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MODEL FOR OPTIMAL CONTROL OF CHARGE LOADING PARAMETERS OF METAL-REDUCING PLANTS

Purpose. The study's main objective is to consider two main factors simultaneously when optimizing the blast furnace loading process. The first is to maximize the potential use of gases in the blast furnace's "dry zone", which increases the efficiency of the ore recovery process. The second is to increase the melting productivity by optimizing the temperature regimes and uniform distribution of the charge over the furnace space, which ensures the stability of the furnace. Achieving a balance between these factors is critical to improving the overall efficiency of blast furnace production.

Methodology. The study used regression analysis to investigate the quantitative dependencies between the utilization degree of reducing gases and the efficiency of blast furnace melting. Evaluation of the results allowed us to create a predictive model to determine the main characteristics of the process.

Findings. The research results allowed us to create a predictive model to determine the main characteristics of the process. The analysis was carried out based on experimental data obtained from industrial blast furnaces, considering different modes of loading and distribution of raw materials.

Originality. The developed model is a new approach to optimizing control influences on blast furnace loading, considering the dynamic change in ore load. This allows including current changes in technological parameters and promptly adjust the smelting process. This approach improves the process's technical and economic performance and effectively predicts further development.

Practical value. The proposed methodology for controlling the loading process provides more accurate control over reducing gases use and the effectiveness of their impact on the ore. That leads to a decrease in fuel losses, a reduction in the environmental burden, and an increase in the overall productivity of the blast furnace by optimizing gas-dynamic processes.

Keywords: *blast furnace, ore load, furnace space, utilization rate, reducing gases*

Introduction. Improving the gas-dynamic parameters of the reducing zone of the mine furnace makes it possible to increase the productivity of the technological process and reduce the consumption of reduced fuel. As of today, most metallurgical enterprises in Ukraine and abroad analyze the operation of the furnace and make decisions about changing the loading program by studying the parameters of the content of reducing gases along the radius of the furnace. This way is rational for evaluating technological factors, but it does not allow for predicting the productivity of the metal reduction unit and coke consumption. Today, at most metallurgical enterprises in Ukraine, the greatest attention is paid to the problem of economic efficiency, reducing the costs of prepared raw materials and energy carriers.

Carbon dioxide is mainly formed by the reaction of indirect reduction of the ore component of the charge, which occurs at temperatures of 600–900 °C. The composition of the blast furnace gas in the final stages is also affected by the decomposition reaction of carbon monoxide, which leads to the formation of soot carbon and CO_2. The use of CO_2 content in the furnace gas or the ratio (CO/CO_2) as key parameters is justified, especially in the case of simplified calculations to determine how gas-dynamic processes affect the productivity and efficiency of melting, provided that their functional dependence is established, which takes into account physicochemical peculiarities of the process of recovery of charge oxides.

Literature review. The degree of use of gases in a blast furnace largely depends on the so-called gas load [1]. The gas load is the volume of gas that reacts with a unit mass of agglomerate charge per unit time. In work [2], it was demonstrated that the real velocity of gases in the furnace space of a blast furnace can be determined based on the study of the chemical balance between oxygen, nitrogen, and carbon. It was established that the degree graphs of gases use and their real speed are mirror-symmetric. Using this approach and having information about the composition of the furnace gases, it is possible to determine the real speed of gas movement along the furnace radius. By knowing the velocity distribution and considering the layers thickness and the material's porosity, it is possible to calculate the actual gas load along the radius of the furnace.

It is known that the best distribution of materials and gases is the one in which a unit mass of agglomerate reacts with the same volume of reducing gas in any part of the charge column. For this purpose, the dependences between the change in the gas load and the amount of agglomerate of the charge along the radius of the furnace during the research should be built.

Source [3] gives a formula for calculating the gas flow rate along the radius of the furnace

$$V_{gf} = \frac{Q}{S\varepsilon}\sqrt{\frac{h(1-\varepsilon)d_i\varepsilon_i}{d\varepsilon \cdot h_i \cdot (1-\varepsilon_i)}}, \tag{1}$$

where Q is the volume of reducing gas reacting in a specific ring zone; S – gas flow crossing; ε – average porosity of the material; h – the height of the agglomerate layer; d – the average size of the agglomerate; d_i – the average size of the agglomerate in a specific radial-circular zone; ε_i – porosity of a specific zone.

