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Improvement of methods for calculating the distribution of charge components in the volume of a blast furnace

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Удосконалення методів розрахунку розподілу компонентів шихти в об'ємі доменної печі

Abstract. *The analysis of known calculation methods and mathematical models of the distribution of charge materials on the top of a blast furnace, used in technological and research practice, was performed. It was noted that mathematical modeling, including those based on the discrete element method (DEM), and experimental studies (both in industrial conditions and using physical models) are used to determine the distribution of charge in a blast furnace. At present, there are no instrumental means of controlling the distribution of charge components. It is shown that the distribution of components on the surface of the backfill is the result of the interaction of a number of processes occurring at all stages of the formation of portions of charge materials, their delivery to the top and unloading into the furnace. There are three approaches to describe the process of the movement of charge materials in hoppers, on the basis of which mathematical models have been created for specific objects at the present time and results acceptable for practical use have been obtained. The first one - in the form of geometric dependencies determines the volume of the zone of active material movement, the shape of which is determined experimentally, and the volumes of bulk material arrays, which in a given sequence enter further into the zone of active material movement, and then move vertically to the outlet of the hopper. The second approach is an attempt to take into account the kinematic patterns of bulk material movement in the zone of active movement in combination with the provisions of the first approach to describe the behavior of bulk outside the active zone. The third approach is based on DEM, mathematical models based on which require input data, the receipt of which causes difficulties in determining, or data, the reliability of which does not have sufficient confirmation. A developed complex mathematical model of the formation of multicomponent portions of charge materials, their loading into the hopper of a cone-free loading device (CFLD), unloading from the hopper and distribution on the surface of the backfill is presented, which was created on the basis of the synthesis of a number of models developed and improved by the Institute of Ferrous Metallurgy Z.I. Nekrasov of the National Academy of Sciences of Ukraine of mathematical models that most fully describe the entire complex of processes of loading a multicomponent charge into a blast furnace. The model provides determination of the current component composition of the flow formed during unloading of multicomponent portions from the BLT hopper, and the full composition of mixtures of charge components in various annular zones of the top. The developed complex model is successfully used by the Institute of Ferrous Metallurgy Z.I. Nekrasov to solve a number of technological problems regarding the selection of rational loading modes of operating blast furnaces operating on a multicomponent charge, including the selection of parameters of special loading modes that ensure the creation of the necessary conditions for lining or washing depending on the current requirements of the smelting process. Information on the distribution of charge components across the furnace cross-section, which can be obtained using the developed complex model, is also necessary for conducting analytical studies of physical - mechanical and physical - chemical processes in a blast furnace, in particular, the conditions of slag formation and the distribution of melt properties in the volume of the blast furnace.*

Key words*: blast furnace, charge, components, loading system, coneless loading device, charge distribution, mixtures, mathematical models.*

Анотація. *Проведено аналіз відомих методів розрахунку та математичних моделей розподілу шихтових матеріалів на колошнику доменної печі, що використовуються в технологічній та дослідницькій практиці. Зазначено, що для визначення розподілу шихти в доменній печі використовується математичне моделювання, зокрема на основі методу дискретних елементів (МДЕ), та експериментальні дослідження (як у промислових умовах, так і з використанням фізичних моделей). Наразі інструментальних засобів контролю розподілу компонентів шихти не існує. Показано, що розподіл компонентів на поверхні засипки є результатом взаємодії низки процесів, що відбуваються на всіх етапах формування порцій шихтових матеріалів, їх подачі на колошник та вивантаження в піч. Існує три підходи до опису процесу руху шихтових матеріалів у бункерах, на основі яких на даний момент створені математичні моделі для конкретних об'єктів та отримані результати, прийнятні для практичного використання. Перший – у вигляді геометричних залежностей визначає об'єм зони руху активного матеріалу, форма якої визначається експериментально, та об'єми масивів сипучого матеріалу, які в заданій послідовності входять далі в зону руху активного матеріалу, а потім рухаються вертикально до виходу*

