Improvement of the Burden Column Structure by Controlling the Multicomponent Burden Loading Mode into the Blast Furnace

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Abstract. The purpose of this work was to study the possibility of correcting the shape and position of the plastic zone, as the main element of the structure of the burden column in a blast furnace, by controlling its loading mode. To achieve this goal, a new method has been developed for determining the coordinates of the lines of softening and melting of the burden based on information about the gas temperature above the surface of the charge and the characteristics of the distribution of burden materials, a criterion for the technological assessment of the cohesive zone has been proposed, and the relationship between its thickness and the distribution of the burden has been studied. Important results are the established connections between the coordinates of the softening and melting lines with the gas temperature above the surface of the charge and the characteristics of the distribution of burden materials, as well as the development of a criterion for the technological assessment of the formed cohesive zone and the justification for the possibility of adjusting its parameters by changing the distribution of charge components with the calculation determination of the composition and prediction of high-temperature properties of their mixtures in different zones of the furnace. The significance of the obtained results lies in the justification of the possibility and solution of the problem of improving the parameters of the cohesive zone by adjusting the charge loading regime to ensure the energy efficiency of the blast furnace process.
***Keywords*:** blast furnace, multicomponent burden, mixtures, high temperature characteristics, cohesive zone, melting and softening lines, criterion, control.

DOI: https://doi.org/10.52254/1857-0070.2023.2-58-12
UDC: 669.162.21.27.012.3

Îmbunătățirea structurii coloanei de încărcare prin controlul modului de încărcare a încărcăturii cu mai multe componente în furnal

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Rezumat. Scopul acestei lucrări a cercetarea posibilității de îmbunătățire a parametrilor zonei de coeziune, elementul principal al structurii de încărcare a furnalului, prin controlul regimului de încărcare. Pentru a atinge acest obiectiv, a fost elaborată o nouă metodă de determinare a parametrilor zonei de coeziune bazată pe informații despre temperatura gazului deasupra suprafeței de încărcare și compoziția încărcăturii în diferite zone ale furnalului, un criteriu de raționalitate pentru zona de coeziune, a fost propusă și a fost studiată relația dintre grosimea zonei de coeziune și distribuția sarcinii. Rezultatele importante includ stabilirea conexiunii dintre coordonatele liniilor de înmuiere și topire cu temperatura gazului deasupra suprafeței de încărcare și caracteristicile distribuției componentelor de încărcare. Dezvoltarea criteriului de raționalitate pentru zona de coeziune și justificarea posibilității de ajustare a parametrilor acesteia prin modificarea distribuției materialelor de încărcare cu calculul preliminar al compoziției amestecului componentelor de sarcină în diferite zone ale cuptorului și prezicerea temperaturii lor ridicate proprietățile sunt, de asemenea, rezultate semnificative. Semnificația rezultatelor obținute constă în justificarea posibilității și soluționării problemei îmbunătățirii parametrilor zonei de coeziune prin ajustarea regimului de încărcare a sarcinii pentru a asigura eficiența energetică a procesului de furnal. Se arată că corectarea parametrilor zonei plastice, alegerea direcției și mărimii acțiunii de control în fiecare caz specific ar trebui să se bazeze pe rezultatele modelării matematice a distribuției materialelor de sarcină de-a lungul razei vârfului, determinând compoziția amestecurilor de componente de sarcină în diferite zone ale cuptorului și prezicerea proprietăților lor la temperatură ridicată, precum și tendințele de modificare a acestor proprietăți la modificarea compoziției componentelor amestecului.
Cuvinte-cheie: furnal, sarcină multicomponentă, amestecuri, caracteristici de temperatură ridicată, zonă de coeziune, linii de topire și dedurizare, criteriu, control.

Усовершенствование структуры столба шихты путем управления режимом загрузки многокомпонентной шихты в доменную печь

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Аннотация. Целью настоящей работы являлось исследование возможности корректировки формы и положения пластичной зоны, как основного элемента структуры столба шихты в доменной печи, путем управления режимом ее загрузки. Для достижения поставленной цели разработан новый метод определения координат линий размягчения и плавления шихты на основании информации о температуре газа над поверхностью засыпи (температуре поверхности засыпи) и характеристиках распределения шихтовых материалов в сочетании с использованием ряда математических моделей, предложен критерий для технологической оценки сформировавшейся пластичной зоны, исследована связь ее толщины с содержанием компонентов шихты в различных зонах доменной печи. Важным результатом выполненных расчетно – аналитических исследований являются корреляционные связи координат линии плавления с температурой газа над поверхностью засыпи в соответствующих зонах колошника, температур размягчения - плавления и толщины пластичной зоны в рабочем пространстве печи с распределением основных железосодержащих шихтовых материалов по радиусу колошника. К важным результатам следует отнести также разработку критерия для технологической оценки пластичной зоны и оценка возможности корректировки ее параметров путем изменения распределения рудных нагрузок и компонентов шихты. Показано, что корректировка параметров пластичной зоны, выбор направления и величины управляющего воздействия в каждом конкретном случае должны основываться на результатах математического моделирования распределения шихтовых материалов по радиусу колошника, определении состава смесей компонентов шихты в различных зонах печи и прогнозировании их высокотемпературных свойств, а также тенденций изменения этих свойств при изменении компонентного состава смеси. Значимость полученных результатов заключается в обосновании возможности и решении задачи улучшения параметров пластичной зоны путем корректировки режима загрузки шихты в доменную печь для обеспечения энергоэффективности доменной плавки.

