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RESEARCH PAPER

MODEL DECISION-MAKING SYSTEM IN THE TASK OF CHOOSING THE OPTIMAL COMPOSITION OF THE BLAST FURNACE BURDEN UNDER SPECIFIC OPERATING CONDITIONS OF BF

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ABSTRACT

This paper presents the methodological basis for creating a model system for selecting the optimum composition of blast furnace burden, providing the required technical and economic performance and the melting of pig iron of the required composition. The system implements a new systematic approach to modeling the processes of directed formation of blast-furnace melts. The description of the composition and properties of metallurgical systems in different states is based on an original concept of directional chemical bonding using integral parameters of the interatomic interaction of components in the system. The developed complex of mathematical and physical-chemical models and criteria provides a solution to the direct problem of predicting pig iron composition and blast furnace slag properties, depending on the burden and technological conditions. Determination of the optimal burden composition is carried out using vector optimization methods with mandatory verification of compliance with the technological requirements of high-temperature properties of the burden. The results of testing the model system on actual industrial data of blast furnace operation are illustrated, which made it possible to formulate recommendations on the composition of the loaded feed, taking into account the available raw material and energy resources.

Keywords: Blast furnace burden, iron ore materials, pig iron, slag, melt properties, predictive model, optimization of burden composition, decision-making system

INTRODUCTION

Blast furnace technology is currently undergoing significant changes. To a large extent, this is related to the shortage of natural and energy resources, the expansion of the use of low-grade ores, industrial and household waste, which is due to the need to utilize the accumulated secondary resources. The negative aspect of the use of secondary materials in the blast furnace burden is associated with their significant impact on the stability of blast furnace melting and with large fluctuations in the processes of softening and melting of materials in the furnace. This leads to deterioration of the quality of pig iron and service conditions of blast furnace linings. Also, these processes are significantly affected by the involvement of pulverized coal fuel in blast furnace production, the use of which, along with coke of low strength properties, increases the probability of accumulation of small fractions and heterogeneous inclusions formed as a result of incomplete combustion of pulverized coal fuel in the furnace. "Macro-heterogeneous" inclusions sharply worsen the properties of slags and, as a result, the quality of pig iron.
These circumstances determine the need for the development of non-traditional approaches to the formation of quality indicators of iron-containing materials and the component composition of the burden, as well as determine the urgency of solving the problem of optimizing the composition of a multi-component blast furnace burden, providing the necessary technical and economic indicators of iron smelting process in variable smelting conditions.
An effective solution to this problem should be based on the use of modern information technologies, which integrate the achievements of fundamental research into the processes of aggregate transformations of iron ore materials in the blast furnace and the accumulated experience of managing blast furnace smelting in the industrial conditions of BF production.
The complexity of an adequate description of high-temperature fast-flowing processes in a blast furnace requires in-depth studies in the issues of mathematical modeling of these processes and the creation of predictive models, in particular, for the operational assessment of physicochemical and technological properties of the forming melts, which determine obtaining of required quality pig iron.
Work on the development of existing means of optimizing the composition of the blast furnace burden and the creation of new effective methods for increasing the efficiency of automated blast furnace smelting control systems is constantly being carried out all over the world, as well as at the Institute of Ferrous Metallurgy of the National Academy of Sciences of Ukraine.
The analysis of domestic and foreign publications over the past decades [1-11] shows that modern control systems for technological processes of domestic and foreign blast furnaces have implemented a wide range of models and methods of monitoring, analysis and technological decision-making, including ones for solving the tasks of choosing a rational burden composition when changing the feeding of iron ore raw materials and the properties of coke.

As a rule, the well-known methods of solving the problem of choosing the composition of the burden are based on the predictive determination of blast furnace smelting indicators using calculations of the material and heat balances of the process. The methodological aspects of these methods at the modern level of modeling of smelting processes are widely covered by the authors of the work [1]. In the conditions of a metallurgical enterprise, the regulation of the blast furnace burden is carried out based on the given basicity of the slag with constant coefficients of distribution of silicon and iron between the smelting products. At the same time, the influence of technological parameters is not taken into account, which often leads to violations of the thermal and slag regime and production of iron with significant fluctuations in the chemical composition, in particular, in terms of sulfur and silicon content.

The model for calculating the burden composition and blast furnace parameters [2], is based on the material and heat balances of smelting and takes into account the influence of technological process parameters on heat losses, the degree of indirect reduction and the transition of elements into pig iron. However, the method of calculating the composition of smelting products, based on the given value of slag basicity and iron temperature, does not take into account changes in the parameters of the loaded burden and the blast mode and can lead to a discrepancy between the actual and calculated characteristics of the smelting products, as well as their thermodynamic mismatch.