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з бункера. Другий підхід – це спроба врахувати кінематичні закономірності руху сипучого матеріалу в зоні активного руху в поєднанні з положеннями першого підходу для опису поведінки сипучого матеріалу поза активною зоною. Третій підхід базується на DEM, математичні моделі на основі яких потребують вхідних даних, отримання яких викликає труднощі у визначенні, або даних, достовірність яких не має достатнього підтвердження. Представлено розроблену комплексну математичну модель формування багатокомпонентних порцій шихтових матеріалів, їх завантаження в бункер безконусного завантажувального пристрою (БЗЗП), вивантаження з бункера та розподілу по поверхні засипки, яка була створена на основі синтезу низки моделей, розроблених та вдосконалених Інститутом чорної металургії ім. З.І. Некрасова Національної академії наук України математичних моделей, що найповніше описують весь комплекс процесів завантаження багатокомпонентної шихти в доменну піч. Модель забезпечує визначення поточного компонентного складу потоку, що утворюється під час вивантаження багатокомпонентних порцій з бункера BLT, та повного складу сумішей компонентів шихти в різних кільцевих зонах колошника. Розроблена комплексна модель успішно використовується Інститутом чорної металургії імені З.І. Некрасова для вирішення низки технологічних задач щодо вибору раціональних режимів завантаження доменних печей, що працюють на багатокомпонентній шихті, включаючи вибір параметрів спеціальних режимів завантаження, що забезпечують створення необхідних умов для футеровки або промивки залежно від поточних вимог плавильного процесу. Інформація про розподіл компонентів шихти по поперечному перерізу печі, яку можна отримати за допомогою розробленої комплексної моделі, також необхідна для проведення аналітичних досліджень фізико-механічних та фізико-хімічних процесів у доменній печі, зокрема, умов шлакоутворення та розподілу властивостей розплаву в об'ємі доменної печі.
Ключові слова: *доменна піч, шихта, компоненти, система завантаження, безконусний завантажувальний пристрій, розподіл шихти, суміші, математичні моделі.*

Introduction.

Controlling the blast furnace operation "from above" by changing the parameters of the loading mode is one of the most effective tools for the operational adaptation of the blast furnace smelting process to changes in charge conditions and regulation of temperature-thermal and gas-dynamic modes. Control "from above" is carried out on the basis of information on the distribution of charge materials, gas flow and its characteristics. At present, a number of technical means of controlling the distribution of the composition and temperature of the gas flow are used, which have proven themselves quite well. Regarding the distribution of charge materials, the main source of information remains computational methods - mathematical models. At the same time, it should be noted that various devices that have been widely introduced recently for determining the configuration of the charge surface and its temperatures in different zones of the blast furnace make it possible to obtain an indirect, very approximate (qualitative) idea of the distribution of raw material and fuel components of the charge as a whole, without the possibility of any quantitative assessment of their masses in different zones of the blast furnace. There are currently no instrumental means of controlling the distribution of individual components of the charge. At the same time, the distribution of the charge components and the composition of their mixtures formed in different zones of the blast furnace largely determine the formation and development of the gas flow, its characteristics and their distribution in the volume of the furnace, the condition of the lining and the possibility of risks of violating its integrity, the formation of fields of primary slag formation, the gas permeability of the zone of low-mobility materials, the parameters of the plastic zone and a number of other processes and factors that determine the course and indicators of blast furnace smelting.

The objective of the study, carried out at the Iron and Steel Institute of Z.I. Nekrasov of the National Academy of Sciences (NAS) of Ukraine (ISI), was to develop a computational tool that enables the determination of the distribution characteristics of each charge component within the furnace volume, with subsequent determination of ore loads and the composition of charge material mixtures formed in the conventionally defined annular zones of the blast furnace.

Calculation methods and mathematical models for the distribution of charge materials on the crucible of a blast furnace, used in technological and research practice.

Increasing the efficiency of using the regenerative power of gases in the blast furnace, and as a result, the overall technical and economic indicators of smelting is ensured, first of all, due to the rational distribution of charge materials on the furnace [1].

Charge distribution has an important effect on heat transfer, mass transfer, and chemical reactions in blast furnaces [2]. Since the 1970s of the last century, metallurgical scientists have been studying the laws of the movement and distribution of the charge in its working space for the well-founded management of blast furnace operation. Among the most significant, the research of V.K. Gruzynova In work [3], he first systematically analyzed the features of the formation of layers of charge on the surface of the backfill, clarified the methodology for calculating the trajectories of the movement of charge materials after leaving a large cone. The results of the following studies under the leadership of V.K. Gruzinova are presented in works [4, 5].