Ключевые слова: доменная печь, многокомпонентная шихта, смеси, высокотемпературные характеристики, пластичная зона, линии размягчения и плавления, критерий, управление.

INTRODUCTION AND FORMULATION OF THE PROBLEM

The efficiency of blast furnace smelting and the quality of cast iron are largely determined by the characteristics of the burden column formed in the furnace. The current level of knowledge of blast furnace smelting processes, summarizing the results of the work of leading researchers in this field, suggests the development of methods for controlling the parameters of the cohesive zone in the furnace as one of the main tasks. It is known that the cohesive zone, being the most important structural element of the burden column, which is mainly formed as a result of the implementation of a given mode of loading a blast furnace, determines the distribution of the gas flow and the main melting indicators. As a rule, the choice of parameters of the blast furnace loading mode is carried out on the basis of an assessment of the distribution of burden materials using calculation methods (mathematical models, calculation methods, etc.) and subsequent analysis of the results and their compliance with the specified parameters and indicators of blast furnace smelting.

It should be noted that earlier, when considering the relationship between the loading mode and the configuration (shape) of the cohesive zone, the main attention was paid to the influence of the distribution of ore loads on the furnace top [1]. Such an approach could be considered correct for the conditions of loading a mono-charge into a blast furnace, which would cause the invariance of the high temperature properties of burden materials and their melts in various sections of the furnace. At the same time, the blast furnace charge in modern conditions is multicomponent. Until recently, it was not possible to predict the high temperature properties of mixtures of iron-containing burden materials in various zones of the furnace, since there are no tools for determining the distribution of individual charge components. However, with the advent of appropriate mathematical models, refinements can be made to the solution of the problem of determining the configuration of the cohesive zone, taking into account the distribution of high temperature characteristics of the charge layer in the working space of a blast furnace. In this work, we used a complex model for the distribution of burden materials, developed at the Iron and Steel Institute of Z.I. Nekrasov of National Academy of Sciences (NAS) of Ukraine (ISI), which has been repeatedly used with positive results in blast furnaces to determine the distribution of charge components and predict the properties of the resulting melts in industrial conditions in order to correct the applied technological regimes and increase the efficiency of melting. The availability of data on the composition of mixtures of burden materials in various zones of the blast furnace makes it possible to determine the temperatures of the onset of softening and melting in these zones as points of the corresponding lines.

The main characteristics of the cohesive zone are considered to be its shape, position in the furnace and thickness, which significantly affect the productivity and other performance indicators of the blast furnace. To date, generally accepted analytical, sufficiently substantiated methods for determining the shape of the cohesive zone have not been developed. The ISI has developed a method for determining the parameters of the cohesive zone, based on information about the distribution of the temperature of the gas flow or the surface of the charge along the radius of the top [Method of determining the position and shape of the cohezive zone in a blast furnace using gas flow temperature distribution indicators] / Muravyova I.H., Ivancha M.H., Shcherbachov V.R. and etc. // Fundamental and applied problems of ferrous metallurgy. 2022. Collection 36. P. 95 - 108. [In Ukrainian]. DOI: 10.52150/2522 – 9117 – 2022 – 36 - 95 - 108.]. The method is based on a systematic set of mathematical models, including those developed by the authors, and also includes a new method for determining softening and melting lines in a blast furnace. The method is implemented using a complex mathematical model for calculating the distribution characteristics of the charge components in the annular zones of the top.

An analysis of the published results of earlier studies showed that the bulk of the work on studying the features of the formation of a cohesive zone in a blast furnace was carried out in the 70s of the last century [2]. Their focus was determined by the unique studies of Japanese scientists carried out on frozen blast furnaces, as a result of which it was found that the burden column in a blast furnace is a combination of structural elements, the main of which is the cohesive zone. In subsequent years, studies of the formation of a cohesive zone in a blast furnace using mathematical models were actively continued in Germany, China and Japan.

