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MATHEMATICAL SIMULATION OF CHEMICAL AND ENERGOTECHNOLOGICAL PROCESSES AND PROCEDURES OF COKE FINES BURNING IN AGGLOMERATED LAYER

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ABSTRACT

The paper is devoted to chemical and metallurgical processes of pelletizing of iron ore raw material. Thermally activated chemical and energotechnological processes of raw material sintering in iron and steel industry are considered, as well as mathematical models for their description, taking into account the following physical and chemical transformations: moisture evaporation, firing of coke fines, dissociation of carbonates, burning of coke fines, melting of charge particles, appearance of sintering cake, condensation of moisture vapours in the lower levels of the agglomerated layer of sinter charge. The features of conducting of these processes in different levels of agglomerated layer are researched. The results of analysis of the effect of fuel firing procedure in the hearth of a sintering machine on sintering process and the results of forming of the burning area and period of stable burning (i.e. finishing time of firing process) are examined. The effect of the following parameters: initial stage of the reaction front dissemination during dissociation of carbonates, burning-out of coke fines, oxygen consumption for the sintering process are investigated. The relationship between firing time of agglomerated layer (from one side) and heat-carrying gas consumption and temperature of burning products (from other side) is presented.

Introduction

Sintering of iron ore materials in belt-type conveyors (sintering machines) is the main method of pelletizing of these materials before blast furnace practice in metallurgical industry [1, 2]. Processing of complicated and heterogeneous raw materials in iron and steel industry needs their preliminary thermal processing in order to provide meeting by raw materials all required technological properties as well as homogeneity in granulometric composition, absence of hygroscopic and chemically bound water, containing of minimal amount of carbonates, gaseous and harmful impurities [3, 4]. Different physical and chemical endothermic transformations conduct simultaneously at different layer heights during charge sintering in the layer [5]: moisture evaporation, firing of coke particles, dissociation of carbonates and other chemical reactions, coke burning and melting of charge particles, appearance of sintering cake, condensation of moisture vapours in the lower layers. All these processes depend on heat exchange conditions in the layer [6–8]. Sintering in the layer is considered as one of the most perfect chemical and technological processes in the heat and power meaning [9–12]. Charge material is processed to its softening and partial melting at fuel consumption from 3–7%, with achievement of temperature about 1500 °C in the area of sinter forming [13–16]. The sintering process is characterized by air sucking through agglomerated layer of charge, what provides fuel burning and heat transfer from heated upper layers of charge to the lower layers [17, 18].

The aim of the research

The presented paper is aimed on completion of the data required for mathematical description of heat and mass transfer chemical and energotechnological processes in metallurgical sintering machines based on deterministic multi-scale mathematical models. The considered models of heat and gas dynamic processes can be used for optimization of operating procedures in the existing sintering machines, as well as for calculation of parameters during their designing.

Methods and materials

Let's analyze the main relationships for description of agglomerated layer drying at cross feed of heat-carrying gas with temperature t_{g_0}. Let's consider surfacial moisture evaporation. We shall accept that gas and particles near the surface are characterized by equilibrium state at the temperature t_m of wet thermometer.

The heat balance for a flow of heat-carrying gas is presented by the equation:

$$-r_g c_g W_g (dt_g/dy) = \alpha_V (t_g - t_m). \tag{1}$$

The boundary conditions make $y = 0$, $t_g = t_{g_0}$, where c_g — gas heat capacity; α_V — volumetric heat exchange ratio; t_g — gas temperature in the layer; y — coordinate of the layer height; W_g — gas rate in the layer.

The equation (1) with mentioned boundary conditions can be solved in the following way:

$$t_g = (t_{g_0} - t_m)\exp(-by), \qquad (2)$$

where $b = \alpha_V/(c_g W_g)$.

Varying of material moisture content in the layer is also connected by the heat balance and is described by the next equation:

$$\rho_m L_i (du/d\tau) = -\alpha_V (t_g - t_m). \qquad (3)$$

The initial conditions: $\tau = 0$, $u = u_n$, where u — moisture content in charge; u_n — initial moisture content in charge; L_i — heat of moisture evaporation; τ — time.