The gas load was calculated by the authors [4, 5] according to the formula

$$Q_{gn} = \frac{V_{gf} \cdot \varepsilon}{h \cdot \gamma}, \tag{2}$$

where γ is the agglomerate density.

According to formula (2), formula (1) can be written in the form

$$Q_{gn} = \frac{Q}{S\gamma}\sqrt{\frac{(1-\varepsilon)d_i\varepsilon_i}{hd\varepsilon \cdot h_i \cdot (1-\varepsilon_i)}}. \tag{3}$$

Unlike formulas (1 and 2), using formula (3), it is possible to calculate the gas load for each radial-circular zone (RCZ) of the furnace. At the same time, to use formula (3), it is necessary to have data on the equivalent size distribution of the agglomerate particles along the furnace radius, and their porosity.

Analysis of research materials conducted by employees of the Institute of Ferrous Metallurgy of the National Academy of Sciences of Ukraine under the leadership of Academician V. I. Bolshakov makes it possible to determine how the pieces of charge materials are distributed in the blast furnace zone of the recovery furnace when using a coneless loading device. The data relating to the agglomerate content of the charge in terms of size in different places of the radius of the furnace (Table 1) allowed calculating the average equivalent diameter of the pieces, which, in turn, allows calculating the gas permeability parameters of the agglomerate and coke column.

In Table 1, the first column shows the distance values from the furnace's far end. The next columns show data on the percentage content of specified particle size composition charge.

The main disadvantage of directly reducing elements from their oxides is that these reactions are endothermic. That is, they require additional heat energy, which increases the consumption of the reducing agent.

Under production conditions, the degree of direct reduction in furnaces often exceeds the optimal level (> 40 %). Therefore, conditions must be created to promote the use of CO's physical and chemical energy [6].

Despite many studies, rational ratio between indirect and direct reduction of charge oxides has yet to be clearly defined.

The absence of a strict relationship (functional dependence) between the content of carbon dioxide in the blast furnace gases, which changes by about 5 %, and carbon monoxide, the content of which almost does not change with the different distribution of the components of the charge on the blast furnace [7, 8], can be explained by the following reasons.

At the mine top, in the temperature range of two hundred to six hundred degrees Celsius, on newly recovered pieces of iron, a carbon monoxide decomposition reaction occurs with the formation of carbon and CO_2, accompanied by a significant release of heat. That leads to the fact that when the proportion of carbon monoxide decreases, the concentration of carbon dioxide in the furnace gases increases accordingly.

Table 1

Segregation of agglomerate in the "dry" zone of the blast furnace charge column

Coordinate	Percentage content by size, %			Avg. diameter, mm
	The thickness is more than 25 mm	Coarseness 5–25 mm	Coarseness 0–5 mm	
0.2	4	67	29	8.425
1.25	2.5	65	32.5	7.9375
2.1	3	68	29	8.275
3.3	2	76	22	8.65
4.05	3	82	15	9.325
4.9	7	80	13	10.075
5.4	9	79	12	10.45

So, to solve the task set in this work regarding the development of a rational method of loading and optimal distribution of charge components in a blast furnace, based on data on the composition of blast furnace gases, certain conditions were chosen, and the following assumptions were adopted.

Many studies are devoted to developing control algorithms for the blast furnace process based on the analysis of the composition and temperature of the blast furnace gas. The practical implementation of this concept was first substantiated in work [9]. According to the authors of the study [10], problems arising in blast furnace management due to changes in the content of reducing gases in the furnace are caused by the use of gas analyzers, with a significant error in the measurement of concentrations of carbon monoxide and carbon dioxide, reaching 2.5 %. The results of the analysis show that a change in the total content ($CO + CO_2$) in the blast furnace gas by 1 % leads to a change in the temperature of the output products by fifty to sixty degrees Celsius. The blowing temperature, which compensates for such a deviation, varies within 60–80 °C.