Publications of recent years indicate the further development of research on the development of mathematical models for determining the parameters of the cohesive zone, including models that take into account non-stationary processes in the furnace. Nippon Steel Corp. continues research in this direction; its employees have developed a method for determining and visualizing the position of the cohesive zone root under the assumption that the root abuts against the centers of gravity of the figures determined by the results of evaluating the change in a number of controlled parameters over time [3]. In [4], a method was proposed for determining the position of the root of the cohesive zone based on an analysis of the nature of changes in the temperatures of the refractory lining of the mine and cooling water, as well as the degree of CO utilization along the height of the furnace, and a number of other parameters. In [5], a method for determining the characteristics of the cohesive zone in a blast furnace is described, which is based on the mass conservation equations and the heat conservation equations, which, according to the authors, govern the chemical reactions occurring in the furnace. Based on this assumption, dividing the blast furnace into a number of concentric circles, the authors determine the temperature fields of the furnace, and then, depending on the fusibility of iron-containing burden materials, the shape and position of the cohesive zone are predicted.

In [6], the results of the development of a mathematical model describing the flow of liquid, heat and mass transfer, as well as chemical reactions in a blast furnace are presented. Unlike the previous models, the proposed one considers three variants of the structure of the layers of the cohesive zone - layered, isotropic non-layered and anisotropic. The authors have studied the influence of these three options on the processes of distribution of the gas flow in the furnace. It is shown that the calculated estimate of the parameters of the cohesive zone, which is alternating layers of iron-containing materials and coke, which corresponds to the layer-by-layer loading of the charge, makes it possible to predict (simulate) the passage of the gas flow through the "coke windows".

To determine the shape of the cohesive zone in [7], mass and heat transfer in three separate furnace zones is considered. As the initial information, the readings of the probe that measures the composition and temperature of the gas and is located below the level of the charge. Calculated as isotherms, the lines of the beginning of softening and melting determine the location of the cohesive zone in the furnace.

Also known is the approach to determining the shape and position of the cohesive zone in a blast furnace, proposed by the researchers of Tata Steel Ltd. (India) [8, 9], who use a combined approach to determine the shape and position of the cohesive zone, which involves the use of a mathematical model in the form of differential equations, in combination with furnace operation indicators, and information from various probing devices.

To estimate the shape and position of the cohesive zone in a blast furnace, researchers actively use computational fluid dynamics (CFD) models. In [10], the results of improving the blast furnace smelting model, which was previously developed by Nippon Steel Corp., are presented. In addition to the existing private models (mass transfer, reactions and heat transfer in the dry and cohesive zones of the furnace), models have been developed to assess the distribution of ore loads on the top, a model of the tuyere hearth, as well as a model to estimate the porosity of the zone of low-mobility materials. All these models describing the flow processes in the blast furnace are integrated into the model used to calculate the parameters of the cohesive zone. A similar mathematical apparatus is used in the works of a number of other researchers [11 - 14]. In [11], the model describes in detail the layered structure of the cohesive zone. It was shown in [12] that the upper boundary of the cohesive zone is set as a constant temperature, and the lower boundary, the melting line, is defined as the liquidus temperature. Moreover, the liquidus temperature is established as a function of the chemical composition of the slag. To obtain such a function, the authors performed a regression analysis based on the data given in published sources, and obtained a third-order polynomial dependence for calculating the liquidus temperature.

In [13], a model developed by the authors is presented, which includes a description of the dynamics of the gas flow, the movement of the burden, chemical reactions, heat and mass transfer between the gas phase and the burden. The burden in the blast furnace is presented in the form of alternating layers of iron ore and coke. The multilayer CFD model, according to the authors, quite accurately estimates the shape and location of the cohesive zone, which are determined by the iterative method based on the distribution of the melting temperature of the ore part of the charge. Of the works that also use CFD modeling methods to determine the shape and position of the cohesive zone in a blast furnace, it should be noted [15], where the influence of the charge loading program on the position of the cohesive zone - its root and top. In this case, the position of the root of the cohesive zone is determined by changes in the temperature of the cooling water in the lower part of the furnace shaft.

There is also a work on predicting the position and configuration of a cohesive zone, in which the computational fluid dynamics model (CFD) and the support vector method (SVM) are combined to solve this problem [16]. The authors have created an axisymmetric two-dimensional stationary CFD model for describing the processes of fluid flow, heat and mass transfer in a blast furnace shaft. Prediction of the position of the cohesive zone is carried out using SVM.

In the development of models for determining the position of the cohesive zone in a blast furnace, the discrete element method (DEM) is also used [17]. A feature of the application of this method for the conditions of blast furnace smelting is the discretization of the charge in the volume of the furnace into its individual elements, which involves the use of many assumptions about their interaction.

In recent years, when developing mathematical models of blast furnace melting, in particular, a model for determining the cohesive zone, researchers combine continual and discrete models. The model combined in this way received the terminology «DEM - CFD model» [18 - 20]. The CFD-DEM model is suitable for modeling fluid-solid or fluid-particle systems. In a typical CFD - DEM model, the phase motion of discrete solids or particles is described using the discrete element method (DEM), which involves the application of Newton's laws to the motion of each particle, and the flow of a continuous fluid is described by the local averaged Navier - Stokes equation, which is solved using the methods traditional computational fluid dynamics DEM - CFD. In the studies reported in [19], the melting characteristics of iron ore and the structure of the layers during the operation of the furnace with low coke consumption were entered into the DEM - CFD model, and then the gas and moving bed behavior in the blast furnace was modeled. As a result of the calculation, the influence of the thickness of "coke windows" in the cohesive zone on the gas flow rate is demonstrated.