Integration of (3) equation with corresponding initial conditions and using (2) equation finalizes in the following relationship:

$$u = u_n - (\alpha_V/\rho_m L_i))(t_{g_0} - t_m)\exp(-by)\tau. \qquad (4)$$

The balance based on evaporated moisture makes it possible to evaluate moisture content in gases x_w for initial moisture content in gases x_{w_n}:

$$-\rho_m (du/d\tau) = \rho_g W_g (dx_w/dy), \qquad (5)$$

where ρ_m — material density; ρ_g — gas density.

Thereby we integrate with initial conditions $y = 0$, $x_w = x_{w_n}$, and taking into account (2–4) we get the equation: $x_w = x_{w_n} - ((\alpha_V b)/(\rho_g W_g L_i))(t_{g_0} - t_m)[1 - \exp(-by)$.

When the upper layer of charge reaches equilibrial (with gases) moisture content u_g, after τ_g time the drying area starts its motion down, i.e. evaporation front begins to move. The time interval τ_g is calculated from the equation (4) for the following conditions: $y = 0$, $\tau = \tau_r$, $u = u_r$

$$\tau_r = ((u_n - u_r)(t_{g0} - t_m))/(\alpha_V/(\rho_m L_i)). \qquad (6)$$

Analyzing the motion of evaporation front, we shall consider that at present time the charge on evaporation front heats immediately from t_m to t_{g_0}, while gases are cooled to the temperature t_{g_ξ}. Based on the heat balance on evaporation front, we shall get the expression for the rate of a.m. flow:

$$d_\xi/d\tau = (\alpha_V/(\rho_m L_i))(t_{g_\xi} - t_m)/(du/dy)_{y=\xi}. \qquad (7)$$

Thereby, we need to know the gas temperature t_{g_ξ} on evaporation front and $(du/dy)_{y=\xi}$ value for evaluation of drying rate.

Gas temperature in the area of phase transition t_{g_ξ} is determined from the heat balance equation for dried area, taking into account a.m. allowances:

$$\rho_g c_g W_g (t_{g_0} - t_{g_\xi})d\tau = (1 - \varepsilon)\rho_m (c_m + c_w u_\xi)(t_{g_0} - t_m)d_\xi.$$

Therefore

$$t_{g_\xi} = t_{g_0} - a_w (t_{g_0} - t_m)(d_\xi/d\tau), \qquad (8)$$

where $a_w = [(1 - \varepsilon)\rho_m (c_m + c_w u_\xi)]/[\rho_g c_g W_g]$.

After integration of the heat balance equation within the limits of the wet area from $_\xi$ to y we shall get the relationship: $t_g = t_m + (t_{g_\xi} - t_m)\exp(-b(y - \xi))$, and replacing t_{g_ξ} by the expression (8), we shall have

$$t_g = t_m + \left(t_{g0} - t_m\right)\left(1 - a_w\left(d\xi/d\tau\right)\right)\exp\left(-b\left(y - \xi\right)\right). \qquad (9)$$

Distribution of moisture content in material is got via integration of evaporation kinetics within the limits from τ_r to τ with conditions $\tau = \tau_r$, $u = u_r$:

$$u = u_r + \left(\alpha_V/\left(\rho_m L_i\right)\right)\int_{\tau_r}^{\tau}\left(t_g - t_m\right)d\tau. \qquad (10)$$

Using the equation (4) at $\tau = \tau_r$, we shall get: $u_r = u_n - (\alpha_V/(\rho_m L_i))(t_g - t_m)\exp(-by)\tau_r$.