A distinctive feature of the system of complex analysis of agglomerate production presented in work [3], is the possibility of operative selection of the composition of sintering and blast furnace burdens in order to achieve better technical and economic indicators of joint blast furnace and sintering workshops. In particular, the optimal costs of the components of the sintering and blast furnace burdens are determined based on traditional method of the material-heat balance, taking into account the cost of pig iron. This approach makes it possible to carry out a technical and economic justification of several alternative variants of the blast furnace burden. However, like most known approaches, it does not take into account the complexity of the current physicochemical processes of blast furnace smelting.

The automated system of analysis and forecasting of production situations of the blast furnace [4-5] implements a model of optimal management of raw materials and fuel and energy resources in the blast furnace, which includes end-to-end calculation of sintering and blast furnace burden, technical and economic indicators of smelting when changing the blast parameters and properties of iron ore materials and coke. The solution of the problem of optimizing the burden composition is carried out using non-linear programming methods. Traditional criteria are used as target functions: minimum coke consumption and maximum productivity, minimum sulfur content in pig iron and minimum blast furnace slag viscosity. At the same time, a number of restrictions regarding the thermal, slag, and gas dynamic modes of smelting and the quality of pig iron are taken into account. A certain advantage of the optimization model is the ability to solve the problems of optimal distribution of fuel and energy resources (natural gas and oxygen consumption) within a group of blast furnaces in various technological situations.

A technological model of burden calculation was implemented within the well-known expert system "Vairon TNG", which was developed by the company "Voestalpine Stahl" (Austria) due to the need to use burden materials of reduced quality [6]. The model determines the required composition of the burden depending on the results of chemical analysis of iron ore materials, target values of reducing agent consumption and slag basicity based on material and heat balance calculations for a certain period of time.

The work [7] presents the results of using the methodology of constructive theory for the aim of maximizing the yield of pig iron. To achieve the goal, the optimal composition of the burden is determined based on the "generalized optimal designer", which leads to good economic characteristics of the iron production process in the blast furnace and gives recommendations for the design of this process. A certain advantage of this approach is the ability to analyze the influence of blowing parameters, consumption of agglomerate and pulverized coal fuel on increasing the output of pig iron for the actual production of a blast furnace with a fixed total cost of pig iron.

A distinctive feature of the burden optimization model presented in [8] is the determination of the consumption of iron ore materials with an emphasis on optimizing the amount and ratio of fluxing materials (pyroxenite, quartz, dolomite and limestone) from the point of view of metal obtaining of a given chemical composition. The calculation of the optimal consumption of the loaded materials is carried out using matrix operations of the mass balance iteratively to achieve the target chemical composition of the slag in real time. In particular, the model is integrated with the system located in the laboratory, which provides for an automatic mode of entering input data of raw materials chemical composition. At the same time, at each iteration stage, a procedure is performed to compare the calculated optimization results with the actual analysis of pig iron and slag obtained after laboratory analysis. Taking into account technological limitations in terms of load parameters (availability and consumption of raw materials, bunker capacity, uniform distribution of ore load along the radius of the furnace, etc.) significantly increases the probability of converging the theoretical calculation with the actual chemical composition of the slag, which in turn determines the final goal, namely - smelting of pig iron of a given composition.

There are other models for choosing the optimal composition of blast furnace burden, which are based on the method of calculating material and heat balances with various methods of their improvement and adaptation to specific burden and technological conditions [9, 10].

Thus, the analysis of the published results of the application of various models shows their wide functionality and successful operation for optimizing the composition of the burden in specific operating conditions of blast furnaces. However, in our opinion, the analyzed models do not have enough prognostic qualities, namely the ability to predict the final compositions of pig iron and slag based on characteristics of the loaded burden and taking into account the technological regime of smelting. Thus, in the work [11] an attempt is made to describe the distribution of burden elements between pig iron and slag using the principles of thermodynamics. At the same time, the lack of consideration of technological parameters of blast furnace melting reduces, in our opinion, the effectiveness of using the developed model for real conditions. In addition, to date, optimization procedures have not fully worked out the issue of a more thorough consideration of the quality of iron ore raw materials, as well as a description of the processes of aggregate transformations of iron ore materials in different zones of the furnace and formation of primary and final melts from them. Accordingly, the specificity of the properties of the obtained melts is not taken into account, which significantly reduces the reliability of balance and optimization calculations.

In order to obtain a real solution to the task of optimizing the selection of the burden composition, it is necessary to take into account a number of technological restrictions regulating the requirements for physical and chemical processes in the furnace, the properties of iron ore raw materials and melts formed from them. Thus, the uneven distribution of burden materials in the volume of the furnace determines the difference in the properties of the obtained melts, which can negatively affect the lining of the furnace and the processes of recovery and melting. This feature makes it possible to include an additional class of restrictions based on loading burden indicators (ore load, melting temperature of burden materials, FeO content in the primary slag melt, etc.) when mathematically solving the task of blast furnace burden optimization in real conditions.

The purpose of this work is to develop and test the information-mathematical support of the decision-making model system in the task of choosing the optimal composition of the blast furnace burden, which provides the necessary technical and economic indicators of the iron smelting process for specific conditions of blast furnace operation.