We believe that the change in the chemical composition in the blast furnace zone of the furnace (CO and CO_2) reflects only a change in the degree of direct and indirect reduction, which is not fully justified. In the study [11], the value of the total content of monoxide and carbon dioxide was used to determine the effect of the composition of the blast furnace gas on the thermal characteristics of the blast furnace process. However, according to the authors of the article, this indicator has only an indirect effect on the main characteristics of the process. It is not an effective tool for managing processes in the recovery furnace. In particular, the amount or ratio of the content of reducing gas to CO_2 of reduction reactions without identifying their relationship in the form of an analytical dependence, which takes into account the peculiarities of the course of reduction processes, can lead to incorrect conclusions.

The level of the residual content of reducing gas in the furnace shaft depends on the conditions of its transportation through the thickness of the charge, which is determined by the method of loading and distribution of the charge, that is, the gas permeability of the layer. This level determines the degree of use of carbon monoxide's reducing and thermal properties. The content of CO_2, for its part, consists of the chemical reactions' products, both with the release of heat and its absorption, which takes place under the conditions of reducing processes in the charge column in the temperature range from 200 to 1,250 °C.

The data on the content of CO_2 at different levels of the blast furnace, i.e., at different temperature conditions [12], show that at the lower and middle levels of the furnace shaft (800–1,100 °C), the concentration of carbon dioxide is higher than predicted by the Boudoir reaction (C (solid) + CO_2 (gaseous form) = 2 CO (gaseous form)). This phenomenon is explained by the significant accumulation of CO_2 due to the intensification of "indirect" reduction reactions. As mentioned earlier, the gasification of coke carbon is practically eliminated in such conditions. In the furnace's upper part, the carbon dioxide concentration is much lower than the equilibrium value; this is explained by the low level of Boudoir reaction development at temperatures below 800 °C and its almost complete stoppage, so the gases leave the furnace in an almost constant composition.

It should be taken into account that, according to the research results, no more than a fifth of the mass of the generated reducing gas is directed to carbon gasification; the final concentration of CO in the gases leaving the furnace should decrease within 3–4 %. Changes in the CO content when changing the loading method [13] occur only within 0.4 % for the selected options with the lowest and highest efficiency of distribution of materials in the upper part of the column of the furnace charge.

Thus, the temperature distribution along the height and cross-sections of the blast furnace and the composition of gases depends on the distribution of falling materials, the composition and quality of the charge, and the blowing characteristics.

Purpose. The purpose of the work is to optimize the process of loading the furnace with the maximization of the use of the regenerative potential of gases in the “dry zone” and increase the melting productivity by optimizing the temperature regimes and uniform distribution of the charge over the furnace space to achieve a balance between these factors.

Methodology. It is known that the more homogeneous the charge in terms of particle size characteristics, the better the distribution of reducing gases along the charge column cross-section. That ensures uniform gas permeability of the charge column and the same gas flow distribution over the entire furnace section. Many studies are devoted to determining the optimal composition of the charge and its average equivalent dimensions. In this regard, the conditions for the reducing gas flow through the charge layer and the degree of its use require extensive analysis. The analysis should be carried out from the perspective of finding the optimal solution for the distribution of the components of the charge on the furnace, which in turn requires modernization of the furnace loading technology.

The following can be attributed to the synergy effects that negatively affect the flow of recovery technological process:

- increase in agglomerate consumption due to the effect of removal of small particles by the flow of gases in the furnace; this, in turn, complicates the maintenance of the equipment that directs and cleans the gas and disrupts the flow of the technological process of recovery;
- reduction of the gas permeability of the charge layer due to the penetration of small particles of the charge into the space between the main pieces of agglomerate and coke;
- agglomerate distribution violation, coke, and reducing gas flows.

The data in Table 1 allow getting the graphical dependence shown in Fig. 1 and show the change in the charge size along the furnace’s radius. Accordingly, equivalent size in each radial-circular zone (RCZ) is calculated according to the formula

$$d = \sum a_n d_n,$$

where a_n is the fraction content; d_n – fraction diameter.