Let's rewrite the equation (10) taking into account the equation (9) as follows:

$$u = u_n - \left(\alpha_V/\left(\rho_m L_i\right)\right)\left(t_{g0} - t_m\right)\exp(-by)\times$$
$$\times\left[\tau_r + \int_{\tau_r}^{\tau}\left(1 - a_w\left(d\xi/d\tau\right)\right)\exp\left(b\xi\right)d\tau\right]. \qquad (11)$$

From the equation (11) we shall conclude the expression $(du/dy)_{y=\xi}$:

$$(du/dy)_{y=o} = b\left(\alpha_V/\left(\rho_m L_i\right)\right)\left(t_{g0} - t_m\right)\exp\left(-b\xi\right)\times$$
$$\times\left[\tau_r + \int_{\tau_r}^{\tau}\left(1 - a_w\left(d\xi/d\tau\right)\right)\exp\left(b\xi\right)d\tau\right]. \qquad (12)$$

Placing t_{g_ξ} from the equation (8) and expression $(du/dy)_{y=\xi}$ from the equation (12) in the equation (7), we shall have:

$$d\xi/d\tau = \frac{1 - a_w\left(d\xi/d\tau\right)}{b\left[\tau_r\exp\left(-b\xi\right) + \int_{\tau_r}^{\tau}\left(1 - a_w\left(d\xi/d\tau\right)\right)d\tau\right]}.$$

For the case of permanent drying rate and taking into account that $\xi = 0$ if $\tau = 0$, we shall get:

$$d_\xi/d\tau = 1/(a_w + b\tau_r). \qquad (13)$$

Integrating of the equation (13) within the limits from τ_r to τ finalizes in:

$$\xi = (\tau - \tau_r)/(a_w + b\tau_r). \qquad (14)$$

Substituting the equations (13) and (14) in the equation (11) and integrating then the obtained expression, we can write down the expression for distribution of moisture content in the wet area:

$$u = u_n - (\alpha_V/(\rho_m L_i))(t_{g_0} - t_m)\exp(-b(y - \xi))\tau_r.$$

Otherwise, after replacement of t_r from the equation (6), we have:

$$u = u_n - (u_n - u_r)\exp(-b(y - {}_\xi)). \qquad (15)$$

The balance equation for evaporated moisture (5) allows to obtain distribution of moisture content in the gaseous phase after substitution the equation (15) and integration within the limits from ξ to y, taking into account the condition

$$y = \xi, x_w = x_{wr}\text{:}\ x_w = x_{w_r} + \frac{(u_n - u_r)\rho_m(1 - \exp(-b(y-\xi)))}{\rho_g W_g(a_w + b\tau_r)}.$$

Description of heat exchange in the agglomerated layer is based on the energy equations for solid and gaseous phases. Sintering charge is characterized by the size of particles as large as 5–6 mm, while coke fines are added as fuel. These coke fines meet the following requirements: size of particles 0–3 mm, doses from 3 to 7%, ash content within 12%, sulfur less than 0.5%, moisture up to 12%, volatile compounds less than 1.5%. Bio criterion is not very nigh for sintering process [19].

Heat exchange between the particles of sintering charge is conducted using heat-carrying gas, i.e. via convection [20]. The heat balance of the elementary layer with dy thickness can be expressed as the equation for charge:

$$(1-\varepsilon)\rho_m c_m \left(dt_m/d\tau\right) =$$
$$= \alpha_V\left(t_g - t_m\right) - \omega_k\rho_m q_k + \omega_s\rho_m q_s - j_w L_i - \omega_m Q_{pl}\,, \quad (16)$$

where ω_k, ω_s, j_w, ω_m — rates of decarbonization, coke burning-out, moisture evaporation and sintering; q_k, q_s, L_i, Q_{pl} — corresponding heating effects of these processes.

To evaluate fuel burning-out, we shall write down the material balance of consumption of oxygen and coke fines in the agglomerated layer during burning process [21]:

$$dc_c\rho_m dyS = \beta_s SW_g d\tau\rho_{O_2} dc_{O_2}\,, \quad (17)$$

where dyS — volume of the elementary layer with height dy and square S; $SW_g d\tau$ — volume of gases, entering in this volume of the elementary layer during time period $d\tau$; c_{O_2}, c_c — oxygen and coke concentration respectively; β_s — stoichiometric coefficient.