MATERIAL AND METHODS

The method of physicochemical modeling of the composition and properties of metallurgical systems in different states based on the original concept of directional chemical bond [12, 13] and mathematical methods of vector optimization are used as the methodological basis of the fulfilled research and the developed system approach to solving the problem of optimizing the composition of a multicomponent blast furnace burden.

Modeling the processes of formation and interaction of metal and slag phases during pig iron smelting at the level of interatomic interaction of components in melts allows us to summarize the achievements of various studies from a single theoretical position and describe the relationships between the composition, electronic structure and properties of compounds using integral parameters. It provides a complete accounting the influence of each component on the properties of "metal-slag" system and the possibility of practical implementation of predictive models in automated control system for technological process of blast furnace smelting (ACSTP BF).

An informational basis for creating predictive models for calculating the physical and chemical properties of metallurgical melts is the information accumulated in databases as a result of fundamental and experimental research on the properties of iron ore materials, metal and slag melts. The databases "Iron ore materials", "Slag" and "Metal-Slag" are indispensable part of the integrated Knowledge Base "Metallurgy", created for end-to-end analysis and optimization of metal products manufacturing at the Institute of Ferrous Metallurgy of the National Academy of Sciences of Ukraine. In particular, the "Slag" database has accumulated information on more than 8,000 slag warehouses for various purposes with a retrospective of more than 80 years.

Decision-making model system in the task of choosing the optimal composition of the blast furnace burden was developed on the base of the method of modeling the processes of directional formation of melts [14], which is based on the following main provisions (**Fig. 1**):

– the description of the processes of aggregate and phase transformations of materials in the blast furnace and the formation of liquid smelting products is carried out taking into account the mineralogical composition through the ratio of the characteristics of iron ore materials and slag melts;

– the composition and properties of pig iron and blast furnace slag are predicted using physicochemical models and integral indicators, which allows for interconnected evaluation the quality of the burden and the properties of blast furnace smelting products;

- the selection of the optimal composition of the blast furnace burden is carried out on the basis of the optimization of slag regime according to the set of properties of the final slag, which ensure its high sulfur-absorbing capacity and the production of pig iron of the required composition with minimal energy and raw material costs.

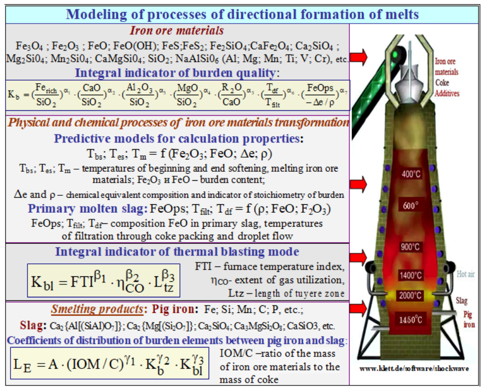

Fig. 1 Methods of modeling the processes of directed formation of blast furnace melts

This method is implemented in the form of a set of physical and chemical models and criteria, which include:

• the model of the metal melt for calculation of integral parameters - the chemical equivalent of the composition of pig iron Z^Y and the structural index d [12].;

• slag melt model for calculating the integral parameters of the oxide system: the chemical equivalent of the slag composition Δe and the slag stoichiometry index ρ (an analogue of basicity) [12];

• predictive models for calculating high-temperature properties of iron ore materials (softening and melting temperatures) in the form Property = f (Fe_2O_3, FeO, Δe, ρ), where Fe_2O_3, FeO are their content in the burden;

• predictive models for calculating the complex of properties of primary and final slag in the form Property = f (Z^Y, Δe, ρ), in particular, for estimating viscosity (η, Pa·s) and surface tension (σ, mN/m) at a given temperature, enthalpy for a given temperature in the range of 1400 ÷ 1550^{0}C (ΔH, kJ/kg), sulfur absorption capacity, temperatures of the beginning of crystallization (liquidus, T_l, ^{0}C) and the end of crystallization (solidus, T_s, ^{0}C), heterogenization temperature (Tε, ^{0}C) , the degree of deviation of the "metal-slag" system from equilibrium and the alkaline capacity of the slag;

• integral burden quality indicator K_b.;

• integral indicator of the temperature-blast mode of blast furnace melting K_{bl};

• predictive models for calculating coefficients of interphase distribution of burden elements (sulfur, silicon, manganese, iron) depending on K_b and K_{bl} in the form of equations: $L_E = f_E(K_b, K_bl)$.

The method of calculating the high-temperature properties of iron ore materials allows you to estimate the interval of their softening - melting, which is characterized by the values of the temperatures of the beginning and the end of softening (T_{bs}, T_{es}) and the melting temperature (T_m) [15]. These temperatures characterize the changes in iron ore materials during the transition to the liquid state in blast furnace conditions. These values allow determining the location and length of the melting zone of the burden in the blast furnace, taking into account alkaline compounds. The method of evaluating aggregate transformations of iron ore materials can be used to determine their properties, taking into account the distribution of burden components along the cross-section of the top part of the blast furnace using the burden distribution model presented in [16].