Among the most significant should also be attributed the results of research carried out by M.M. Babarykin [6], V.M. Klempert, A.O. Hryshkova [7], A.M. Pokhvisnev, I.P. Kurunov, V.O. Dobroskokom [8], V.I. Loginov [9], V.P. Tarasov [10].

It should be noted that until recently, the mathematical models of the loading and distribution of charge materials in the blast furnace did not consider the loading and distribution of any specific component loaded as part of the iron ore or coke feed parts. In addition, from the entire complex of processes of forming portions (feeds) of charge materials (delivery of them to the furnace, loading of portions into the loading device and unloading from it, movement along the path of the loading device, in particular, a rotating tray, free fall of the charge flow in the furnace space to the surface of the backfill, its interaction with the existing profile and the formation of a new one) in the vast majority of known models were considered the movement of charge materials along the path of the loading device, the movement of the charge in the furnace space and the formation of the backfill surface after unloading the next portion (feed). Accordingly, the capabilities of these models were limited to the calculation of charge movement trajectories in the blast furnace space, the determination of the geometric characteristics of the backfill profile, and the calculation of the mass distribution of the fuel and raw materials components as a whole along the radius of the blast furnace, with further determination of their ratios (ore loads) in conditionally selected ring zones of the blast furnace. Such models include the one developed by Nippon Kokkan Corporation [11], which describes the processes of the downward movement of the charge inside the bowl during the lowering of the large cone, the pouring of the charge materials from the bowl and the subsequent fall to the peripheral area on the surface of the backfill, as well as the movement from the periphery to the center of the furnace with the formation of a slope and the change in the shape of the surface during the rise of the charge materials. The simulation model of charge distribution on the blast furnace furnace, also developed by researchers in Japan [12], takes into account additional factors: the formation of a mixed layer in the center of the furnace during the discharge of ore onto the coke layer, the reduction of the slope angle under the influence of the gas flow, the change of the slope angle due to the difference in the charge descent speeds along the radius of the furnace. The authors believe that the formation of a mixed layer has the greatest influence on the distribution of the ore load.

Mathematical models developed in Finland with the use of neural networks should be singled out in a separate direction of research on the distribution of materials on the blast furnace crucible. The published works [13 - 15] present a developed model of the formation of a charge layer in a blast furnace, the initial information of which is the thickness of the layers, which is determined by radar measurements of the charge level in the furnace. Based on the results of the model testing, conclusions were made about the possibility of its use as a tool for evaluating changes in the charge distribution indicators - the fuel part of the charge and the ore load - in operating furnaces. The distribution of individual components - constituents of both ore and fuel parts of the charge - was not considered at all.

The installation of bell less blast furnace top charging system (BLT) with a tray charge distributor on blast furnaces (since the mid-seventies of the last century) and the need to select and justify their operating modes for controlling the technological parameters of the furnace initiated the beginning of active research aimed at developing mathematical models of the movement of charge materials along the path of the loading device.

In addition to ICM, which will be discussed below, studies of the process of loading blast furnaces equipped with BLT with a tray distributor, aimed at studying the distribution of charge materials, including studies using mathematical modeling, were carried out at the Dnipropetrovsk Metallurgical Institute under the leadership of V.M. Kovshova [16], A.K. Tarakanova, N.Sh. Grinstein and V.V. Barrels [17, 18]. In work [16] V.M. Kovshov presented the results of the development of a mathematical description of the movement of the charge through the inclined surfaces of the distribution devices - a cone, a tray, in the furnace space and on top of the backfill. The mathematical model of loading the furnace with a tray loading device, developed at NMetAU, allows obtaining quantitative characteristics of the distribution of iron ore and coke components of the charge across the cross section of the furnace [17, 18]. As input parameters of the model, the following are used: type of materials to be loaded; mass of coke and iron ore portions; bulk mass and slope angles of materials; working angular positions of the tray; backfill level; the speed of lowering the charge materials along the radius of the furnace; the number and sizes of annular zones for which the quantitative characteristics of the charge distribution are determined; the number and sequence of portions of the charge in the cycle; time of loading portions into the oven; dimensions of the furnace furnace; the main dimensions and characteristics of the operating mode of the boot device. The initial parameters of the model are: the value of ore loads of the charge in the annular cross-sectional areas of the blast furnace, the profile of the backfill surface of the materials after loading the batch cycle, the plot of the thickness of the layers of coke and iron ore materials in the vertical cross-section of the furnace for the batch batch cycle.

