ ; \qquad (4)$$

$$\rho_g W_g \partial x_w/\partial y = \beta_W f_{sp}(P_{VR} - P_V)/R_V T_g; \qquad (5)$$

$$w_1 = \partial u/\partial\tau = \beta_W f_{sp}(P_{VR} - P_V)/\rho_m R_V T_g; \qquad (6)$$

$$\omega_1 = \partial\eta_1/\partial\tau = k_{0l}(1-\eta_l)^{nl}\exp(-E_l/RT_m), l = 2.3; \qquad (7)$$

$$\omega_4 = \partial c_c/\partial\tau = \beta_c W_g(\rho_{O_2}/\rho_m)\ (\partial c_{O_2}/\partial y); \qquad (8)$$

$$\omega_5 = \partial\varepsilon/\partial\tau = 2\sigma_T\varepsilon/(4/3)\mu_m(1-\varepsilon)^2\rho_m. \qquad (9)$$

Initial and boundary conditions are as follows:

$$\tau = 0,\ t_m = t_{m0},\ \varepsilon = \varepsilon_0,\ \eta = \eta_0,\ u = u_0,\ c_c = c_{c0}; \qquad (10)$$

$$y = 0,\ t_g = t_{g0},\ p = p_0,\ c_{O2} = c_{O20},\ x_w = x_{w0}, \qquad (11)$$

where t_m, t_g, ρ_m, ρ_g, c_{pm}, c_{pg} — temperature, density, heat capacity of material and gas; ε — fractional void volume of the layer; $\omega_к$ — rate of moisture evaporation, decarbonization, coke burning-out, agglomeration; Q_k — corresponding calorific effects of these processes; c_{O2}, c_c — concentration of oxygen and coke; β_c is a stochiometric coefficient; K_s^{O2} is a specific surface combustion rate constant; ρ_c is density of coke particles; d_c is a diameter of coke particles; ρ_{O2} – density of oxygen; ν_g — kinematic viscosity of gases; σ_T — coefficient of surface tension; μ_m — dynamic viscosity of the fused material; r_m — radius of the sintered particles; P_{VR} , P_V — pressure of moisture vapours on the surface of particles and in gases; R_V — gas constant of water vapours; β_W — overall mass transfer coefficient; d_m — diameter of charge particles; ψ is a fractional void volume dependent parameter.

Durability is connected with fractional void volume by a semiempirical correlation $\sigma = \sigma_K\exp(-b\varepsilon)$, where b is an empirical coefficient.

The charge particles are accepted as thermically thin, since the Biot number criterion for this system is less than 0.1. Equations (1), (2) describe heat exchange between the charge and gas phase, the role of which play an air before the combustion front and combustion products below the combustion front line. An oxygen decrease takes place during combustion process, that is, on the surface of coke particles within the layer. Material oxygen balance (3) is written down taking into account an association between coke concentration with diameter of coke particles $(c_c/C_{cO}) = d_c/d_{cO}$). Hence, coke combustion in a layer is described by differential equation (8), interrelated with the ratio for estimation of the oxygen concentration changes. As it follows from these equations, the coke combustion rate is affected by: diameter of coke particles; the coke content in sintering mixture; density of coke and sintering mixture; an oxidant concentration in heat carrier. In its turn, the oxygen concentration is determined by: environment; thermal mode in a combustion zone; pressure of gases in the layer. Pressure of gases varies by layer depth and is described by equation (4) with anisothermic correction. The Reynolds criterion is determined by the following formula: $Re_m = W_g d_m/\nu_g\psi$. The moisture transfer processes, described for the steady speed mode are represented by ratios (5), (6), as well as by the following dependences: $P_{VR} = 617.7\exp[17.25t_m/(238 + t_m)]$, $P_v = Px_w/(0,622 + + x_W)$. Equations (7) describe kinetics of dissociation of carbonates (7). The sintering process is accompanied by compacting of material, which is connected with the fractional void volume changing and corresponding growth of hydraulic friction in a sintering zone. Both solid-phase and liquid-phase sintering may be fulfilled with predominance of different mechanisms subject to the raw material composition and agglomeration conditions. Ratio (9), based on rheological model which allows reflecting the fractional void volume change dynamics, is used for describing these processes. Generally, to estimate the rate of agglomeration and sinter manufacturing it is necessary to know heat capacity of material, which appreciably depends on the phase transformations kinetics and combustion kinetics, as well as concomitant endothermic processes of dissociation of carbonates. Heat capacity should be rising taking into account calorific effects for decomposition of $CaCO_3$ ($Q = 1778$ kJ/kg) and $MgCO_3$ ($Q = 1395$ kJ/kg), as well as phase transformations in the course of melting the charge particles. In an ignition process and in the further agglomeration process, the hot gases impact on sintering mixture is in the first place connected with moisture removal out of pellet particles. On analyzing the initial stage of heat exchange in a layer, it is necessary to estimate drying rate, gas and material temperatures at this stage. Solution of combined equations permits analyzing effects of operating measures on sintering energy. Standard integration procedures for ordinary differential equations are found to be quite fruitful.