Oxygen decrease occurs during burning, i.e. on the surface of particles of coke from the elementary layer. Oxygen material balance can be written as follows:

$$SW_g\rho_{O_2} dc_{O_2} = K_S^{O_2}\rho_{O_2} c_{O_2} dS_{ch}\,, \quad (18)$$

where $dS_{ch} = (6Sc_s\rho_m dy)/(d_s\rho_s)$ — surface of coke particles in the elementary layer; $K_s^{O_2}$ — constant of specific surfacial burning rate; ρ_s — density of coke particles; d_s — diameter of coke particles; ρ_{O_2} – oxygen density.

Then we can conclude from the equation (17):

$$\partial c_c/\partial\tau = \beta_s W_g\left(\rho_{O_2}/\rho_m\right)\left(\partial c_{O_2}/\partial y\right).$$

Based on the balance of oxygen consumption during burning we have from the equation (18):

$$\partial c_{O_2}/\partial y = K_S^{O_2} c_c\left(\left(6\rho_m c_{O_2}\right)/\left(\rho_s d_s W_g\right)\right). \quad (19)$$

Based on this balance, we shall write down the connection between content of coke fines and diameter of burning-out coke particle $c_c/c_{c_0} = (d_s/d_{s_0})^3$. Expressing d_s and substituting it in the equation (19) we shall have:

$$\partial c_{O_2}/\partial y = K_S^{O_2} c_c\left(\left(6\rho_m c_{O_2}\right)/\left(\rho_s d_s W_g\right)\right)\sqrt[3]{c_{c0}/c_c}\,. \quad (20)$$

Therefore, burning of coke fines in the agglomerated layer is described by the two mutually connected differential equations for varying of concentration of oxygen and coke fines. It can be concluded from these equations that the following parameters have the effect on coke burning rate: diameter of coke particles, coke content in charge, density of coke and charge, concentration of oxidant in heat-carrying gas.

Oxygen concentration, in its turn, is determined by the external conditions, thermal procedure in the burning area and pressure of gases in the layer.

Pressure of gases varies along depth of the layer and cam be described by the equation with the remark for non-isothermality:

$$\partial P/\partial y = 1.5\left(\frac{1-\varepsilon}{\varepsilon\psi}\right)\left(1 + \frac{422}{\text{Re}_m}\right)\left(\frac{\rho_g W_g^2}{d_m}\right)\left(\frac{\text{Pr}_s}{\text{Pr}_{zh}}\right)^{0,33}, \quad (21)$$

Processes of moisture transfer, presented for the procedure with permanent drying rate, are described by the following relationships:

$$\rho_m\left(du/d\tau\right) = \left(\beta_w f_{sp}\left(P_{VR} - P_V\right)\right)/\left(R_V T\right), \quad (22)$$

$$\rho_m\left(du/d\tau\right) = \rho_g W_g\left(\partial x_w/\partial y\right), \quad (23)$$

$$P_{VR} = 617{,}7\exp\left(17{,}25t_m/\left(t_m + 238\right)\right), \quad (24)$$

$$P_{VR} = P\left(x_w/\left(0{,}622 + x_w\right)\right), \quad (25)$$

where P_{VR}, P_V — pressure of moisture vapours on the surface of particles and in gases; R_V — gaseous constant of water vapours; β_w — mass transfer ratio.

Mass transfer ratio is determined from the criterial equation of mass exchange in the layer:

$$\text{Nu}_m = 2 + 0{,}83\,\text{Re}^{0,53}\,\text{Pr}_m^{0,33}\,\text{Gu}^{0,135}\,, \quad (26)$$

where $\text{Nu}_{m} = \beta_w d_M/D$, $\text{Pr}_{m} = \nu_g/D$, $\text{Gu} = (t_g - t_m)/t_g$; $D = 0.216(T/273)^2$ — diffusion ratio of moisture vapours.

The process of moisture condensation on the surface of cold particles is calculated after x_w reaches x_{ws} value, i.e. moisture content is in the state of saturation.