Active research on the development of mathematical models for the movement of bulk materials along the BLT tract was carried out in Germany at the end of the last century. The work of L. Kreutz and B. Bergman [19] is of interest, which provides a model that provides a mathematical description of the movement of particles of charge materials through a tray distributor and the descent of materials from the end of the tray, the calculation of the trajectories of their movement in the furnace space, the formation of the backfill surface, in particular, under lateral constraints imitating the wall of the furnace furnace. A number of input parameters of the model were determined on the physical model of the crucible of the blast furnace with BLT. The presented results of experimental studies and calculations contain data on the formation of the flow of charge materials on the tray and the peculiarities of the stacking of materials on the backfill surface. L. Kreutz, H.V. Goodenau and N. Standish investigated the asymmetric distribution of materials on the furnace crucible caused by the design features of the BLT with a tray distributor [20]. Various modifications of the tray distributor have been studied and constructive recommendations and technological measures have been proposed, contributing to the improvement of the distribution of charge materials.

At the beginning of the current century, work on the creation of mathematical models of the movement of charge materials along the BLT tract and in the furnace space of the furnace intensified in China [21 - 23, 25, 26]. [21] shows the importance of reliably determining the trajectory of the charge materials after leaving the tray and, accordingly, the point of its fall on the backfill surface for further calculation of the formed profile. In order to clarify the algorithm for calculating the charge movement trajectories in the blast furnace space, the authors performed experimental studies on a blast furnace model with a volume of 2500 m^3, made on a scale of 1:15. In [22], a mathematical model of the movement of the charge after its exit from the tray distributor is presented, taking into account the Coriolis force and the gas resistance force. With the help of the developed model, the coordinates of the points of fall of the charge on the backfill surface and the width of its flow were obtained and analyzed. The values of particle velocities at the unloading end of the tray were compared with and without taking into account the Coriolis force. With the help of the developed model, research was also carried out to determine the influence of the length and torque of the tray on the flight range of the charge particle in the blast furnace space. The results of the simulation were confirmed by measurements made at the blast furnace using a laser range finder.

In work [23], using mathematical modeling, the influence of the different cross-section of the furnace at the rate of descent of the charge on its distribution on the furnace is considered. The influence of the rate of descent of the charge in different zones of the blast furnace on the formation of layers of charge materials on the surface of the backfill was also studied by scientists of the Republic of Korea [24]. An overview of modern methods of modeling and control of the charge distribution on the blast furnace crucible is given in [25], where the peculiarities of the discharge of charge materials from parallel-installed BLT hoppers are considered, as well as the equations of the movement of the charge particles through the tray distributor and the subsequent formation of layers on the surface of the backfill, taking into account the displacement of coke, are given. In [26], the conditions of movement along trays of rectangular and semicircular cross-section are considered, the forces acting on the particle moving through the tray are shown, and the equations of its motion are given. The trajectories of particle movement after exiting the tray were determined and dependencies were obtained for calculating the coordinates of their meeting points with the backfill surface. The reliability of the model was confirmed by the results of pre-commissioning studies at the blast furnace, during which measurements of these coordinates were performed using laser instruments.

Works [27 - 38] also consider the calculation equations of the movement of the charge through the tray distributor, the trajectory of its fall in the blast furnace space, and the characteristics of the layer formed on the surface of the backfill. The model presented in [28] contains the equations of the trajectory of the charge after it leaves the tray and the dependences that describe the formation of the dependence surface taking into account the actual values of the angles of the materials. In [29], a model was considered that provides the possibility of calculating the trajectories of the fall of the charge before it falls on the backfill surface, estimating the profile of the formed surface, and the distribution of ore loads along the radius of the blast furnace. The model functions using data from radar meters that monitor the charge level at various points on the backfill surface, which increases the accuracy of calculations.