On basis of the considered model of sintering process, a software program for analysis of the sintering machine operating modes has been elaborated. The program allows to visualize thermal, hydrodynamic field and moisture distribution in the layer in the course of drying. User-friendly interface supports conversational mode for controlling the heat exchange processes in the layer, agglomeration by varying hydraulic action, sintering time by varying travel speed of pallets. With the help of this integrated environment one can analyze influence of the charge chemical composition, granulometric composition, binding additions, bed on thermal behaviour of sintering layer, ignition conditions, agglomeration, and the sinter strength. Finally, the program serves as a computer simulator for training of operators in habits of the sintering machine control. The program uses the ideas of virtual reality, that is, allows fixing inaccessible areas of the object of control, permitting to monitor physical state of the layer and to reach the reasoned technical decisions about control parameters.

Verification of the sintering model

Verification of mathematical model of heat exchange during sintering and parameters of the sintering machine computer trainer has been implemented by comparison of the release testing results and design characteristics. The results of release testing carried out in accordance with the sectoral scientific and technical program have been adduced as typical ones [13]. In the course of testing, the charge granulometric composition has been determined given different modes of charge loading, which has allowed to make certain of satisfactory accuracy with which the granulometric composition influence on the layer gas-dynamics and the process as a whole is reproduced by the model.

Features of the charge layer are listed in Table 1. Data on the strength of obtained sinter are also placed in it. As it is evident from the results, the sinter ranks below pellets in strength (Table 2).

The study has been implemented on sintering machines No. 1, 2, 3 of Novodzhambul Phosphorus Plant at the charge loading onto pallets of the sintering machine by drum feeder with deflector, the slope of which was against travel of pallets (experiment 1); without deflector (experiment 2) and with deflector, the slope of which was in the direction of travel of pallets (experiment 3). Depending on the feeding way, the charge material distribution has been varying throughout the height of the layer (Table 1). The most favourable conditions for the charge permeability have been formed in experiment 3, which has permitted to increase the agglomeration rate and output by useful sinter of the sintering machine (Table 2).

The layer parameters realized in experiments have been set for performance check of mathematical model. An agglomeration rate has been determined by time of coke burning-out up to 98%. Table 2 contains the results of calculations.

An average sintering time obtained by calculations is in absolute value under the experimental ones, but qualitatively it reflects the mechanisms of the process correctly, with inaccuracy of about 30%. As it follows from the testing results, manufacturing of one ton of useful sinter requires about 20 kg of oil equivalent per ton of natural gas and 110 kg of oil equivalent per ton of coke to be consumed.

Verification of mathematical model of heat exchange during sintering by comparison of the release testing characteristics and the design ones has demonstrated quite satisfactory quantitative and qualitative description of the processes.

The heat losses with sinter come to practically half of all the supplied heat. According to the balance of sintering machine: in target processes (drying, decarbonization, sintering) — 8%; losses with waste-gases — 38%; losses with sinter heat — 51%.

Analysis of the coke ignition modes in the furnace of sintering machine

Analysis of the coke ignition modes in the furnace of sintering machine has been implemented using the program, which realize the examined mathematical model of heat exchange in the course of sintering process and permit to estimate an influence of main factors on sintering process to a first approximation.

An ignition is interpreted as a process of the charge warming-up to the temperatures, at which generation of heat owing to chemical reactions would be sufficient for maintenance of steady-state combustion. Sintering process may be conditionally divided into two stages: ignition in the furnace of sintering machine; agglomeration of the charge on an oxidant feeding into the layer and burning of coke particles.