Analytically, the data presented in Fig. 1 can be presented as follows

$$d = \frac{1}{0.095 + 0.0085 \cdot Rx - 1.05 \cdot 10^{-4} e^{Rx}}, \qquad (4)$$

where Rx is the coordinate along the furnace axis, m.

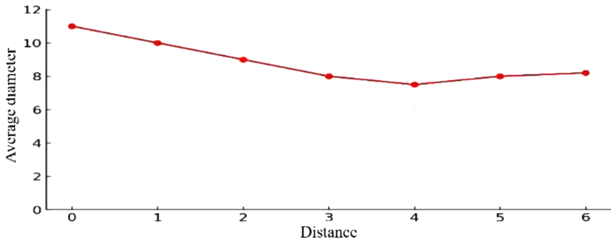

Fig. 1. The average diameter of the charge depends on the distance from the center of the furnace throat

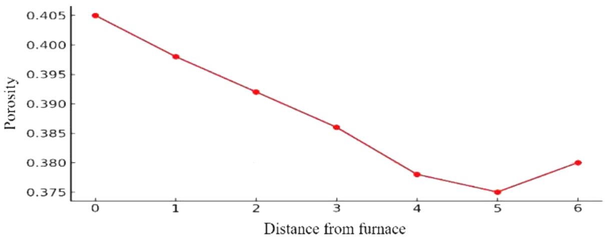

Fig. 2. Agglomerate porosity dependence on the distance from the furnace axis

In the works by Academician V. I. Bolshakov and Professor I. G. Muravyova, the following dependence is used to determine the charge porosity using the average equivalent diameter

$$\varepsilon = 0.222 \cdot d^{0.252}, \qquad (5)$$

where d is the average diameter of the material particles, mm.

Thus, the obtained data allow for a graphical representation of the change in porosity on the furnace throat, as shown in Fig. 2.

The formula can represent the data presented in Fig. 2

$$\varepsilon(Rx) = \frac{1}{2.496 + 0.051 \cdot Rx - 6.2 \cdot 10^{-4} e^{Rx}}.$$

According to the research, the equivalent diameter of the agglomerate is 9.02 millimeters.

The data given in Table 2 characterize the content of carbon monoxide and carbon dioxide in the furnace when different options for the distribution of charge components are used [14]. Small changes in carbon monoxide content in the blast furnace gas prove that almost the same conditions are provided for the indirect reduction of iron oxides in the case of a change in the distribution of the charge components [15].

In order to achieve the goal, it is necessary to assign the main characteristics that can change when adjusting the order of operation of the loading system equipment. The ore load and its distribution along the blast furnace RCZ have the greatest influence on productivity and fuel consumption, the degree of use of carbon monoxide, and gas-dynamic conditions in the charge column of the reduction zone.

Research on the operation of a blast furnace with a volume of 2,000 m^3 with a coneless loading device was carried out by V. O. Petrenko (1984), where the main characteristics of the recovery process were experimentally recorded. Parameters studied by Petrenko V. O. are the following: productivity, coke consumption, and the carbon oxides content in

Table 2

Data on the technical and economic features of 2,000 m^3 furnace

Indicators	Experimental intervals						
	first	II	first	IV	first	VI	first
Productivity, t/day	3,767	3,950	3,962	3,969	3,974	3,921	3,723
Specific consumption of coke, kg/t	514	512	510	508	507	511	522
Content in furnace gas CO_2, %	16.8	20.2	21.1	21.3	21.4	19.8	16.3
The same, CO, %	23.1	23.1	23.0	22.9	22.9	23.0	23.3
Degree of CO utilization	42.1	47.5	47.8	48.2	48.3	48.0	45.9

the blast furnace gas. During the experiment, the furnace charge and blast parameters remained unchanged. The analysis of these data and its results regarding the reproducibility of the iron-containing part of the charge are shown in Table 2. The degree values of carbon monoxide use allowed concluding which interval is the most successful from the point of view of the physicochemical side of iron production technology. Thus, it is necessary to pay attention to such loading parameters, which provide the investigated degree of utilization of CO gas.

Findings. Using the materials in Table 2, we obtained the correlation dependences allowing us to analyze and find the relationship between the gas-dynamic characteristics of the furnace throat zone and its technical and economic indicators.