Confirmation of the results of modeling the formation of charge layers can be obtained by measuring the profile of the backfill surface on an operating furnace with a 3D scanner, as done by the authors of [30], which describes a mathematical model of charge distribution in a blast furnace with BLT. The purpose of the model is to use it in real time for the prompt selection of charge loading programs. The calculation capabilities of the model, as discussed earlier in [19-29], regarding the characteristics of the charge distribution are limited to determining the distribution of ore loads along the radius of the furnace.

The features of the model, created using the finite element method and Visual Basic [32], are the combination of two calculation blocks, one of which allows determining the parameters of charge fall trajectories taking into account the type and mass of portions, the coefficient of friction of the charge on the tray, the speed of rotation and the angle of inclination of the tray, and the other is designed to calculate the characteristics of the distribution of ore loads along the radius of the blast furnace. The values of the coefficients of the charge motion equations were specified based on the results of the model experiment. The model of the formation of the top of the charge fill, described in [33], is distinguished by the development of new equations for the formation of internal and external slopes taking into account the influence of the vertical and horizontal velocities of the charge flow during the formation of the top of the layer on the surface of the fill. Confirmation of the reliability of calculations of the formed surface using the model was also provided by comparing the calculation results with experimental data.

An overview of studies of the laws of the movement and distribution of the charge on the furnace of the blast furnace, carried out by metallurgical scientists, starting from the 1970s, is given in [34]. As a rule, the first studies in this area were limited to experimental measurements of the coordinates of the points of the charge's falling trajectories in the blast furnace space and the characteristics of the resulting backfill profile. Determination of the specified characteristics in a number of cases was carried out using laser or radar devices. In the work of A. Agerevel [36], with the help of a developed mathematical model, a study was carried out with the generalization of the results in the form of geometric characteristics of the layers and the distribution of ore loads along the radius of the blast furnace furnace in conditions of variable content of pellets in the charge, which affects the course of blast furnace smelting. A number of publications, for example [37, 38], show the possibilities of developed mathematical models of charge loading in the part of studies of coke knocking out processes, its redistribution during the unloading of iron ore material on the coke layer and the formation of mixed layers of these materials on the surface of the backfill, as well as the selection of rational parameters of axial portions of coke and technological methods of their loading.

Among the review publications, we can also single out work [39], which examines the development trends of modeling, control and management of charge distribution in a blast furnace. This review examines methods for determining the distribution of ore load on a blast furnace pile, including experimental studies using physical models, as well as mathematical modeling using the discrete element method (DEM) and without using this method. The rapid development of computer technologies has ensured the progress of numerical modeling, in particular, with the use of DEM, in the development of models that ensure the calculation of the distribution of ore loads and the characteristics of the layers of charge materials formed on the blast furnace furnace.

In recent years, on the basis of DEM, studies related to the modeling of phenomena and interactions in the bulk medium, which have a significant impact on the distribution of the ore load on the furnace of the blast furnace during loading of charge materials and the distribution of gas permeability characteristics of the layers of charge materials being formed, have been actively carried out. A detailed analysis of blast furnace charge distribution studies using DEM-based models is given in a review [40]. According to the authors, the use of DEM provides a quantitative determination of the forces acting on each particle, and, therefore, the possibility of forecasting the spatio-temporal evolution of the granular flow. The advantages of DEM are that it can be used to analyze both the parameters of the bulk material flow in general and the behavior of individual particles, which makes it promising to use this method not only to study the distribution of ore load, but also to study the gas permeability characteristics of the layer and its individual zones. The initial parameters of the models created on the basis of DEM are the morphological characteristics of the material (distribution of particles by size and shape), its strength properties (Poisson's ratio and Young's modulus), parameters characterizing the interaction of the particles of the charge (recovery and friction coefficients, indicators of the shape of the particles and their surface roughness). Obtaining reliable results with the help of this model, which reflect the actual behavior of the material observed in experiments, is determined by the level of reliability of the values of the input parameters listed above, the determination of which in real conditions causes great difficulties.

