Experimental examination of the chemical-metallurgical roasting process for iron ore raw materials on the fire grate of a roasting conveyor machine

V. I. Bobkov, Dr. Eng., Associate Prof., Head of the Dept. of Higher Mathematics [1], e-mail: vovabobkoff@mail.ru;
M. I. Dli, Dr. Eng., Prof., Head of the Dept. of Information Technologies in Economics and Management [1], e-mail: midli@mail.ru;
N. S. Kulyasov, Cand. Econ., Leading Researcher of the Scientific and metological center "High School of Tariff Regulation" [2], e-mail: Kulyasov.NS@rea.ru

[1] Smolensk Branch of the National Research University "Moscow Power Engineering Institute" (Smolensk, Russia)
[2] Plekhanov Russian University of Economics (Moscow, Russia)

The results of experimental power engineering examination of operating roasting conveyor machines are presented. These machines are used for complicated energy-intensive chemical-metallurgical process of roasting of iron ore raw materials in moving dense layer with cross feed of heat-carrying gas. The studies were conducted within the temperature ranges of thermal and aerodynamic operating conditions of the existing roasting conveyor machines. The causes of insufficient power engineering efficiency of the chemical-metallurgical roasting process were revealed, qualitative analysis of thermal conditions of roasting dense layer of iron ore raw materials was carried out. The data on temperature distribution of heating gas and iron ore material in different areas of a dynamic dense layer and on a fire grate in different sections of the roasting machine were obtained. The experimental data from technological control of the roasting conveyor machine were presented, as well as the results of chemical and granulometric analyses of roasting iron ore raw materials. Essential deviations in the thermal conditions of operating roasting machine in comparison with designed parameters were found out. The data on roasting conditions of iron ore raw materials in the experimental unit – the sintering pan, which provides simulation of the roasting conditions close to designed ones, are displayed. Insufficient heating in the lower layer levels at the operating roasting machines (in comparison with the designed parameters), stipulated by low speed of heat-carrying gas sweeping in the roasting area was revealed. Temperature heterogeneity along the width of a fire grate, caused by heterogeneity of heat-carrying gas sweeping due to segregation of iron ore material by its size during its loading to the roasting conveyor machine was substantiated scientifically.

Key words: iron ore, high-temperature roasting, decarbonization, temperature, heat exchange, roasting machine, heat-carrying gas.
DOI: 10.17580/cisisr.2023.02.02

Introduction

The process of high-temperature roasting of iron ore raw materials in a roasting conveyor machine is rather energy-intensive and can be related by its main features to non-stationary heat and mass exchange class of tasks in stationary layer which is seeped by heating gas [1, 2]. Technical literature pays essential attention to this class of tasks, what is stipulated by wide distribution of heat exchange processes in dense layer in different industries [3, 4].

The researches in the field of improvement of iron ore raw materials processing technologies in the layer can be divided by two main groups [5, 6]. The works connected with mathematical simulation of heat exchange processes and analysis of the obtained exact and approximate values can be related to the first group [7, 8]. Analytical solutions can be usually obtained only at significant simplifications of a mathematical model [9, 10]. Temperature relationships of thermal-physical properties of processed iron ore material and heating gas are not taken into account as a rule, while heat sources (drains) in the layer of ore material are also not taken into account or taken into account rather approximately [11, 12].

Technological devices and their thermal operating conditions were calculated using such simplified models and they need to be adjusted, sometimes rather substantially and in any cases outside the boundaries of tuning the thermal procedure [13, 14].

Experimental researches of the processes of heat and mass transfer in dense layer, which are directed on determination of parameters of mathematical models, as well as experimental simulation of devices and pilot search of the favourite conditions for implementation of activated chemical-metallurgical processes, are related to the second group [15].