An analysis of the above results shows that only one of the considered works studied the effect of the charge loading program on the position of the cohesive zone - its root and top [15], but the studies were limited to taking into account the effect of the ore and fuel components of the charge as a whole. Features of the distribution of the components of the iron ore part of the charge, as well as the relationship of its characteristics with the parameters of the cohesive zone, were not considered in the known models, which reduces the reliability of the calculation results and limits the ability to control the process of formation of the cohesive zone.

The results of previous work also allow us to conclude that researchers agree on the approach to controlling the parameters of the cohesive zone: the main influence on the formation of the cohesive zone is exerted by the mode of loading burden materials, which determines the size of the melting surface area of iron-containing materials (the lower surface of the cohesive zone) and the thickness of the "coke windows", providing gas permeability of the burden column in the furnace. At the same time, according to V.M. Parshakov, whose works are closest to solving the problem of improving the technology of blast furnace smelting by adjusting the parameters of the cohesive zone, the results of studies of a quantitative assessment of the relationship between the parameters of the cohesive zone and melting indicators are practically absent at the moment.

This work differs from previous studies by providing a justification and solution for improving the parameters of the cohesive zone in the blast furnace by adjusting the charging regime, taking into account the distribution of components within the charge along the radius of the furnace, as well as the composition and high-temperature properties of their mixtures formed in different zones of the blast furnace.

The aim of this study was to develop a method for the prompt determination of cohesive zone parameters (its configuration, position in the furnace, and thickness) based on information about gas temperature (surface temperature of the charge) and the content of components in the charge in different zones of the furnace, identifying their interconnections, as well as developing a criterion for the technological assessment of the cohesive zone and justifying the possibility of adjusting its parameters by changing the distribution of ore loads and charge components along the radius of the furnace, combined with a computational and analytical prediction of the high-temperature properties of burden mixtures in different zones of the blast furnace.

II. SOLUTION METHODS AND RESULTS

To establish the relationship between the parameters of the cohesive zone and the characteristics of the distribution of burden materials along the radius of the top, using the proposed method for several options for industrial operating conditions of a blast furnace, the coordinates of the points of softening and melting surfaces were determined. The indicated coordinates are determined using the calculation of the melting surface area according to the Goodenau method [21], the composition of mixtures of iron-containing charge components in various zones of the top, determined using a complex mathematical model of burden distribution [Ivancha N.G., Murav'yova I.G., Shumel'chik E.I., Vishnyakov V.I., Semenov Yu.S. / Complex Mathematical Model of the Distribution of Multicomponent Charge in a Blast Furnace. Metallurgist, №5, 2018, v. 62, is. 1 – 2, pp. 95 – 100], as well as a predictive calculation estimate of the high temperature characteristics of these mixtures and the melts formed from them [22]. An example of the resulting cohesive zone configuration is shown in fig. 1, where the difference in the vertical coordinates of the corresponding points of the surfaces in the annular zones characterizes the thickness of the cohesive zone, and the points of intersection of the softening and melting lines with the top wall characterize the position of the root. The validity of the approach to constructing the cohesive zone configuration using information on the temperature of the gas flow above the surface of the charge is confirmed by experimental data on the presence of a fairly close relationship between the vertical coordinates of the points of the melting line and the gas temperature above the surface of the charge (Fig. 2). Based on the results of mathematical modeling of the distribution of burden materials, a relationship was also established between the vertical coordinates of the melting line and ore loads in the annular furnace zones of equal area (Fig. 3). In fig. 2 and fig. 3 shown the results indicate the possibility of using data on the distribution of gas temperatures above the grist charge (or charge surface temperature) to develop methods for controlling the position and shape of the cohesive zone, and also confirm the possibility of adjusting the parameters of this zone by changing the distribution of ore burden along the radius of the blast furnace top. The connection of the vertical coordinates of the points of the melting line *Z* in the annular zones with the corresponding ore burden is characterized by a rather high value of the coefficient of reliability of approximation by a power function of more than 0.80.