The sintering process is accompanied by material compaction, what is connected porosity variation and, respectively, with increase of hydraulic resistance in the sintering area. The above-considered relationships are used for description of these processes. Solution of the system of equations (15–26) with the next initial conditions:

$$\tau = 0\text{: } t_m = t_{m_0},\ c_c = c_{c_0},\ \varepsilon = \varepsilon_0,\ u = u_0;$$

$$\tau = 0:\ t_g = t_{g_0},\ c_{O_2} = c^0_{O_2},\ P = P_0,\ x_w = x_{w_0};$$

makes it possible to analyze the effect of procedure measurements on sintering power engineering.

Firing is identified as the process of charge heating up to temperatures when heat extraction caused by chemical reactions will be sufficient for stable burning holding. Te sintering process can be conditionally divided into two stages: firing in the hearth of the sintering machine and charge sintering during air sucking through the agglomerated layer as a result of burning of coke particles.

High-quality realization of the first stage mainly defines consequent conduction of sintering process. Excessive high temperature in the firing hearth leads to melting of the upper layer of sinter and, respectively, to deterioration of gaseous penetration and lowering of sintering rate. Temperature heterogeneity along the hearth volume is a cause of insufficient firing quality.

The process in the hearth of a sintering machine is conducting with oxidant feed, its amount depends on air excess ratio (meaning air feeding to burners) and suctions. Oxygen concentration at the entrance to the agglomerated layer is evaluated via the relationship:

$$C_{O_2} = 0{,}21\left((\alpha - 1)V_v^0 + V_{pr}\right)\Big/\left(V_g + V_{pr}\right),$$

where V_v^0 — air volume that is theoretically required for burning; V_{pr}, V_g — air volume in the hearth of a sintering machine owing to suctions and burning products.

Oxygen concentration varies after processing in the hearth, because air is fed in the layer. The temperature of gases that are fed in the agglomerated layer in the hearth, can be determined from the hearth heat balance (not taking into account losses in the environment):

$$T_{g0} = \left(Q_n^r + Q_{vf} + Q_{tf}\right)\Big/\left(c_g V_g\right),$$

where Q_n^r — calorific value of gaseous fuel; Q_{vf}, Q_{tf} — physical heat of air and fuel respectively.

Analysis and discussion of the results

The firing processes are analyzed at permanent temperature of gases at the entrance in the agglomerated layer. Based on firing calculations, forming of the burning front of coke fines occurs at the depth 0.06 m. In this case burning becomes more stable, i.e. the firing process is finished. Thereby, heating of the upper level of the agglomerated layer with final thickness is necessary in firing, what corresponds with practical results.

The process of moisture elimination and dissociation of carbonates conducts almost simultaneously as the process of fuel burning, and it covers relatively narrow area along the height of the agglomerated layer. At the same time, fuel burning-out (**Fig. 1**) and oxygen consumption for burning (**Fig. 2**) take place at the initial stage. **Fig. 3** presents experimental data on firing time of the agglomerated layer at different values of heat carrying gas temperature and oxygen concentration.

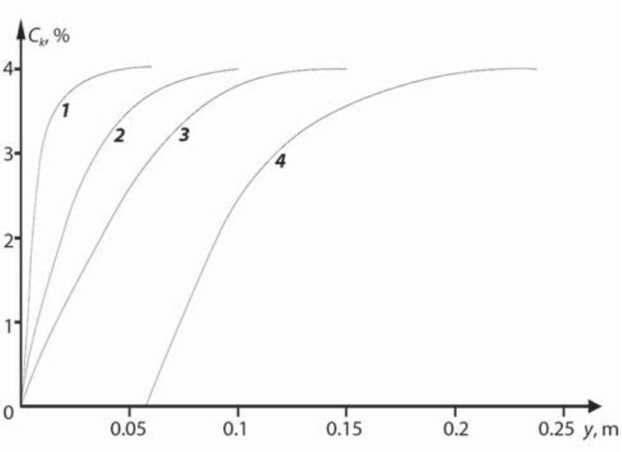

Fig. 1. Distribution of concentration C_k of coke fines from the height *y* of the agglomerated layer in the firing procedure for the following time periods:
1 — τ = 90 s; *2* — τ =120 s; *3* — τ =150 s; *4* — τ =170 s