Technological process of drying and roasting of iron ore raw material is a complicated and multifactor process. Productivity of roasting machines and quality of obtained semiproduct depend on thermal-physical and reacting technological properties of iron ore raw material, such as humidity, content of carbonates, fractional composition and height of loading layer, temperature and speed of gases seeping etc. [16]. Experimental examinations of multifactor systems are very labour-intensive and their success mainly depends on determination of identity degree of chemical-metallurgical processes, occurring in experimental models and real technological devices [17].

Use of reliable initial data, study and taking into account the most significant factors (which determine running of technological processes) allow to solve the problems connected with heat and mass transfer in devices at the principally new level [18]. It is recommended to advance from a labour-intensive experimental search to mathematical simulation and numerical examination of the obtained models [19].

Analysis of causes of insufficient power engineering efficiency of the process of decarbonizing roasting of lump iron ore raw material in dynamic dense layer with cross feed of heat-carrying gas on the fire grate of the roasting conveyor machine is the aim of this work, as well as determination of the ways for improving this complicated energy-intensive chemical-metallurgical process.

Research methods: experimental examinations and analysis of thermal and aerodynamic roasting procedure for iron ore raw material in the existing roasting machines.

Experimental examination of the roasting process of iron ore raw material in the roasting conveyor machine

The roasting conveyor machines are used for roasting of iron ore raw materials [20]. Their operating experience during several years testifies on substantial disadvantages during chemical-metallurgical roasting process [21]. Low energy efficiency of the main technological process and frequent breakdowns due to fire grate burning can be mentioned as the most significant disadvantages [22]. As soon as intensity of decarbonization processes mainly depends on the temperature in the layer of roasted material, we can suggest that the above-mentioned disadvantages are closely associated with the roasting thermal procedure [23].

The operating roasting machines are characterized by absence of direct control of the temperature conditions in a fire grate. The temperature of waste gases, which is measured in vacuum chambers of roasting machines, can be considered as an indirect factor of the fire grate temperature [24]. In this connection, the roasting machines operate in derated thermal conditions, in order to decrease burning possibility of a fire bars. This circumstance has a negative effect on power engineering efficiency of the chemical-metallurgical roasting process [25]. Practically achieved decarbonization degree for iron ore raw materials makes 10-30 % in the industrial conditions.

To reveal the causes of insufficient power engineering efficiency of the chemical-metallurgical roasting process, the qualitative analysis of the thermal conditions in roasted layer of iron ore raw material is required. Conduction of such analysis is impossible on the base of the data of technological control which is provided for a roasting conveyor machine [26]. Additional data on distribution of heating gas temperature in different areas of dynamically dense layer and on a fire grate in different sections of a roasting machine are required. However, getting such information from movable dense layer of iron ore raw material with cross feed of heat carrier is connected with serious difficulties.

To implement examination of the operating roasting machines, the authors developed and manufactured the special measuring device, its structural scheme is presented on the **Fig. 1**. It includes 24 chromel-alumel thermocouples, switching device (SD), block of forming the switching impulses (BFI) and multipoint automatic potentiometer (MAP). The scheme of positioning of sensors and SD in the dense layer of iron ore raw material, which is moving along the conveyor of a roasting machine is also presented in the Fig. 1.