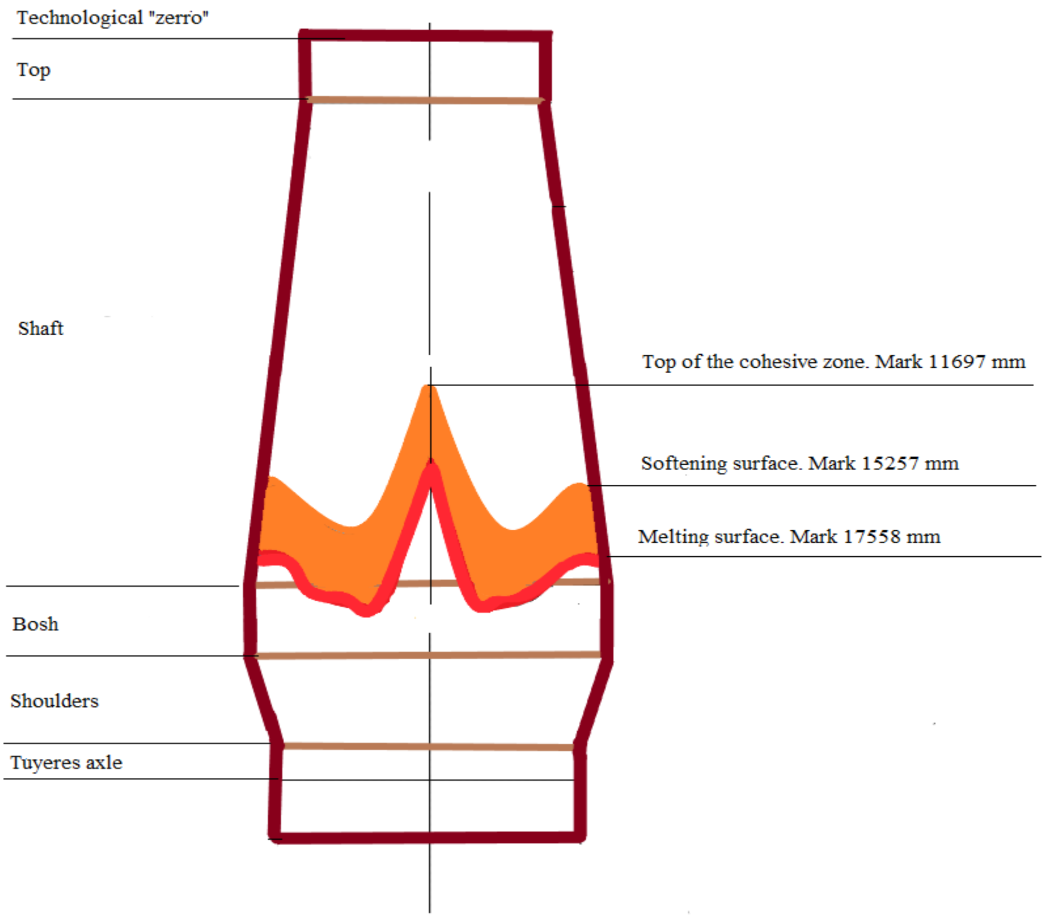

Fig. 1. The configuration of the cohesive zone obtained by the proposed method.

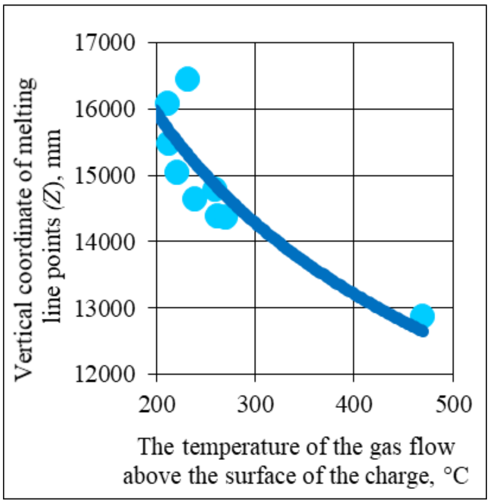

Fig. 2. Linkage of vertical coordinates of the points of the melting line (*Z*) in the annular zones of the blast furnace with the gas temperature above the surface of the charge in these zones.

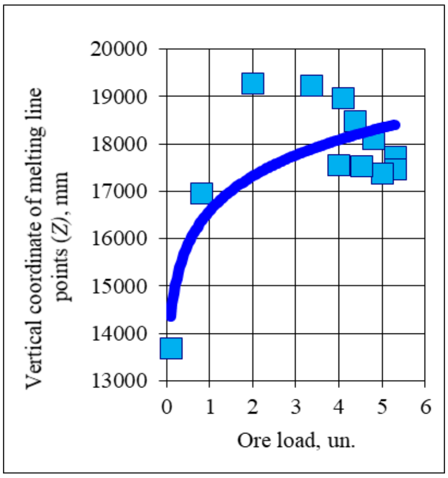

Fig. 3. Connection of vertical coordinates of the point of the melting line (*Z*) near the annular zones of the blast furnace with the ore burden in these zones.

The possibility of calculating the content of the charge components and the mixtures formed from them in the annular zones of the furnace using a complex mathematical model developed earlier in the ISI made it possible to formulate a new approach to the selection of control parameters for correcting the characteristics of the cohesive zone.

Under the conditions of loading a blast furnace with a multicomponent burden, the lines of softening and melting (the boundaries of the cohesive zone) are determined by the composition of mixtures of burden materials formed in different zones of the working space of the furnace, and their individual high temperature properties. As shown by numerous laboratory studies performed in the ISI, the softening and melting temperatures of mixtures of iron ore materials and additives are not a simple additive consequence of the high temperature properties of the components that make up the mixture. The interaction of components during high temperature processing and during the development of reduction processes leads to the fact that a mixture of charge components with known high temperature properties manifests itself as a new type of burden material with properties that differ significantly from the properties of the mixture components.