The calculation of the chemical composition of pig iron and smelting slag is carried out by the method of forecasting the distribution coefficients of the burden elements according to the scheme "Burden" + "Technology" = "Smelting products" [14, 17]. Method is based on predictive models of the distribution coefficients L_E of elements (sulfur, silicon, manganese, titanium and iron) between smelting products. The coefficients of elements transition into slag are considered as variables depending on specific burden and technological conditions: $L_E = f(F_b; F_t)$, where F_b are burden parameters, F_t are technological parameters. Research carried out using the actual data of the operation of some blast furnaces in Ukraine showed the feasibility of using the integral parameters of the burden K_b and the temperature-blast regime K_{bl} for forecasting the composition of smelting products.

The integral quality indicator of the blast furnace burden K_b was developed as a result of computational and analytical studies of hereditary relationships between the components of the empty rock of the burden and mineralogical composition of the blast furnace slag. The experience of studying the mineralogy of final blast furnace slags has shown that the properties of slag melts, in particular, the melting point and viscosity, are a consequence not only of the composition and thermodynamic conditions, but also of its specific structure, which reflects the mineralogical composition.

The K_b indicator includes a combination of the ratios of oxides in the burden and the parameters of primary melts, which characterize the aggregate transformation and reduction of materials in the furnace [18]: Fe_{rich}/SiO_2 – an indicator of the richness of the burden; CaO/SiO_2 – basicity of the burden; MgO/SiO_2, Al_2O_3/SiO_2, R_2O/CaO – magnesium, alumina and alkaline modules of the burden; T_{filt}, T_{df}, - temperature of filtration through the coke filling and droplet flow of the primary slag melt, ^0C; FeO_{ps} – FeO content in the primary slag melt, %; Δe is the chemical equivalent of the slag-forming part of the burden, e; ρ is the stoichiometry indicator of the slag-forming part of the burden.

Characteristics used to assess the influence of technological operating conditions of the blast furnace are: the theoretical temperature of coke combustion T_t, the degree of gas utilization η_{CO}, the length of the tuyere zone L_{tz}, as well as the furnace temperature index FTI (which is determined on the basis of the temperatures of the coke combustion Tt, blast furnace gas T_{bg}, pig iron T_{ci} and the blowing T_{bl} [19]: $FTI^* = \frac{2500-T_t}{T_{bg}} \cdot \frac{1550-T_{pi}}{1250-T_{bl}}$.

The method of constructing of the burden integral indicators based on the use of the generalized Harrington desirability function allows "assembling" various indicators into a single generalized indicator and thus increase the information power of the optimization criterion. Based on the identified relationships of the burden and technology parameters with the distribution coefficients of the burden elements between the smelting products, analytical dependencies were developed for the integral indicators of K_b and K_{bl}, as well as for the predictive calculation of the distribution coefficients of the elements in the form of equations:

$$K_b = \left(\frac{Fe_{rich}}{SiO_2}\right)^{\alpha_1} \cdot \left(\frac{CaO}{SiO_2}\right)^{\alpha_2} \cdot \left(\frac{Al_2O_3}{SiO_2}\right)^{\alpha_3} \cdot \left(\frac{MgO}{SiO_2}\right)^{\alpha_4} \cdot \left(\frac{R_2O}{CaO}\right)^{\alpha_5} \cdot \left(\frac{T_{df}}{T_{filt}}\right)^{\alpha_6} \cdot \left(\frac{FeO_{ps}}{-\Delta e/\rho}\right)^{\alpha_7} \quad (1.)$$

$$K_{bl} = FTI^{\beta_1} \cdot \eta_{CO}^{\beta_2} \cdot L_{tz}^{\beta_3} \quad (2.)$$

$$L_E = A_E \cdot (IOM/C)^{\gamma_1} \cdot K_b^{\gamma_2} \cdot K_{bl}^{\gamma_3} \quad (3.)$$

where IOM/C - represents the ratio of the mass of iron ore materials in the burden to the mass of coke, A_E - the regression coefficient in the equation, α_1 - α_7, β_1- β_3, γ_1-γ_3 - equation coefficients and degree indicators characterizing the significance of a specific indicator. They are determined based on the results of the blast furnace operation in the established burden and technological conditions. Specifically, for the operating conditions of BF-A, the power indicators are as follows: α_i={0,1; 0,22; 0,13; 0,1; 0,2; 0,06; 0,19}; β_i={0,5; 0,2; 0,3}.

$$L_S = A_S \cdot (IOM/C)^{0,15} \cdot K_b^{0,5} \cdot K_{bl}^{0,35} \quad (4.)$$

$$L_{Si} = A_{Si} \cdot (IOM/C)^{0,33} \cdot K_b^{0,15} \cdot K_{bl}^{0.52} \quad (5.)$$

$$L_{Mn} = A_{Mn} \cdot (IOM/C)^{0,2} \cdot K_b^{0,35} \cdot K_{bl}^{0,45} \quad (6.)$$