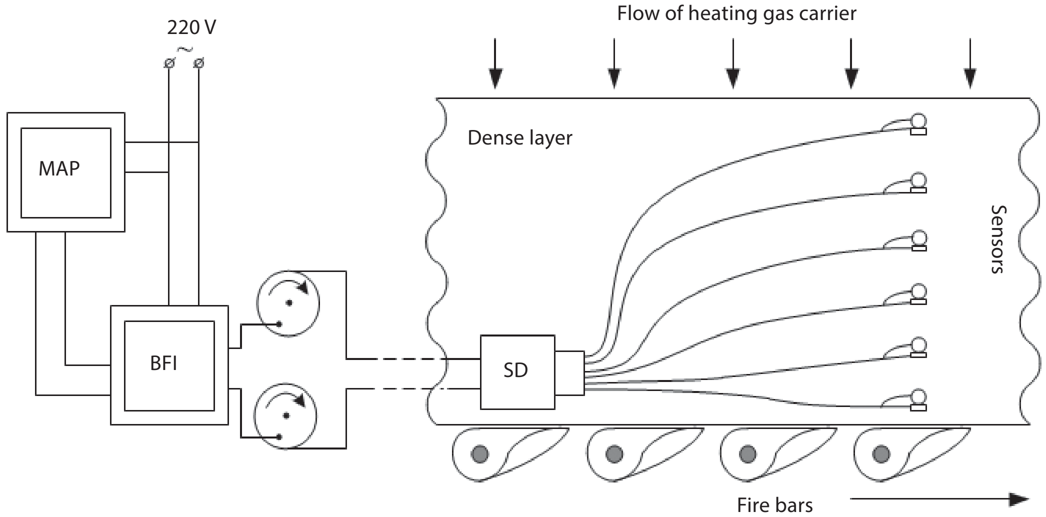

Fig. 1. Structural and functional scheme of the measuring device

To protect from the effect of high temperatures, SD was placed in heat-resistant shell with boiling water jacket. Working junction points of six thermocouples were located in gas-permeable hoods. They were used for measuring the temperature of seeped heating gases in different layer levels. The six remaining thermocouples were embossed in the pieces of fine-dispersed iron ore raw material with size 30-40 mm in such way, that the working junction point is located in the center.

The results of probing of the temperature field for heating gas carrier and ore material in the dense layer at the conveyor of the operating roasting machine are presented on the **Fig. 2**.

The data of technological control of the roasting machine, which correspond to the experiment, as well as the results of chemical and granulometric analyses of iron ore raw material are displayed in the **Tables 1-4**.

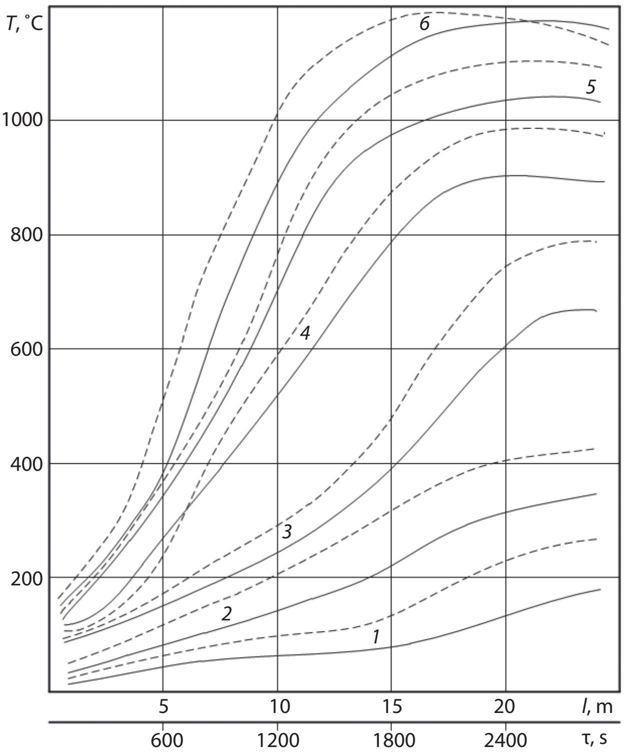

Fig. 2. Temperature distribution of gas (— — — — —) and iron ore material (————) on the conveyor of roasting machine in the dense layer on different level of a fire grate: *1* – 1 cm; *2* – 7 cm; *3* – 17 cm; *4* – 27 cm; *5* – 37 cm; *6* – 45 cm

Examinations of the thermal procedure of the operating roasting machine testify on its essential deviations in comparison with the designed parameters.

The roasting procedure, which is close to the designed one in the results of simulation at a sintering pan, is presented on the **Fig. 3** for comparison.