From the start, an influence analysis of the degree of carbon monoxide gas use on the recovery process's efficiency was carried out. The following functional dependence was obtained

$$P(\eta_{CO}) = \frac{1}{a + b \cdot \eta_{CO} + c \cdot \eta_{CO}^{2}}, \qquad (6)$$

where P is furnace output volume, t/day; η_{CO} – degree of reducing gas use.

Fig. 3 shows the graphical dependence of expression (6).

Calculations performed based on the data in Table 2, as well as the analysis of the graphical dependence presented in Fig. 1, show that increasing the efficiency of CO gas use by 5 % compared to the maximum value, according to the experimental study results, increases productivity by approximately 6 %. This results from implementing a real recovery furnace with the optimal loading order used during the fifth investigated time interval. That, in turn, allowed ensuring the most optimal distribution of agglomerate and coke in the furnace dry recovery zone from the improving gas permeability point of view.

Based on the data in Table 2, the graphical dependence shown in Fig. 4 was constructed.

Analysis of the graphical dependence shows that an increase in the degree of use of CO-reducing gas by one-tenth of a relative part reduces coke consumption by 5.74 %.

During the fifth investigated time interval, the carbon monoxide content in furnace gas was 22.9 %, and for the VII period, it was 23.3 %. Thus, the difference is equal to 0.4 %. Considering stoichiometric parameters of the coke-carbon oxidation reaction, we determine formed monoxide amount.

$$2C + O_2 \rightarrow 2CO$$

Considering that the carbon in coke is 87 %, we get

$$\mu = \frac{\delta \cdot 56}{24} = 2.03,$$

where δ is the mass fraction of carbon.

So, when 1 kg of coke is consumed, 2.03 kg of reducing gas is formed. The decrease in the volumes of the reducing gas in the comparative periods is equal to

$$\Delta CO = \mu \cdot 0.004 = 0.0081.$$

Now, it is possible to calculate the additional amount of iron ore raw material recovered due to the optimization of the distribution of charge components and the gas-dynamic conditions of the charge column of the blast furnace zone.

$$Fe_2O_3 + CO \rightarrow 2FeO + CO_2$$

Additional recovered quantity is

$$\Delta Fe = \frac{160 \cdot 0.0081}{28}.$$

Let us analyze the received data. In the case of providing improved gas dynamics for the blast furnace part of the furnace, one mass fraction of reducing fuel creates conditions for additional recovery of 0.046 kg of agglomerate. Thus, in case of oxidation of 1 ton of reductant fuel, 46 kg of iron oxides will receive additional recovery.

Let us consider the results of changes in the ore load in two-time intervals of the furnace operation under consideration. 522 kg per ton of cast iron is the reducing fuel consumption. During the seventh period, the ore load can be calculated by expression

$$PH1 = \frac{M_A}{M_K}, \qquad (7)$$

where M_A is the mass of the agglomerate; M_K is the mass of the reducing agent.

For the fifth period

$$PH1 = \frac{M_A + 0.046 M_A}{M_K}. \qquad (8)$$

We analyze what limits can be realistically provided for increasing the ore load. Let us divide equation (8) by (7), we get

$$\upsilon = \frac{PH2}{PH1} = 1.046.$$

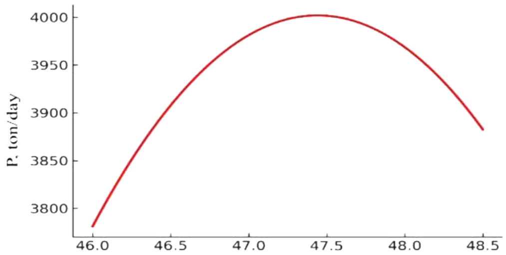

Fig. 3. Dependence of the amount of iron produced on the degree of use of reducing gas

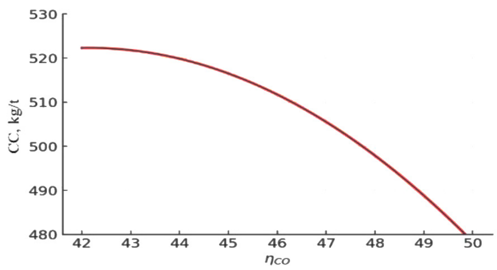

Fig. 4. Dependence of the reducing agent consumption in the furnace and the degree of the reducing gas use