An indirect indicator of the thickness of the cohesive zone, a parameter characterizing its gas permeability, is the difference in melting and softening temperatures. It is believed that to ensure the gas permeability of the cohesive zone, this value should not exceed 300 ºC. The established relationship between the ratio of pellets and agglomerate in a mixture with the difference in melting and softening temperatures of this mixture allows us to conclude that this ratio can be used as a control parameter when adjusting the thickness of the cohesive zone. The basis for this conclusion is the high coefficient of reliability of the approximation of the relationship between the difference in softening and melting temperatures with the indicated ratio, which is 0.99 (Fig. 4).

Geometrically, the thickness of the cohesive zone can also be defined as the difference in the coordinates of the points of intersection of the softening and melting lines with the average lines of this zone at the corresponding level.

On fig. 5 shows the results of studying the relationship between the ratio of the content of pellets and the content of sinter with the difference in the vertical coordinates (thickness) of the cohesive zone (*Z*) in the annular zones of the furnace. The coefficient of reliability of the approximation of the revealed connection is 0.62, which indicates the possibility of using a change in the ratio of the main iron-containing components in the annular zone to correct the geometric parameters of the cohesive zone.

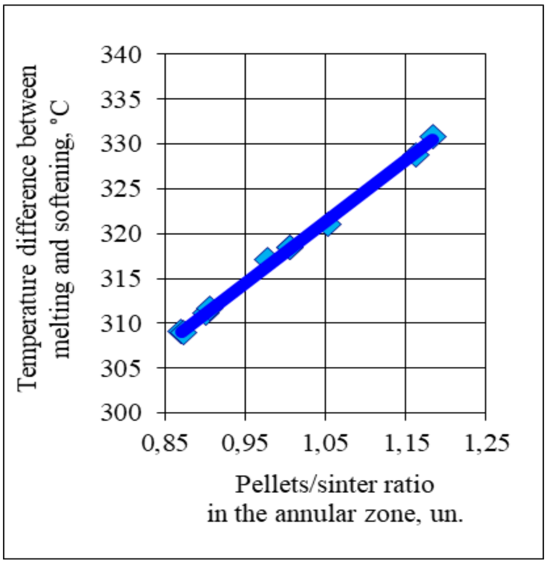

Fig. 4. Relationship between the difference in melting and softening temperatures of mixtures of iron-containing burden materials in the annular zone of the top with the ratio of the number of pellets and sinter in this zone.

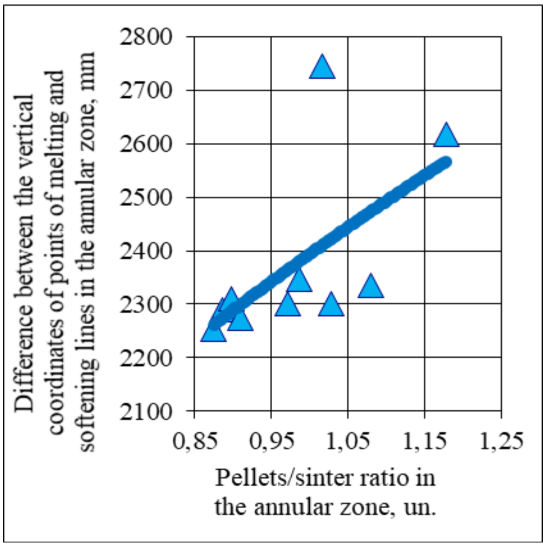

Fig. 5. Connection of the difference in the vertical coordinates of the points of the melting and softening lines (thickness of the cohesive zone (ΔH_{czi})) in the annular zones of the blast furnace and the ratio of the amount of pellets and sinter in these zones.

The necessary correction of the parameters of the cohesive zone within certain limits can also be implemented by changing the distribution of additives in combination with a change in the distribution of the main components of the charge, or exclusively by redistributing additives.

From the above statement about the significant difference in the high temperature properties of mixtures of iron-containing burden materials and similar properties of the initial components of the mixture, it follows that the control of the parameters of the cohesive zone by changing the distribution of burden materials, the choice of the direction and magnitude of the corrective influence in each specific case should be based on the results of mathematical modeling of the distribution of components burden along the radius of the top, determining the composition of mixtures of burden components in various zones of the furnace, predicting their high temperature properties and tendencies of changes in these properties with a change in the component composition of the mixture. The ISI has developed a technology for loading a multicomponent charge into a blast furnace, from the main provisions of which it follows that in order to control the distribution of a specific component of the mixed iron ore portion along the radius of the top, a change in the location of the dose of this component in the volume of the portion (feed) can be used as a control parameter (see our article in the same journal for 2022). In everyday practice, technologists, in the presence of appropriate control systems and mathematical models on a blast furnace, in assessing the rationality of the shape of the cohesive zone, are guided by the results of visual observations, which are interpreted on the basis of their own body of knowledge and technological experience. It is generally accepted that it is rational to consider the L-shaped form of the cohesive zone, however, as technological practice shows, this provision cannot be extended to many options for the technological conditions of blast furnace operation. This is confirmed by the results of previous and own studies: cases of highly efficient operation of blast furnaces with a cohesive zone shape that differs significantly from the L-shaped one have been repeatedly noted. From this we can make a platoon that the shape of the cohesive zone itself, without taking into account other indicators, cannot be used to assess the level of rationality and compliance with the melting regime.