Knowing K_b allows you to judge both the quality level of iron ore raw materials and blast furnace burden, as well as the influence of loading burden parameters on the quality of molten iron, since:

- firstly, the high degree of connection of K_b indicator with the distribution coefficients of burden elements (sulfur, manganese, silicon, titanium) justifies its use as a model parameter for forecasting the composition of smelting products using predictive models of burden distribution coefficients between pig iron and slag (**Fig. 2**) ;
- secondly, the established connection of the integral indicator K_b with the indicators traditionally used to assess the efficiency of the blast furnace process (sulfur content in pig iron, degree of gas utilization, degree of direct reduction of iron) for specific conditions of the blast furnace, makes it possible to determine the optimal intervals of its values. Maintenance of optimal K_b ensures melting of conditioned cast iron with minimal coke consumption. The rational mode of blast furnace smelting is regulated by a change in the integral index of K_b in the range of: 0.5-0.7 (**Fig. 3**) [20].

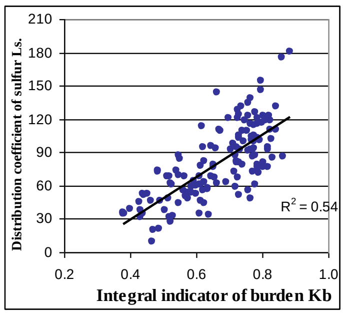

Fig. 2 Dependence of the sulfur distribution coefficient between pig iron and slag on the integral indicator K_b for specific conditions of BF operation

Analytical dependencies for calculating the distribution coefficients of the burden elements between pig iron and slag depending on the integral coefficients K_b and K_{bl} are adapted to specific conditions of the blast furnace and used in the model system to calculate the chemical composition of pig iron and slag. Figure 4 shows an example of calculating the chemical composition of pig iron and slag according to the indicators of the burden and technology parameters for specific operating conditions of a blast furnace with the use of secondary raw materials (briquettes, manganese concentrate, etc.) in a multicomponent burden, as well as replacing the part of natural gas with pulverized coal fuel.

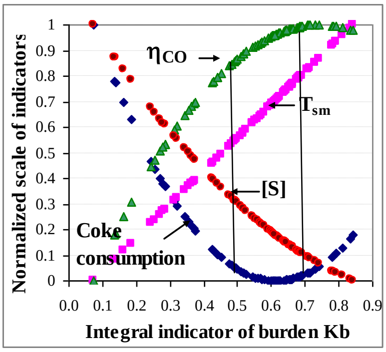

Fig. 3 Correlation of the integral indicator of K_b with the sulfur content in pig iron, the degree of gas utilization, coke consumption and the temperature of the burden melting for specific conditions of BF

The advantage and main difference of the developed system approach to the selection of the burden composition from similar developments is the use of a set of physicochemical criteria characterized the quality of iron ore raw materials, as well as the properties of blast furnace slag. Stabilization of these criteria in a certain "quality interval" ensures the smelting of pig iron of the required composition and the reduction of coke consumption under specific conditions of a blast furnace.

▲ **Chemical composition of charge materials (%)**

Name	Weight, m	SiO_2	Al_2O_3	CaO	MgO	MnO	S	K_2O	Na_2O	TiO_2	P_2O_5	Fe	FeO	Ash	Moisture	Removal
Coke	6.20	0	0	0	0	0	0.78	0	0	0	0	0	0	11.4	4.7	0
Coke ash	0.67	41.95	26.9	7.28	1.82	0	0	2.1	2.4	0	0.049	10.11	0	0	0	0
Agglomerate	16.80	10.35	0.91	16.2	1.49	0.08	0.3	0.090	0.09	0.13	0.078	49.56	9.64	0	0	4
Pellets	7.35	8.95	0.52	0.331	68	0.05	0.15	0.032	0.06		0.034	63.77	1.8	0	0.7	4
Ore	0.15	10.52	0.76	6.377	1.05	0.4	0.05	0	0	0	0	54.47	16.3	0	0	7
Fluxed material	0.34	14.11	1.74	29.15	4.48	1.5	0.1	0	0	0	1.667	50.00	0	0	0	7
Mn concentrate	0.14	12.00	1.98	10.6	2.38	36.2	0.16	0	0	2	0.785	2.80	0	0	0	10
Ash pulverized coal	0.17	43.00	28.9	7.72	1.88	0	0.3	0.3	1.49	0	0	6.96	0	0	1	15
Total		SiO_2	Al_2O_3	CaO	MgO	MnO	S	K_2O	Na_2O	TiO_2	P_2O_5	Fe	FeO			
Tons		2.66	0.40	2.74	0.31	0.07	0.10	0.03	0.04	0.02	0.02	12.54	1.61			
%		11.03	1.68	11.41	1.31	0.27	0.42	0.13	0.15	0.10	0.09	51.90	6.92			