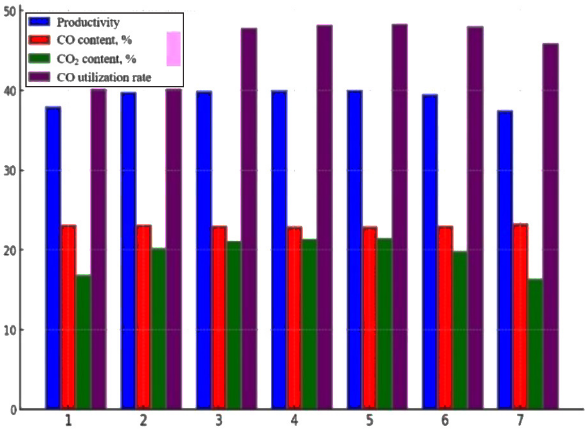

Fig. 5. The ratio of melting indicators

Thus, using gas load optimization [16, 17], the ore load can be increased by 4.6 %.

The influence of the program of charging the furnace with charged materials on the forecast characteristics of the growth of the ore load and the simultaneous drop in the level of consumption of reducing fuel can be determined by analyzing the data on the content of carbon dioxide in the blast furnace gas. The ratio of melting indicators is shown in Fig. 5.

The incorrectness of the ratio CO/CO_2 can be explained by the fact that in the temperature range of 200–600 °C, the upper layers of the dry zone of the furnace intensifies the reaction of the decomposition of carbon monoxide with the formation of CO_2 and solid carbon, which causes the redistribution of the contents of these gases in the direction of increasing CO_2 and by reducing the level of CO content. The reaction proceeds with a high release of heat, increasing the temperature and correcting the reducing unit's heat balance.

An integrated assessment of the gas dynamics of the studied metal reduction unit based on the parameters shown on the histogram in Fig. 5 and Table 2 allowed the ratio of productivity and the total content of carbon monoxide and dioxide in the furnace gases. The curve in Fig. 6 graphically illustrates this.

Using the same data, we obtained the dependence of the carbon dioxide content on the reducing gas content, which was created for the 7 furnace loading programs.

Thanks to the data in Table 2 and Fig. 5 and by calculating the actual increase in the content of carbon dioxide in the gas stream ($+\Delta CO_2$) and the decrease in the content of reducing gas (ΔCO), the expected increase in ore load on the magnetite agglomerate and the expected reserves for reducing the consumption of reducing fuel can be predicted.

Based on expression (3) and formulas (4 and 5), a distribution model of the actual gas load at the ArcelorMittal enterprise was created. This formula allows for estimating how much reducing gas interacts with different volumes of charge materials. The real ratios of the gas load along the radius of the blast furnace are presented in Fig. 8.

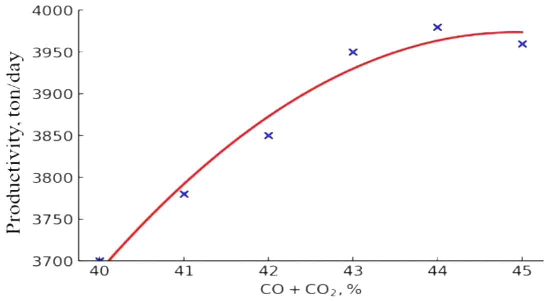

Fig. 6. Dependence of cast iron daily production on the total gas content

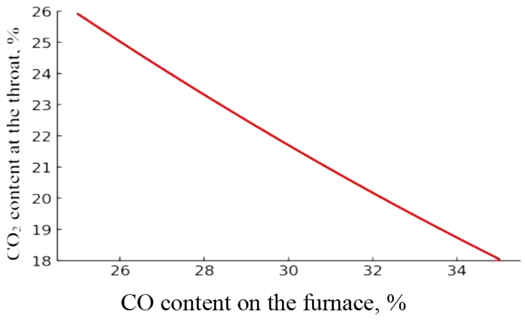

Fig. 7. Dependence of the content of carbon dioxide on the content of reducing gas