For a comprehensive assessment of the level of rationality of the cohesive zone and the correspondence of its parameters to the technological conditions of melting, a criterion has been developed for assessing the shape and position of the cohesive zone in a blast furnace. As arguments of the criterion (K_{cz}), the main parameters characterizing the cohesive zone, i.e., its configuration, thickness, and position in the furnace, are taken. These parameters can be determined using a new method proposed by the authors, based on information about the temperatures of the gas flow (surface of the charge) at various points in the furnace section, obtained using the following tools:

- thermal measuring probes installed above the surface of the level of charge;
- systems based on the determination of gas flow temperatures based on the results of measuring the speed of sound in a gaseous medium and its change depending on the gas temperature;
- systems for measuring temperatures of the grist charge.

Based on the well-known ideas about the parameters that determine the shape and position of the cohesive zone, as well as the results of the correlation analysis of the relationships between these parameters and the technological indicators of melting, complexes are compiled that are arguments for the criterion for evaluating the cohesive zone.

The first argument of criterion X_1 includes the sum of the ratios of the thickness of the cohesive zone in adjacent annular zones (ΔH_{czi} and ΔH_{czi+1}, m, where i is the number of the annular zone), estimated from the difference in melting and softening temperatures of iron-containing materials in these zones, and the ratio of the maximum value thickness of the cohesive zone to the minimum. Thus, the argument reflects the configuration of softening and melting lines in the controlled sections and along their entire length as a whole.

The argument can be represented by the expression:

$$X_1 = \sum_{i=1}^{n} \frac{\Delta H_{czi+1}}{\Delta H_{czi}} + \frac{\max\left(\Delta H_{czi}\right)}{\min\left(\Delta H_{czi}\right)}, \qquad (1)$$

where ΔH_{czi} – cohesive zone thickness in the i-th annular zone of the blast furnace, m;

n – the number of annular zones.

The second argument of the criterion characterizes the relative position of the root of the cohesive zone, the location of which is assumed to be in the zone of the maximum level of readings of thermocouples of the refractory lining of the furnace shaft:

$$X_2 = T_{sh\,max}, \tag{2}$$

where $T_{sh\ max}$ – maximum temperature of the refractory lining of the mine, °C.

The third argument of the criterion is the effective melting surface area [21]:

$$X_3 = A_{ef}. \tag{3}$$

After the normalization procedures, the study to the normal distribution law logit - the transformation of each argument of the criterion of the plastic situation takes the form:

$$K_{cz} = \left(F\left(X_1\right) \cdot F\left(X_2\right) \cdot F\left(X_3\right)\right)^{\frac{1}{3}}. \tag{4}$$

The possibility of using the K_{cz} criterion for

a qualitative assessment of the conformity of the shape and position of the cohesive zone in the blast furnace to the prevailing technological conditions is confirmed by the presence of its connection with the main technological indicators of melting – the level of iron production and the consumption of standard fuel (the coefficient of reliability of the approximation is 0,55 – 0,60).

The need to adjust the cohesive zone parameters (shape, thickness and/or position) by changing the charge loading mode to achieve the specified target functions (maximum iron production, minimum coke consumption) can be determined by comparing the current value of the criterion with the range of its rational values for the technological operating conditions of a particular object.

Based on the established relationships between the characteristics of the burden distribution along the radius of the top (ore loads, the content of the burden components in different zones of the top) with the parameters of the cohesive zone, the main provisions for adjusting the parameters of the charge loading mode, which improves the parameters of the cohesive zone, are substantiated and developed.

The main provisions and the sequence of solving problems for their implementation are given below.

1. Determination of the characteristics of the distribution of the components of the burden in the annular zones along the radius of the top.

2. Calculation - analytical forecast of softening and melting temperatures of mixtures of iron-containing components in the annular zones.

3. Calculation - analytical and graphical modeling of the cohesive zone using the means of controlling the temperature of the gas flow and the surface of the charge based on the proposed method.

4. Determination of rational values of the criterion for evaluating the shape and position of the cohesive zone in a blast furnace under the current technological conditions of blast furnace smelting and the allowable ranges of its change. Evaluation of the level of rationality of the formed cohesive zone and its compliance with the current parameters (indicators) of the melting process using the developed criterion.