▼ **Design parameters of the charge and technology. Transition shares.**

Burden

Name	Value
Fe_2O_3	66.85
Fe_{sch}	51.93
Ore load	3.99
CaO/SiO_2	1.035
$(CaO+MgO)/SiO_2$	1.154
Al_2O_3/MgO	1.28
Δe	-3.19
ρ	0.74

Technology

Name	Value
$CO_2/(CO+CO_2)$	0.466
Tuyere length, m	2.1
Burning temperature, °C	1997

Transition shares

Name	Value
Lsi	0.94321
Lmn	0.30778
Ls	0.95022
Lti	0.918313
Lp	0.2903451
Lfe	0.0019263

▲ **Predicted values of pig iron and slag**

Pig iron

Weight, t	Si	Mn	S	Ti	Fe	C	P
13.315	0.547	0.2674	0.04	0.01	94.4	4.75	0.06

Slag

Slag	Weight	SiO_2	Al_2O_3	CaO	MgO	MnO	S	K_2O	Na_2O	TiO_2	FeO	P_2O_5
Primary	7.71	31.6	3.01	35.81	4.01	0.87	0.74	0.22	0.27	0.30	22.95	0.28
Final	6.36	40.31	6.49	44.19	5.06	0.31	1.54	0.49	0.58	0.34	0.54	0.1

Fig. 4 Calculation of the chemical composition of blast furnace smelting products based on the prediction of the coefficients of interfacial distribution of burden elements for the operating conditions of a particular blast furnace

At the same time, integral parameters of slag (chemical equivalent of composition Δe and stoichiometry indicator ρ) are used as criteria for stabilization of the slag regime. The optimal composition of the slag is determined by such values of Δe and ρ, which ensure a viscosity within 0.3 Pa·s and a crystallization temperature of 1300ºC (**Fig. 5**). Then the value of sulfur-absorbing capacity tends to the maximum, and the value of enthalpy and surface tension - to the minimum, which ensures good desulfurization of pig iron and a reduction in coke consumption. In addition, the degree of approach of the "metal-slag" system to the equilibrium state is controlled by the ratio $\varepsilon = Ls_f / Ls^O$, where Ls_f, Ls^O are the corresponding actual and equilibrium values of the sulfur distribution coefficient. The proximity of the value of ε point to the line of equal values of Ls_f and Ls^O characterizes the degree of completion of desulfurization process of pig iron with slag (achieving sulfur equilibrium).

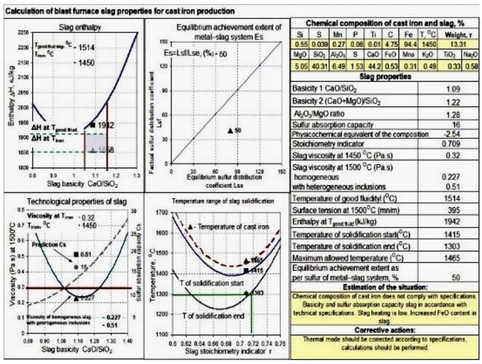

Fig. 5 Assessment of the technological situation by controlled indicators of the slag regime - a set of properties of the final slag

RESULTS AND DISCUSSION

Subtitle of results and discussion

It should be noted that the recently changed conditions of iron production (increased use of pulverized coal fuel) also affected the slag mode of smelting. Therefore, in order to more accurately estimate the viscosity and melting point of real blast furnace slags, it is necessary to take into account the effect on the properties of macro-heterogeneous slag inclusions formed when using coke with low strength characteristics, as well as incomplete combustion of gas and pulverized coal fuel.

Recently, models for calculating the viscosity and enthalpy of final blast furnace slags have received significant development. For this purpose, a set of representative data on slag properties was created using information from the "Slag" database. For a more accurate assessment of the viscosity and melting point of real blast furnace slags, a two-stage approach is used. It includes the calculation of the properties of a homogeneous slag, as well as taking into account its heterogeneity based on a gradient-criterion, considering the relative increase in the property in percent for each percent of the additive (PCF, coke, soot). Completed studies for the operating conditions of a number of blast furnaces in Ukraine with different slag conditions showed that presence of heterogeneous inclusions increases the viscosity of slags by 1.5-2 times, and the melting temperature by 30-50 ^{0}C compared to ideal homogeneous slag.

The predictive model for determining the enthalpy of slag depending on the parameters Δe and ρ was developed by taking into account the temperature of the melt T, which makes it possible to estimate the enthalpy in the range of 1400 ÷ 1550 ^{0}C. Knowledge of the enthalpy of the final slag together with other factors allows for a comprehensive assessment of thermal state of the hearth due to the heat introduced by slag.