Quality implementation of the first stage stipulates in many respects further passing of sintering process. An excessive charge warming-up at the ignition stage may lead to deterioration of gas-permiability of the layer and lessening the sinter strength. The temperature irregularities over volume of the furnace may present an additional reason of poor ignition.

The process in the furnace of sintering machine runs with feeding an oxidant, the amount of which depends on excess air coefficient, supplied to burners, and air inflows. After the furnace, concentration of oxygen changes as air is fed into the layer. During testing of sintering machines there have been determined the heat parameters in a furnace, which characterize an ignition effect on sintering time. Analysis of ignition processes has been fulfilled at constant temperature of gases at the entry to the layer. Data on thermophysical properties of phosphorites has been assumed as temperature independent. According to the results of ignition calculations (Fig. 1), the combustion front formation takes place at the depth 0.06 m. In that case, burning becomes steady, heating of the upper charge layer with finite thickness is necessary during the ignition, which agrees with practical results.

The moisture removal process and dissociation of carbonates proceeds almost simultaneously with the coke burning and occupy relatively narrow area throughout the height of the layer.

The model provides qualitative dependences of thermal parameters of the process and permits analyzing an impact of any parameter on the behaviour of the system. In particular, the dependences of the ignition time on the

Table 1

Grading of ore fines (phosphorite) in the course of release testing

Method of charging	Components of the charg	Fraction by size grade	Relative height of a layer 0.0	Relative height of a layer 0.5	Relative height of a layer 1.0	Strength State Standart 15137–77
Ordinary (experiment 1)	ore fines phosphorite	+10	3.3	3.3	2.7	
		+5	17.4	16.2	21.4	
		+1.6	21.1	26.5	23.6	
		+1	9.5	7.2	7.5	
	coke	–1	16.8	14.7	13.6	
		+3	0.9	1.0	1.0	
		+1.6	1.0	1.2	1.6	
		+1	0.9	0.9	0.4	
	returns	–1	2.7	2.1	2.0	
		+5	3.5	4.8	5.0	
		+1.6	15.8	17.0	18.4	
	ore fines phosphorite	+1	4.5	3.1	1.3	7.9(–5)
Charging without deflector (experiment 2)		–1	2.6	2.0	1.5	68.8(+5)
		+10	3.1	2.9	2.9	
		+5	16.0	15.1	15.9	
		+1.6	23.5	22.2	26.2	
	coke	+1	3.2	4.1	2.2	
		–1	20.4	17.2	20.5	
		+3	0.5	0.9	1.1	
		+1.6	1.4	1.5	0.6	
	returns	+1	0.5	0.7	1.0	
		–1	2.0	1.9	1.8	
Charging with the deflector slope along the pallet movement (experiment 3)		+5	4.3	4.5	3.5	
	ore fines phosphorite	+1.6	20.6	24.5	20.0	
		+1	1.9	1.7	2.6	7.8(–5)
		–1	2.3	2.8	1.7	69.1(+5)
		+10	3.9	3.5	0.5	
		+5	17.2	12.2	14.2	
	coke	+3	20.8	20.1	21.0	
		+1	22.0	20.7	20.5	
		–1	8.3	8.0	10.1	
		+3	0.6	0.4	0.5	
	returns	+1.6	–	–	–	
		+1	1.3	1.5	1.6	
		–1	2.0	2.1	2.7	
		+5	0.7	1.5	0.8	
		+3	12.3	13.2	12.2	
		+1	8.6	12.4	9.8	6.4(–5)
		–1	2.2	4.4	6.1	70.2(+5)

Table 2

Performance of the ore fines (phosphorite) sintering process in the course of release testing

Characteristic	Dimension	Experiment 1	Calculations	Experiment 2	Calculations	Experiment 3	Calculations
Height of a layer	mm	230	230	250	250	250	250
Traverse speed of pallets	m/min	4.52	4.52	4.6	4.6	4.62	4.62
Charge rate	t/h	301	301	307	307	310	310
The ore fines of phosphorite consumption	t/h	187	187	210	210	215	215
Coke rate	t/h	12.6	12.6	14.7	14.7	15.2	15.2
Returns rate	t/h	78	78	85	85	88	88
Humidity of charge	%	26	26	28	28	25	25
Gas flow in furnace	Thous. m^3/h	7.6	7.6	7.1	7.1	7.4	7.4
Air consumption	Thous. m^3/h	64.5	64.5	61.5	61.5	67.8	67.8
Temperature by section 1	°C	1185	1185	1180	1180	1180	1180
Temperature by section 2	°C	1169	1169	1200	1200	1190	1190
Temperature by section 3	°C	850	850	900	900	870	870
Filtration rate	m/s	0.43	0.43	0.41	0.41	0.48	0.48
Agglomeration rate	mm/min	13.4	9.3	14.7	11.6	14.8	13.0
Output by useful sinter	t/h	134	101	150	123	155	136