More high heating speeds for upper layers and low temperatures at a fire grate in the roasting machine (comparing with the designed parameters) are considered as substantial differences. Increased heating rate can be probably explained by partial gas suction from the area of high-temperature roasting. Insufficient heating of lower levels of the layer is stipulated by low gas seeping speed values in the roasting area – 0.095 $m^3/m^2{\cdot}s$ in comparison with the designed data 0.3-0.4 $m^3/m^2{\cdot}s$.

Non-uniformity and stratification of the temperatures along the width of fire grate are caused by non-uniformity of heating gas carrier seeping due to segregation of iron ore raw material for its size during loading to the conveyor of the roasting machine. Examinations of the actual roasting machine show that the temperature of fire bars in the center of fire grate was equal to 220-240 ºC in the end of the roasting area, while fire bars located near sides (150 mm distance) were heated up to 600-670 ºC. It is explained by differences in the iron ore raw material loading systems for the roasting machines. The modern machines are characterized by large angle of a loading runner, what promotes material segregation along band width. Material pieces, which are more coarse and uniform in their fractions, are loaded near sides; as a result, the areas with low aerodynamic resistance are forming near grate edges. In addition, the layer thickness near sides is not provided in these roasting machines.

Comparative analysis of the experimental data and data based on technological control, which were obtained in this research, correlate well with the results of calculating experiments for the temperature of iron ore raw material and heating gas carrier in the dynamic dense layer on the conveyor of the roasting machine, with cross feed of heating carrier, according to the mathematical model which was presented by the authors previously in the works [18, 27].

Conclusion

The conducted research of the thermal procedure for operating roasting machines and analysis of the obtained

Table 1. **The results of analysis of iron ore raw material chemical composition**

Chemical composition	Fe_2O_3	SiO_2	MgO	CaO	CO_2	Other impurities
Before roasting, %	41.33	16.46	-	-	11.17	31.04
After roasting, %	45.85	18,52	7.43	18.82	7.83	1.55

Table 2. **The results of analysis of iron ore raw material fractional composition**

Fractional composition, mm	0-10	10-25	25-50	50-70
Before roasting, %	12	41	38	9
After roasting, %	13	45	32	0

Table 3. **Consumption of natural gas and air for burning based on the data of technological control**

Consumption, nm^3/h	1st burner	2nd burner	3rd burner
Natural gas	200	600	440
Primary air	2,700	7,600	3,200
Secondary air	2,100	1,800	370

Table 4. **Temperature from the sensors based on the data of technological control**

No. of sensor	104	105	106	107	108	109	120	121	122
Temperature, °C	936	1065	1060	840	945	985	200	220	240
No. of sensor	123	114	115	116	113	125	126	127	128
Temperature, °C	305	88	220	492	65	434	256	216	265

results of investigations of chemical-metallurgical roasting processes for iron ore raw materials on a fire grate allow to make the following main conclusions:

- low power engineering efficiency of chemical-metallurgical roasting processes is stipulated by insufficient heating of lower layers of iron ore material, what is connected with insufficient amount of heating gases;
- realization of the designed roasting conditions for conveyor roasting machines also will not provide rather high power engineering efficient parameters;
- acceleration of calcination procedure is not acceptable with the existing loading scheme, because it will lead to burning of firing bars on fire grate sides.

Search of the methods for increase of average temperature of raw material layer, which will not lead to overheating of a fire grate should be probably considered as the direction of improvement of roasting processes on a fire grate for iron ore raw materials. Another such direction is search of the methods for rise of power engineering efficiency for roasting chemical-metallurgical processes, which take into account the featured of processed iron ore materials.

Technological conditions of decarbonizing roasting of iron ore raw material on a fire grate are determined by the temperature of heating gas carrier at the layer entrance T_{gi} and its feeding speed V_{gi}, for each separate vacuum chamber with number i.