Thus, a complex of mathematical and physicochemical models was developed, that describe and connect the processes of distribution and behavior of burden materials in different zones of the blast furnace with technical and economic indicators of melting. It provides information and mathematical support of the decision-making model system in the problem of selection the optimal composition of the multicomponent blast furnace burden, which ensures the production of pig iron of the required composition with minimal energy and raw material costs.

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The developed systematic approach ensures the implementation of the following stages for selection the optimal composition of the blast furnace burden:
- solving the direct problem of forecasting the composition and properties of primary melts and final smelting products depending on the burden and technological conditions of blast furnace smelting;
- evaluation of the technological situation according to the controlled indicators of melting, taking into account the formed system of technological restrictions;
- solving the *inverse* problem of determining the optimal composition of the burden by vector optimization methods, which ensures the achievement of the given target function and satisfaction of the system of constraints.

The formation of the system of technological restrictions is carried out based on the results of generalization of technological practice and existing requirements for the conditions and characteristics of the processes in the blast furnace. In particular, in the developed decision-making system for the selection of the burden composition, special attention is paid to the limitations that characterize the physical and chemical processes in the high-temperature zones of the blast furnace. These include the following conditions: ensuring a minimum difference in softening and melting temperatures of iron-containing materials (minimizing the thickness of the plastic zone, limiting the FeO content in the primary slag and its viscosity). In addition, solving the problem of optimization in the system is possible considering the stabilization of the integral index of the blast furnace burden K_b within the given limits and ensuring the given physico-chemical criteria characterizing the final slag melt.

The expediency of accounting an additional class of technological restrictions, which ensure the rational course of aggregate transformations in the furnace and the directed formation of melts of the required composition and properties, determines the practical reality of the obtained solution during the mathematical processing of the optimization problem.

Optimizing the composition of the blast furnace burden consists in determining such an optimal set of input parameters of the loading feed that will ensure the melting of pig iron of required composition at the maximum productivity of the blast furnace, the minimum consumption of coke or (and) the cost of pig iron. At the same time, it is necessary to satisfy all the requirements that are imposed as restrictions on the input (costs and chemical composition of the burden components) and output parameters, as well as on the parameters describing the processes of blast furnace melting (technological limitations).

The mathematical formulation of the solved optimization problem is formulated as finding the vector of costs of burden materials $X=(x_1, x_2, \ldots x_m)$, which ensures the minimum of the function $Z(X) = Z(x_1, x_2, \ldots x_m)$, where the set X is determined by the following constraints:

$$\begin{cases} a_i \le x_i \le b_i, i = \overline{1,m} \\ c_j \le t_j(X) \le d_j, j = \overline{1,n} \\ e_k \le f_k(X) \le s_k, k = \overline{1,l} \\ g_l(X) = G_l, l = \overline{1,p} \end{cases} \tag{7.}$$

where $t_j(X)$ are the parameters of the smelting technology, on which restrictions are imposed; $f_k(X)$ are the indicators of the smelting process (pig iron quality, etc.), which are calculated depending on the input parameters of the burden and technology; $g_l(X)$ and G_l are possible options and many possible interrelationships between the input parameters of the burden components; m - the number of burden materials; n – the number of burden components; r - the number of parameters of slag and pig iron, on which restrictions are set in the task (external parameters); p - is the number of established ratios between the input parameters of the burden components; a_i, b_i, c_j, d_j, e_k, s_k are given threshold values of available resources and technological limitations.

In addition to defining traditional criteria of optimization (coke consumption, furnace productivity, etc.), the optimization problem can be solved without an objective function by searching for a solution area providing the necessary boundary conditions.

The formulated problem belongs to the class of tasks of multi-criteria conditional nonlinear optimization. The peculiarity of this problem is the implicit task of the objective function, since the output parameters are calculated according to the above-mentioned method of forecasting the composition and properties of the final smelting products depending on the integral indicators of the burden and technology. The algorithmic task of the target function, interdependence of input parameters, fulfillment of all constraints in the form of inequalities and equalities determines the complexity of the algorithm for solving this problem. Verification and implementation of restrictions not only on the input and output parameters, but also on the intermediate calculation characteristics of the furnace melting and reduction processes, when searching for a solution, lead to the development of additional algorithmic methods using known mathematical optimization methods.

None of the existing methods of multidimensional conditional nonlinear optimization is universal. The most acceptable way of solving the problem of multi-criteria optimization in our case is the use of the deformed polyhedron method [21], taking into account the condition of success in choosing a step or direction. The advantage of the simplex method is the use of only the function values at the points and the absence of the gradient calculation. The optimal solution is due to the sequential movement and deformation of the simplex (N-dimensional polygon) in the region of the extremum point. However, the simplex method and the method of the deformed polyhedron (Nelder - Mead) belong to the methods of unconditional optimization. The complex method of Box [22] is a modification of the simplex method of Nelder – Mead, but allows taking into account limitations. The main idea of the complex Box method is to replace successively a set of points of a certain configuration, distant from the extremum, with those closer to it.