In [41], the results of modeling based on DEM are presented, which show the influence of the speed of movement of the particles of the charge on its distribution on the surface of the backfill and the process of segregation by size. The modeling results were confirmed by experimental studies, during which it was established that the distribution of the angular velocity of particles in the cross section of the chute has a U-shaped character, while the distribution of the translational velocity has the form of a convex curve. As you approach the unloading end of the tray, the distribution of both velocities becomes more uniform. The flow width and material mass distribution in the flow were also determined. The results of the research made it possible to clarify the features of the formation of the layer of charge discharged onto the surface of the backfill and the distribution of particle size in it.

In Japan, with the help of a model developed with the use of DEM, the circumferential unevenness of the charge, which occurs when it is unloaded from the BLT with two parallel-installed hoppers, was investigated, and its negative effect on the stability of the blast furnace operation was shown [42]. The model describes the movement of the flow of charge particles in the valve assembly, the central pipe and on the rotating tray distributor at different angles of its inclination. The simulation showed that the cause of the circumferential unevenness is the displacement of the charge particles towards the walls in the central pipe, and the degree of the circumferential unevenness depends on the angle of inclination of the tray. With the help of the model, recommendations for installing a conical vertical gutter were developed to reduce circumferential unevenness.

Unlike previous studies using DEM, which mostly modeled the behavior of a charge with spherical particles, in [43] a charge with non-spherical particles was considered, which is characteristic of real charge materials. The authors performed a comparative study of the effect of different particle shapes on the charge distribution in a blast furnace.

Thus, the analysis of previously performed research in the field of developing mathematical models and methods for calculating the characteristics of the distribution of charge materials showed that the vast majority of works [11 - 43] were devoted to the distribution of iron ore and coal-containing parts of the charge in general, without assessing the distribution of the components that are part of them.

The steady trend of increasing the cost of raw materials and fuel determines the operation of blast furnaces in batch conditions that change continuously and are characterized by the use of low-quality materials, the use of a multi-component batch with the simultaneous use of two or more types of each of the main components (agglomerate, pellets and coke), the introduction of substandard (screened) fractions of batch materials into the batch, as well as the use of various fuel-regenerative, garnish-forming and washing additives [44, 45]. In blast furnace production, technological methods of introducing various non-traditional iron-containing materials (including fractions of agglomerate and pellets that are sifted out), fuel and carbon-containing additives into the composition of the charge, which were actively developed by V.I. Bolshakov [1], V.O. Dobroskok, Y. Buchwalder, E. Lonardi, S. Koehler [46, 47], L.D. Nikitin, Bugaev S.F. [48], E.A. Shepetovskyi [49], S.L. Yaroshevskyi, V.O. Nozdrachov, O.V. Kuzin [50, 51] and others. As shown in these works, improvement of blast furnace loading technology by finding and implementing rational formation parameters and modes of loading portions of multicomponent charge is a promising direction for reducing the consumption of scarce energy sources and ensuring the necessary level of energy efficiency of blast furnace smelting. For example, the practical experience of introducing pellets into the blast furnace charge and the results of numerous studies conducted under the leadership of V.I. Bolshakov [1], proved the advantages of loading them in a mixture with agglomerate in the form of mixed portions with a given structure, as well as the negative consequences of separate loading of these components. The results of previously performed research and the experience of industrial testing of various technological methods of loading a multi-component charge showed that mixing iron ore charge materials and coke before loading into the blast furnace, introducing into the charge additives of the desired purpose with the formation of a mixed layer of charge materials on the furnace of the blast furnace, as well as introducing sifted fractions of charge materials into the blast furnace charge and loading them into composition of multicomponent mixed portions is one of the most effective ways to reduce the energy intensity of blast furnace smelting and reduce the cost of cast iron, provided that the parameters of the formation of mixed portions of the charge and their loading mode are well-founded [1, 44 - 46].