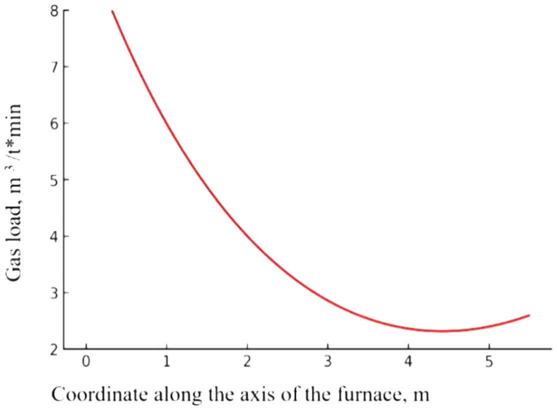

Fig. 8. Gas loads dependence on the coordinate along RCZ

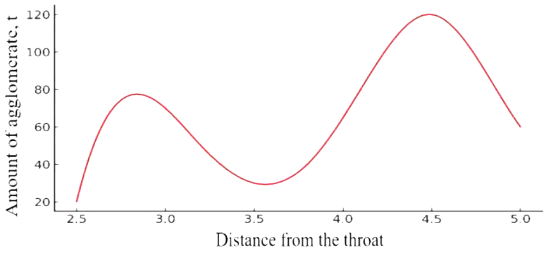

Fig. 9. Dependence of the agglomerate amount on the furnace on the distance from its axis

In order to assess the effect of the gas load on the iron-containing part of the charge materials, it is important to know their real amount (mass), which is located in a specific radial-circular zone (RCZ) of the blast furnace. That can be done with the help of a visual graphical dependence, which demonstrates changes in the agglomerate mass along the furnace's radius during a cycle that includes ten feeds. The dependence is presented in Fig. 9. The quantities of iron ore materials were determined using a radar-type charge surface monitoring system. Effective distribution of gas in the column of the furnace charge can be ensured by fulfilling the condition of uniform gas passage through a unit mass of agglomerate of the charge throughout the entire layer of the furnace. Based on this criterion, it is proposed to introduce the concept of the coefficient of uneven gas distribution of the furnace throat zone, which is equal to the ratio of the gas load to the mass of agglomerate in all radial-circular zones of the furnace throat in a row.

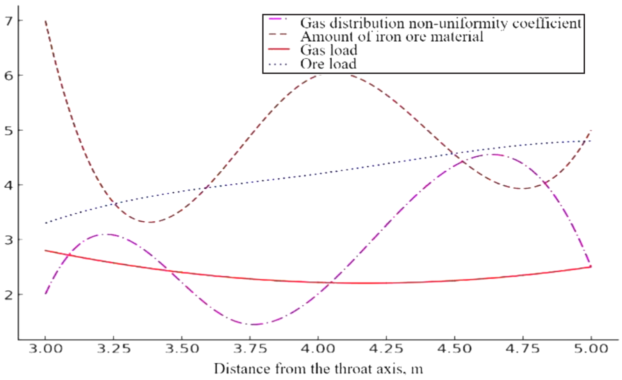

Fig. 10. Dependence of the ore and gas load values, the agglomerate amount, and the unevenness coefficient of gas distribution along the blast furnace radius

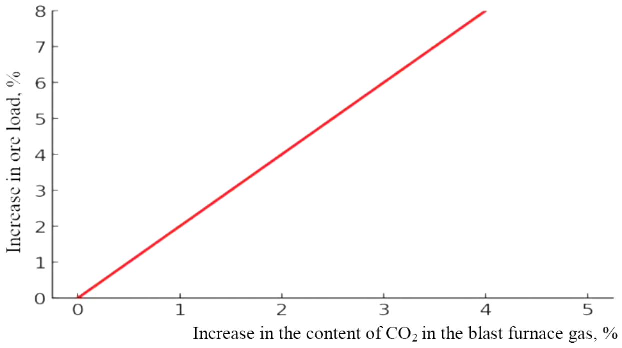

Fig. 11. Dependence of theoretical change in the ore load on the carbon dioxide content in the blast furnace gas when optimizing method of loading the charge into the reducing furnace

Therefore, it is possible to determine the actual distribution of ore and gas loads along the RCZ. Thus, in order to adjust the furnace loading program, it is suggested that the coefficient of uneven loading with charge materials be used, defined as the ratio of gas and ore loading. That approach allows the coefficient for each RCZ to be calculated.