To optimize the composition of blast furnace burden on the base of modified simplex methods (Box, Nelder-Mead), we developed an algorithm taking into account the given priorities of the objective functions (optimization criteria) and the relationship of the input parameters to find optimal values in the given area of limitations. The developed algorithm includes a step-by-step optimization procedure according to the highest priority, an analysis of the relationship between the input indicators and the gradient of influence on the given functions. As a result, an acceptable (Pareto) optimal compromise solution is found in the given area of limitations, including technological restrictions on the use of various components in the burden composition.

When solving the problem of choosing the optimal composition of a multicomponent burden for the modern operating conditions of a blast furnace process with the use of pulverized coal fuel and natural gas [23], the maximum production of pig iron (weight of pig iron in tons) and the limit on sulfur content in pig iron were chosen as optimization criteria which should be within 0,03-0,035% for these technical conditions of blast furnace melting. The following optimization resources were chosen: the weight of pellets (to increase the production of iron), the weight of the metal fluxed steelmaking additive FSM-2 (to ensure the stabilization of the basicity of the burden/slag) and the content of MgO in the agglomerate (to improve the liquid mobility of the slag and increase its desulfurization ability). Restrictions are

imposed on the selected indicators in the form of a range of permissible values (**Fig. 6**).
With optimization algorithm operating, a solution was found that satisfies the selected objective function in the formed system of restrictions on input and intermediate parameters. In particular, due to an increase in the supply of pellets from 7,35 to 7,71 tons and FSM-2 additives from 0,34 to 0,97 tons, as well as an increase in the MgO content in the agglomerate from 1.49% to 1.8% the pig iron production can be increased from 13,31 to 14 tons. At the same time, the technical conditions for the chemical composition of pig iron and slag will be met: the content of silicon [Si]=0,51% (decreased by 0,035%), sulfur [S]=0,035% (decreased by 0,005%) and the value of basicity in pig iron slag CaO/SiO_2 = 1,1 units. When searching for a solution, technological limitations were checked and fulfilled, in particular, regarding the parameters of the primary and final melts formed (according to the optimal loading composition), the properties of which ensure the normal course of recovery and melting processes and contribute to high technical and economic indicators of melting.
Thus, with the help of the developed algorithm using vector optimization methods, the optimal compromise solution was found in the given area of limitations. This makes it possible to form scientifically based recommendations for choosing a rational composition of burden materials in modern conditions of blast furnace production.

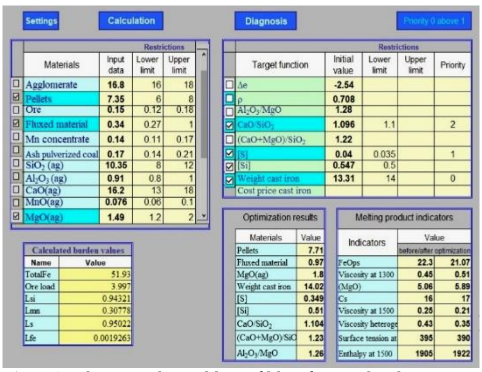

Fig. 6 A solution to the problem of blast furnace burden optimization for specific blast furnace operating conditions

CONCLUSIONS

A systematic approach has been developed in order to solve the strategic tasks of forming a rational composition of a multi-component blast furnace burden for a target purpose and forecasting the negative consequences of using secondary resources, which leads to unstable furnace operation and deterioration of the quality of pig iron. This approach implements the concept of modeling the processes of directional formation of melts using modern physicochemical and mathematical methods of predicting and optimization of complex systems.
The information-mathematical support of the system for choosing the optimal composition of a multi-component blast furnace burden has been developed using a complex of developed mathematical and physico-chemical models that describe and connect the processes of distribution and behavior of burden materials in different zones of the furnace with technical and economic indicators of melting, as well as using methods of vector optimization. This allows:
- to calculate the high-temperature properties of iron ore materials, the complex of physical and chemical properties of primary and final slag melts;
- to predict the chemical composition of pig iron and blast furnace slag depending on the characteristics of the loading burden, taking into account the parameters of the blast mode;
- to perform an assessment of technological situation according to the controlled melting parameters and the formed system of technological restrictions;
- to solve the problem of multi-criteria optimization of the burden composition taking into account the technological requirements, justified from the point of view of the rational flow of aggregate transformations in the furnace and the directed formation of melts of required composition and properties with increased productivity in modern blast furnace smelting conditions.
The main feature of the developed system approach to solving the tasks of optimizing the composition of the blast furnace burden is taking into account the laws of physical and chemical transformations of iron-containing materials in the high-temperature zones of the furnace and directed formation of melts, which is regulated by a system of justified technological restrictions in order to ensure the necessary indicators of blast furnace smelting.
The results of testing the created decision-making model system for choosing the optimal composition of the blast furnace burden based on the actual industrial data of blast furnace operation in modern conditions, using pulverized coal fuel and natural gas, made it possible to form scientifically based recommendations on the component composition of the loading, taking into account the available raw and energy resources.

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