The average (by layer loading height) raw material temperature $\overline{T} \rightarrow$ max can be considered as an optimality criterion of the chemical-metallurgical roasting process. The price of finished product during thermal preparation is usually forming on the expense of specific consumption of energy carriers $S=Q_{el} \cdot S_{el}+Q_{heat} \cdot S_{heat}$, and we can take into account exceeding of electric power price S_{el} comparing with heating power price S_{heat}. In current conditions of production and economy, the roasting procedure, when the required quality of finished roasted iron ore raw material is achieved with minimal cost of power expenses, is considered as an optimal one.

The problem of optimization at the *i*-th step (for separate vacuum chamber with number *i*) can be formulated in such way: to find such values of the vector of managing parameters (T_{gi}, W_{gi}), in order to provide maximal and minimal values of $\overline{T}$ and S parameters for the following

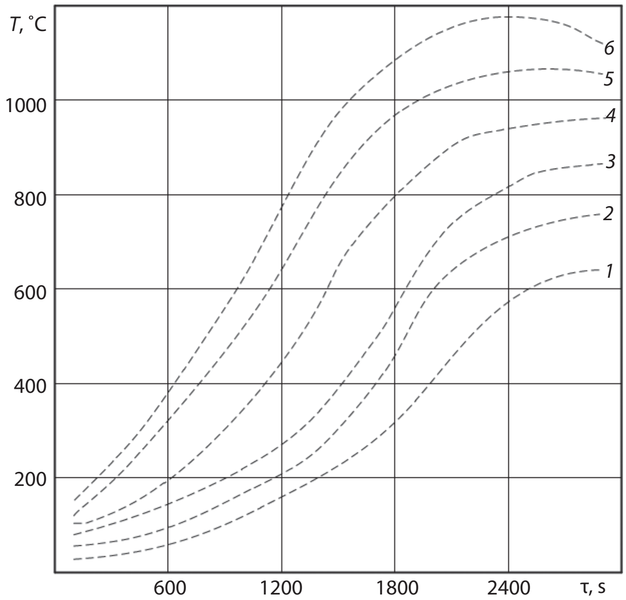

Fig. 3. Gas temperature distribution in a sintering pan (experimental unit):
1 – 1 cm; *2* – 7 cm; *3* – 17 cm; *4* – 27 cm; *5* – 37 cm; *6* – 45 cm

restrictions: managing parameters speed $W_{gi} \leq W_{gMAX}$ and heat carrier temperature $T_{gi} \leq T_{gMAX}$ (at the layer entrance) and $T_{ghi} \leq T_{ghMAX}$ (at the layer exit), as well as heating speed $\partial T_m / \partial \tau \leq \Delta_1 T_m^{MAX}$ and material temperature gradient $\partial T_m / \partial x \leq \Delta_2 T_m^{MAX}$ - in order to prevent overheating of firing bars (owing to the technical features of the unit).

To search the optimal procedure, the functional $\Phi = \alpha_1 \overline{T} - \alpha_2 S$ should be examined. The coefficients α_1 and α_2 will provide ordering of criteria within the dual-criteria task of lexicographic optimization. To solve the preset problem of conditional optimization, different computer methods and specialized software packages can be applied. However, it should be taken into account that restrictions for the managing parameters (speed $0 \leq W_{gi} \leq W_{gMAX}$ and heat carrier temperature at the layer entrance $273 \leq T_{gi} \leq T_{gMAX}$) are the most strict because they provide mathematically correct and physically implementable solving the optimization problem.

Based on the results of the theoretical and experimental researches, which were carried out by the authors, the computerized model for optimization of multi-stage chemical-metallurgical process of iron ore raw material roasting on a fire grate of the conveyor roasting machine was built. It is characterized by taking into account appearances of internal heat transfer and heat absorption during dissociation of carbonates.