5. Expert assessment of the necessary changes in the shape, location and thickness of the cohesive zone, based on the results of calculations using the proposed method, and taking into account the objective technological parameters of the melting process, as well as the readings of the means of controlling the distribution of the burden and gas flow.

6. Choice of a possible direction for correcting the loading mode, depending on the required change in the parameters of the cohesive zone.

The choice of corrective action is carried out depending on the need to solve a specific problem, the main of which are given below.

6.1. Changing the position of the “root” and/or top of the cohesive zone in the axis of the furnace.

6.1.1. Changing the position of the “root” and/or top of the cohesive zone in the furnace axis with a change in the shape of the cohesive zone.

6.1.2. Changing the position of the “root” and/or top of the cohesive zone in the axis of the furnace without changing the shape of the cohesive zone.

6.2. Change in the volumetric location of the cohesive zone.

6.3. Change in the temperature interval ("thickness") of the cohesive zone.

The tasks according to clause 6.1 are solved by changing the ore loads and/or by changing the distribution of components along the radius of the top. Clause 6.2 is implemented mainly by changing the total ore load in the charge. The task according to clause 6.3 is solved solely by changing the distribution of components.

The choice of control parameters for adjusting the loading mode in each particular case is determined by the degree of technological significance of possible influences, among which the distribution of ore loads is predominant in relation to the content of the charge components in the annular zones along the radius of the top. However, the optimization of the distribution of components in conjunction with the rational distribution of ore loads is also one of the significant reserves for increasing the efficiency of smelting. In this regard, the development of a rational regime for loading a blast furnace should be carried out in two, and if necessary, in three stages.

The first stage is the development of a loading program, which is carried out on the basis of an analysis and selection of a rational distribution of ore loads along the radius of the top. At the second stage, the choice of a rational distribution of the components of portions of burden materials should be made with minimization of deviations in the distribution of ore loads from that adopted at the first stage. If, according to the results of the computational and analytical prediction of the high temperature properties of the mixture of components in the furnace zones, it is not possible to achieve the specified softening and melting temperatures, it is necessary to change the composition of the burden materials, taking into account technological limitations regarding the distribution of components, their mixtures and melts formed from them (third stage).

III. THE DISCUSSION OF THE RESULTS

The applicability of the proposed method for determining the shape and position of the cohesive zone in a blast furnace using information on the distribution of gas temperature over the surface of the charge or the temperature of this surface is confirmed by the analysis of the features of the formation of the cohesive zone under various technological melting conditions. The study of the influence of various melting conditions, characterized by the corresponding technological parameters, on the position of the cohesive zone in the furnace is a multifactorial task. Multivariate comparative analysis was used to identify the most informative and significant indicators. The results of assessing the influence of technological parameters on the position of the cohesive zone in the furnace, determined by the coordinates of the softening and melting lines, allow us to conclude that the existing relationships of the studied values, characterized by the obtained factor loads, confirm the validity and reliability of determining the position of the cohesive zone in the blast furnace using the proposed method, which can be used online during the operation of the blast furnace.

The proposed method of justified adjustment of the parameters of the cohesive zone expands the technological possibilities of smelting control by using the distribution of charge components along the radius of the top as a control parameter in addition to the traditionally used distribution of ore loads. Accounting for the characteristics of the distribution of charge components makes it possible to determine the composition of mixtures of iron-containing materials, as well as the calculated prediction of their high temperature characteristics and properties of melts in various zones of the blast furnace, thereby contributing to an increase in the accuracy of determining the coordinates of softening and melting lines that limit the cohesive zone.

IV. CONCLUSIONS

A new method is proposed for determining the parameters of the cohesive zone (shape, position and thickness) in a blast furnace equipped with means to control the temperature of the gas flow or the level of charge. The method is based on a systematized set of mathematical models, including those developed by the authors, as well as on a new method for determining the coordinates of softening and melting lines in a blast furnace using information obtained by means of monitoring the distribution of gas temperature over the charge surface (or charge surface temperature) , as well as on the calculated determination of the characteristics of the distribution of charge components in various annular zones along the radius of the top using a complex mathematical model. Relationships between the coordinates of the melting line points and the gas temperature above the charge surface, the softening and melting temperatures and the thickness of the cohesive zone in various zones of the blast furnace with the ratio of the amount of sinter and pellets in these zones are established. The relationship between the coordinates of the points of the melting line and the ore load in the annular zones of the blast furnace has been confirmed. A criterion for evaluating the rationality of the formed cohesive zone has been developed and the possibilities of adjusting its parameters by changing the distribution of ore loads and charge components have been shown. It is shown that the correction of the parameters of the cohesive zone, the choice of the direction and magnitude of the control action in each specific case should be based on the results of mathematical modeling of the distribution of burden materials along the radius of the top, determining the composition of mixtures of charge components in various zones of the furnace and predicting their high temperature properties, as well as trends in change these properties when changing the component composition of the mixture.

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