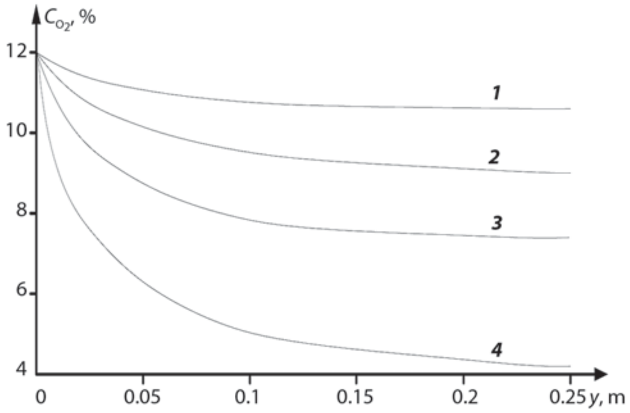

Fig. 2. Distribution of oxygen concentration C_{O_2} depending on the height *f* the agglomerated layer *y* in the firing procedure for the next time periods:
1 — τ = 90 s; *2* — τ =120 s; *3* — τ =150 s; *4* — τ =170 s

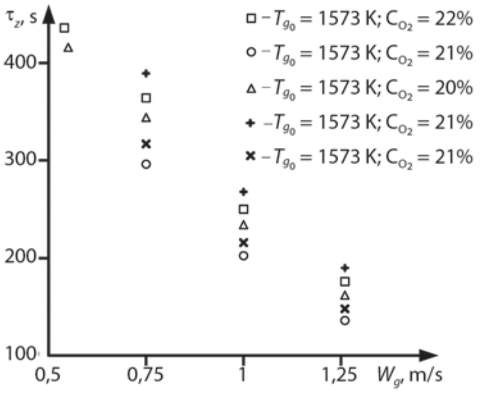

Fig. 3. Dependence of firing time τ_g of sintering charge on feed rate W_g of heat carrying gas in the agglomerated layer at its different temperatures and oxygen concentrations

Conclusion

The presented paper describes multi-scale mathematical model based on differential equations with partial derivatives for thermally activating chemical and energotechnological process of sintering of iron ore raw materials, with complex account of mutual effect of thermal physical as well as chemical and technological energy-intensive processes. The following technological processes are investigated: moisture elimination, burning of coke fines, decarbonization, sintering, moisture condensation in the levels of the agglomerated layer with different heights. The values of forming time for the stable burning area are obtained. Multifactorial relationship between operation of chemical and energotechnological system for sintering of iron ore raw materials (from one side) and parameters of fuel burning area, oxygen consumption and decarbonization reactions (from other side) is revealed.

The developed multi-scale mathematical model provides high-quality relationships of thermal parameters during sintering process and allows to analyze the effect of each parameters on behaviour of the complicated chemical and energotechnological system in iron and steel industry, to reveal the potential of energy- and resource-saving, to rise energy and resource efficiency of the noted system based on optimization of the described chemical end energotechnological processes.