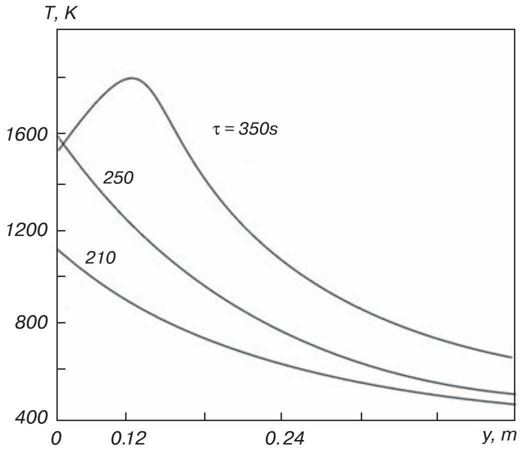

Fig. 1. Distribution of temperature of gases and sintering mix by layer depth

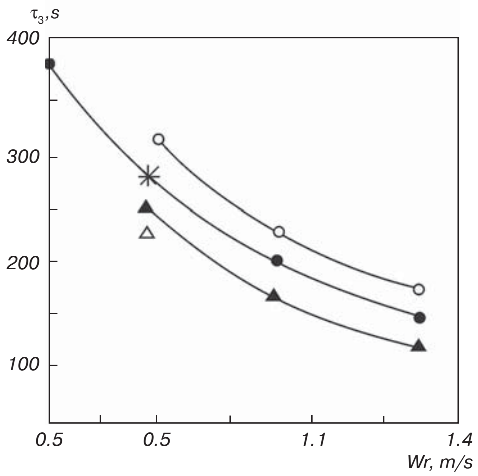

Fig. 2. Dependence of ignition time on the mode of gas feeding into the layer:
— T_g =1373 K, c_{O_2} = 0.21; — 1473 K, 0.21; — 1573K, 0.21;
○— 1573 K, 0.21 (impulse ignition) ●; ∗ – 1573K, ▲ 0.12; *W*r — rate
△ of gases fed into the layer

gas flow rate (normal speed of gases advance into the layer) and the temperature of combustion products are depicted in Fig. 2.

It is obvious, that the intensity of thermal processes in the layer is affected not only by gas temperature, but also by the gas suck speed, increase of which causes an energy exchange between gases and charge. This suggests that it is possible to achieve more reliable ignition by increasing the rate of gas feeding at initial ignition stage, and to reduce heat inputs in the furnace of sintering machine by intensification of charge warming-up.

Similar results regarding lessening the sintering time when decreasing rate of gases in the sinter layer are obtained in [14—15].

Conclusion

In the coming years, pelletizing and sintering would be the prevailed technologies due to ore reserve depletion, when processing of ore fines from dumps is profitable. In particular, the depletion of bauxite deposits is already felt for the Russian Federation. At the same time, some well-organized enterprises actively use the ore fines even at present, partially eliminating the territory contamination and utilizing the ore fines, which are considered as wastes.

The examined model of sintering process allows to analyze influence of different factors on ignition and agglomeration of sintering mix taking into account its granulometric composition, moisture removal and drying the charge materials, changes of gas-permiability of the layer, the fuel burning out. Application of the model makes possible to tune the modes of gas feeding into the layer in order to rise the efficiency of heat exchange between material and gases and in that way to form a heat impulse of high temperature, which improves the ignition mode by local thermal effect on fuel components of sintering mix. The fuel distribution among the burners in the furnace of sintering machine permits to analyze an impact of temperature of the gases on ignition mode and to choose the conditions close to optimum.

The processes studied in this paper are energy-efficient, since they provide saving of natural gas. Though share of costs on ignition mode is not so big, the total fuel economy for production as a whole and even more so for the entire industry may be quite weighty.

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