To facilitate the analysis, Fig. 10 shows graphs showing the values of the gas load, the agglomerate mass, and the gas distribution unevenness coefficient along the RCZ.

Changes in the loading program are performed as follows: the necessary correction of the gas load is determined. Considering the ratio coefficient of gas and ore load for a certain RCZ, the necessary correction of ore load is calculated. That allows changing the control parameters (e. g., the inclination angle of the tray, the shutter opening angle of the storage hopper, the mass fraction of the loaded material, etc.) to achieve the desired ore load along the radius of the blast furnace.

The correlations study between parameters such as the carbon monoxide reduction degree in the blast furnace gas, furnace productivity, and coke consumption allowed developing a model for forecasting changes in furnace performance in the case of a change in the charge components distribution [18, 19].

Conclusions. The analysis shows that the increase in carbon dioxide content in the furnace gas can be up to 5.1 %. In this way, it is possible to calculate a possible reduction in the consumption of reductant fuel due to the optimization of the gas dynamics of the charge column during the fifth period of melting under the condition of constancy of the agglomerate mass. Analysis of reactions gives the following results: 44.01–12.01; 2.245-xC, where xC equals 0.612 mass units, which is 5.09 % in terms of reducing coke carbon consumption.

Using the non-uniformity factor enables optimal automatic adjustment of the placement of the components of the blast furnace charge to achieve the most efficient melting performance of a particular recovery furnace. The combination of the above methodology with the monitoring system for the surface of the charge backfill on the blast furnace provides grounds for extensive automation of the smelting technological process by loading control influences, which is especially relevant when using coneless loading devices of mine recovery furnaces.

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Модель оптимального управління параметрами завантажування шихтою металовідновлювальних установок

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Мета. Основна мета дослідження полягає в тому, щоб при оптимізації процесу завантаження доменної печі враховувати одночасно два основних чинники. Перший – максимізація використання відновлювального потенціалу газів у «сухій зоні» доменної печі, що дозволяє підвищити ефективність процесу відновлення рудних матеріалів. Другий – підвищення продуктивності плавки шляхом оптимізації температурних режимів і рівномірного розподілу шихти по колошниковому простору, що забезпечує стабільність роботи печі. Досягнення балансу між цими чинниками є критично важливим для підвищення загальної ефективності доменного виробництва.

Методика. У процесі дослідження був використаний регресійний аналіз для дослідження кількісних залежностей між ступенем використання відновлювальних газів і показниками ефективності доменної плавки. Оцінка результатів дозволила створити прогнозну модель для визначення основних характеристик процесу.

Результати. У результаті дослідження була створена прогнозна модель для визначення основних характеристик процесу доменної плавки. Аналіз проводився на основі експериментальних даних, отриманих із промислових доменних печей з урахуванням різних режимів завантаження й розподілу сировини.

Наукова новизна. Розроблена модель є новим підходом до оптимізації керуючих впливів на завантаження доменної печі з урахуванням динамічної зміни рудного навантаження. Це дозволяє враховувати поточні зміни технологічних параметрів й оперативно вносити корективи у процес плавки. Такий підхід дає можливість покращити техніко-економічні показники процесу та ефективно прогнозувати його подальший розвиток.

Практична значимість. Запропонована методика керування процесом завантаження забезпечує більш точний контроль за використанням відновлювальних газів і ефективність їх впливу на руду. Це призводить до зниження втрат палива, зменшення екологічного навантаження, а також підвищення загальної продуктивності доменної печі за рахунок оптимізації газодинамічних процесів.

Ключові слова: *доменна піч, рудне навантаження, колошниковий простір, ступінь використання, відновлювальні гази*

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