The obtained optimal thermal and aerodynamic procedure for roasting of iron ore raw material in the dense layer on the roasting machine forms attenuating heat wave, which intensifies thermally activated roasting chemical-metallurgical processes. It provides decrease of fuel consumption appr. by 1.2 t of conditional fuel per t of finished products, lowering of return part, improvement of quality of finished product.

Multiple calculating experiments for determination of the values of procedure parameters for complicated multi-stage roasting chemical-metallurgical process of iron ore raw material at different technological characteristics of initial ore raw material and heating gas carrier were conducted. They allowed to determine influence of thermally activated endothermic dissociation reactions of carbonates on quality of roasted iron ore raw material.

This study was performed within the framework of the state assignment, project namber FSWF-2023-00.

REFERENCES

1. Ming Yan, Xinnan Song, Jin Tian, Xuebin Lv, Ze Zhang, Xiaoyan Yu and Shuting Zhang. Construction of a New Type of Coal Moisture Control Device Based on the Characteristic of Indirect Drying Process of Coking Coal. *Energies*. 2020. Vol. 13 (16). 4162. DOI: 10.3390/en13164162.
2. Tomtas P., Skwiot A., Sobiecka E., Obraniak A., Ławińska K., Olejnik T. P. Bench Tests and CFD Simulations of Liquid—Gas Phase Separation Modeling with Simultaneous Liquid Transport and Mechanical Foam Destruction. *Energies*. 2021. Vol. 14 (6). 1740. DOI: 10.3390/en14061740.
3. Shekhovtsov V. V., Vlasov V. A., Skripnikova N. K., Semenovykh M. A. Structure Formation of Concrete Systems Modified By Nonstandard Particles. *Russian Physics Journal*. 2021. Vol. 63 (9). pp. 1590-1595.
4. Zhu X., Ji Y. A digital twin—driven method for online quality control in process industry. *International Journal of Advanced Manufacturing Technology*. 2022. Vol. 119 (5-6). pp. 3045-3064.
5. Bobkov V. I., Dli M. I., Sokolov A. M., Rubin Y. B. Analysis of chemical-metallurgical agglomeration processes during charge sintering. *CIS Iron and Steel Review*. 2020. Vol. 20. pp. 7—11.
6. Shvydkii V. S., Fatkhutdinov A. R., Devyatykh E. A., Devyatykh T. O., Spirin N. A. On mathematical modeling of layer metallurgical furnaces and aggregates. Report 2. *Izvestiya Ferrous Metallurgy*. 2017. Vol. 60 (1). pp. 19—23.
7. Li J., An H.-F., Liu W.-X., Yang A.-M., Chu M.-S. Effect of basicity on metallurgical properties of magnesium fluxed pellets. *Journal of Iron and Steel Research International*. 2020. Vol. 27 (3). pp. 239-247.
8. Kavchenkov V. P., Kavchenkova E. V.,Chernenkov I. D. Modeling of the relationship between the earth population growth and the electric energy production processes. *Journal of Applied Informatics*. 2021. Vol. 16. No. 4 (94). pp. 110-121.
9. Wang S., Guo Y., Zheng F., Chen F., Yang L. Improvement of roasting and metallurgical properties of fluorine-bearing iron concentrate pellets. *Powder Technology*. 2020. Vol. 376. pp. 126-135.
10. Nayak D., Ray N., Dash N., Pati S., De P. S. et al. Induration aspects of low-grade ilmenite pellets: Optimization of oxidation parameters and characterization for direct reduction application. *Powder Technology*. 2021. Vol. 380. pp. 408-420.
11. Kossoy A. Effect of thermal inertia-induced distortions of DSC data on the correctness of the kinetics evaluated. *Journal of Thermal Analysis and Calorimetry*. 2021. Vol. 143. No. 1. pp. 599-608.