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REFERENCES

1. Shapovalov A. N. Use of sintering cake heat for additional heating of sintering charge. *Teoriya i tekhnologiya metallurgicheskogo proizvodstva*. 2018. No. 4 (27). pp. 32–36.
2. Mnykh A. S., Dovgal V. V., Shumikin S. A. Management on distribution of sintering charge along height of the layer at the sintering machine for different conditions of its loading. *Metalurgiya*. 2018. No. 1(39). pp. 109–114.
3. Bobkov V. I., Borisov V. V., Dli M. I., Meshalkin V. P. Study of the Thermal Characteristics of Phosphate Raw Materials in the Annealing Temperature Range. *Theoretical Foundations of Chemical Engineering*. 2017. Vol. 51. No. 3. pp. 307–312.
4. Ganin D. R., Druzhkov V. G., Panychev A. A., Bersenev I. S. Microstructure and mineralogical composition of agglomerates in use of additives of brown ironstone ores, bentonite clays and serpentinite-magnesites. *Chernye metally*. 2018. No. 5. pp. 10–14.
5. Bobkov V. I., Borisov V. V., Dli M. I., Meshalkin V. P. Thermally activated chemical technology processes of agglomeration of phosphorites. *Theoretical Foundations of Chemical Engineering*. 2018. Vol. 52. No. 1. pp. 35–41.
6. Yuan S., Zhou W., Han Y., Li Y Efficient enrichment of low-grade refractory rhodochrosite by preconcentration-neutral suspension roasting-magnetic separation process. *Powder Technology*. 2020. Vol.361. pp. 529–539.
7. Yang X.-F. Mechanism of roasting and agglomeration on the pellets produced by blended iron ore fines of hematite and magnetite. *Journal of Iron and Steel Research*. 2010. Vol. 22. No. 2. pp. 6–8.
8. Luis P., Van der Bruggen B. Exergy analysis of energy-intensive production processes: advancing towards a sustainable chemical industry. *Journal of Chemical Technology and Biotechonology*. 2014. Vol. 89. No. 9. pp. 1288–1303.
9. Elgharbi S., Horchani-Naifer K., Férid M. Investigation of the structural and mineralogical changes of Tunisian phosphorite during calcinations. *Journal of Thermal Analysis and Calorimetry*. 2015. Vol. 119. No. 1. pp. 265–271.
10. Shapovalov A. N. Improvement of sinter quality in the conditions of “Ural Steel” JSC. *Teknologiya metallurgi,i mashinostroeniya i materialoobrabotki*. 2017. No. 16. pp. 10–20.
11. Panchenko S. V., Shirokikh T. V. Thermophysical processes in burden zone of submerged arc furnaces. *Theoretical Foundation of Chemical Engineering*. 2014. Vol. 48. No. 1. pp. 77–83.
12. Montastruc L., Azzaro-Pantel C., Biscans B., Cabassud M., Domenech S. A thermochemical approach for calcium phosphate precipitation modeling in a pellet reactor. *Chemical Engineering Journal*. 2003. Vol. 94. No. 1. pp. 41–50.
13. Matyukhin V. I., Yaroshenko Yu. G., Bragin V. V. Technological possibilities of iron ore sinter production using combined fuel. *Stal*. 2019. No. 11. pp. 3–8.
14. Frolov Yu. A., Aggarwal N., Polotskiy L. I. Study of sintering process with recirculation of waste gases. *Metallurg*. 2017. No. 8. pp. 25–32.
15. Fan X.-H., Gan M., Jiang T., Yuan L.-S., Chen X.-L. Influence of flux additives on iron ore oxidized pellets. *Journal of Central South University of Technology (English Edition)*. 2010. Vol. 17. No. 4. pp. 732–737.
16. Kowalska J., Kowalska H., Cieślak B., Derewiaka D., Lenart A. Influence of sucrose substitutes and agglomeration on volatile compounds in powdered cocoa beverages. *Journal of Food Science and Technology*. 2020. Vol. 57(1), pp. 350–363.
17. Cui L., Ba K., Li F., Hong J., Zuo J Life cycle assessment of ultra-low treatment for steel industry sintering flue gas emissions. *Science of the Total Environment*. 2020. 725, 138292.
18. Hu S., Li J., Yang X., Weng L., Liu K. Improvement on slurry ability and combustion dynamics of low quality coals with ultra-high ash content. *Chemical Engineering Research and Design*. 2020. Vol. 56. pp. 391–401.
19. Melamud S. G., Yuryev B. P. Oxidation of iron ore at moderate and high temperatures. *Steel in Translation*. 2016. Vol. 46. No. 6. pp. 384–389.
20. Chen Y., Shi L., Du J., Zhang H., Jiao X. Preparation and Properties of the Lightweight Thermal Insulation Wall Materials with Iron Tailings. *Journal of Building Materials*. 2019. Vol. 22(5). pp. 721–729.
21. De Gisi S., Romaniello L., Dalessandro M., Todaro F., Notarnicola M. Recovery of iron rich residues from integrated steel making process by hydrated lime/molasses pressurized cold agglomeration. *Journal of Cleaner Production*. 2019. Vol. 233, pp. 830–840.