12. Kurilin S. P., Sokolov A. M., Prokimnov N. N. Computer program for simulation pf technical state parameters of electromechanical systems. *Prikladnaya informatika*. 2022. Vol. 17. No. 2. pp. 105—119.
13. Tian H., Pan J., Zhu D., Wang D., Xue Y. Utilization of Ground Sinter Feed for Oxidized Pellet Production and Its Effect on Pellet Consolidation and Metallurgical Properties. Minerals, Metals and Materials Series. *11th International Symposium on High-Temperature Metallurgical Processing*. 2020. pp. 857-866.
14. Matkarimov S. T., Berdiyarov B. T., Yusupkhodjayev A. A. Technological parameters of the process of producing metallized iron concentrates from poor raw material. *International Journal of Innovative Technology and Exploring Engineering*. 2019. Vol. 8 (11), pp. 600-603.
15. Puchkov A. Yu., Lobaneva E. I., Kultygin O. P. Algorithm of predicting the parameters of processing system for wastes of apatite-nepheline ores. *Prikladnaya informatika*. 2022. Vol. 17. No. 1. pp. 55—68.
16. Akberdin A. A., Kim A. S., Sultangaziev R. B. Experiment Planning in the Simulation of Industrial Processes. *Steel in Translation*. 2018. Vol. 48 (9). pp. 573—577.
17. Dli M. I., Vlasova E. A., Sokolov A. M., Morgunova E. V. Creation of a chemical-technological system digital twin using the Python language. *Journal of Applied Informatics*. 2021. Vol. 16. No. 1 (91). pp. 22-31.
18. Dli M. I., Bobkov V. I., Kulyasov N. S., Sokolov A. M. Features of research of iron ore thermal decarbonization kinetics during roasting. *CIS Iron and Steel Review*. 2021. Vol. 22. pp. 7—11.
19. Meshalkin V. P., Bobkov V. I., Dli M. I., Fedulov A. S. Mathematical simulation of chemical and energotechnological processes and procedures of coke fines burning in agglomerated layer. *CIS Iron and Steel Review*. 2020. Vol. 19. pp. 13—17.
20. Novichikhin A. V., Shorokhova A. V. Control procedures for the step-by-step processing of iron ore mining waste. *Izvestiya vuzov. Chernaya metallurgiya*. 2018. Vol. 60. No. 7. pp. 565-572.
21. Belyakov N. V., Nikolina N. V. Plant protection technologies: From advanced to innovative. *Journal of Physics: Conference Series*. 2021. Vol. 1942 (1). 012072
22. Kurilin S., Fedulov Y., Sokolov A. Scientific Substantiation of Topological Diagnostics Methods of Electrical Equipment. *International Conference on Industrial Engineering, Applications and Manufacturing (ICIEAM)*. 2021, pp. 288-293. DOI: 10.1109/ICIEAM51226.2021.9446356.
23. Shvydkii V .S., Yaroshenko Y. G., Spirin N. A., Lavrov V. V. Modeling of metalized pellets firing with the account of physicochemical transformations in them. *Izvestiya Ferrous Metallurgy*. 2018. Vol. 61 (4). pp. 288—293.
24. Tian Y., Qin G., Zhang Y., Zhao L., Yang T. Experimental research on pellet production with boron-containing concentrate. *Characterization of Minerals, Metals, and Materials*. 2020. pp. 91-102.
25. Yaroshenko Y. G. Thermal physics as the basis for energy and resource conservation in steelmaking. *Steel in Translation*. 2017. Vol. 47 (8). pp. 505-516.
26. Novichikhin A. V., Shorokhova A. V. Procedures for stage processing of iron-ore wastes in industrial mining areas. *Izvestiya Ferrous Metallurgy*. 2017. Vol. 60 (7). pp. 565—572.
27. Bobkov V. A., Dli M. I., Rubin Y. B.. Influence of the conditions of internal heat exchange on the process of thermal decomposition of carbonates in iron ore raw materials. *CIS Iron and Steel Review*. 2022. Vol. 24. pp. 4—8.