The distribution of components on the surface of the backfill is the result of the interaction of a number of processes that occur at all stages of the formation of portions of charge materials, their delivery to the furnace and discharge into the furnace [45]. Depending on the method of delivery of the charge to the furnace, the formation of portions of charge materials is carried out by unloading the components of the charge onto a conveyor or into skips in a specified sequence and with a given distribution of component masses on the basis of technological requirements for the structure of the portion. In the process of forming multi-component portions and loading them into the blast furnace, as a result of repeated overloads, the location of the components in the volume of the portion changes significantly, the components are mixed, and masses of unmixed materials and mixtures with different compositions are formed. As a result of the redistribution of components in the portion volume, the sequence of unloading components from the BLT hopper is significantly different from the sequence of their loading into the hopper, therefore the current component composition of the output flow of the charge, which comes from the hopper to the distribution tray, is not determined, which significantly reduces the informativeness and technological value of the calculations of the distribution of charge materials in the blast furnace. In this regard, at a certain stage, the effectiveness of the use of multi-component charge was restrained by the lack of technical means of control and calculation tools for evaluating the distribution of components in the blast furnace, which led to the urgency of developing mathematical models that would describe the processes of loading multi-component portions of charge materials to BLT hoppers and unloading from them with the possibility of determining the component composition of the output stream throughout the portion unloading time. In combination with mathematical models of the formation of portions, the movement of the charge along the BLT tract and along the distribution tray after leaving the hopper, flight in the blast furnace space, and the formation of the backfill surface, the availability of such data provides the possibility of further calculation of the characteristics of the distribution of each component of the charge on the surface of the backfill, forecasting the composition of mixtures of charge materials in different zones of the blast furnace and the properties of the melts that are formed from them. Accordingly, there is an opportunity to implement the technological requirements for the distribution of charge components, which provide the most rational thermal and gas-dynamic regimes, as well as recovery and slag formation regimes that correspond to the composition of mixtures of charge materials in different zones of the blast furnace. Information on the distribution of components of the blast furnace charge across the cross-section of the furnace is important not only for the selection or prompt adjustment of parameters of the operating modes of the blast furnace, it is also necessary for conducting analytical studies of the physico-mechanical and physico-chemical processes occurring in it. To solve these tasks, it is necessary to develop a complex mathematical model of loading a blast furnace, which can be created as a result of the synthesis of a number of mathematical models that take into account to the maximum possible extent the peculiarities of the movement of multi-component portions of charge along the path "charge supply - surface of the backfill", and first of all, the movement and mixing of arrays of charge materials in the process of forming portions on the main conveyor, in skips, during their sluicing in BLT hoppers and distribution on the backfill surface. Thus, a complex mathematical model should contain separate mathematical models describing the behavior of bulk materials:

- a model of the formation of multi-component portions of the charge in bell less blast furnace top charging system and with skip delivery of the charge to the furnace;
- a model for loading multi-component portions of the charge into the BLT hopper, which for systems with skip delivery of the charge to the coke takes into

account, including, the redistribution of components in the volume of the skip when turning it in the unloading curves;

- a model for unloading multi-component portions of the charge from the BLT hopper, which provides a calculated determination of the content of each component in the output stream;

- the model of the movement of charge materials along the BLT tract (in the valve assembly, the central pipe and along the tray distributor) and the blast furnace space;

- a model of the fall of a multi-component charge on the surface of the backfill and distribution on it in the form of the formation of layers, which provides a calculated determination of the component composition of the charge in a given zone of the blast furnace.

From the listed models, we currently do not know of models for loading multicomponent portions of the charge into the BLT hopper, which describe the redistribution of components in the volume of the skip when it is turned in the unloading curves.

Regarding the models for unloading multicomponent portions of the charge from the BLT hopper, it should be noted that until recently there were only single examples of models that provided a calculated determination of the content of each component in the output stream. These include studies of the distribution of fine coke loaded as part of iron ore portions [52, 53], as well as the work of I. Matsui, A. Sato, T. Oyama, T. Matsuo [54], which should be noted as containing very interesting results from a practical point of view. It presents the results of research on large-scale physical models, which show the change in the content of pellets loaded into the iron ore portion together with the agglomerate, in the outlet flow from the hopper and along the radius of the blast furnace, depending on the location of the dose of pellets in the portion.

The limited number of research results on the distribution of individual (separated) components of the charge is primarily due to the fact that the mathematical description of the movement of bulk materials, which are the charge materials of blast furnace production, has always encountered significant difficulties. This is explained by the specific properties of bulk materials, which are a discrete medium made of solid particles, the behavior of which in the process of movement in some manifestations under certain conditions may be similar to the behavior of liquids, but in most cases obeys specific regularities inherent only to bulk media.

Modern ideas about the flow patterns of bulk materials were formed on the basis of research into this process over the past 100 years. Despite the large amount of theoretical and experimental research carried out up to now, a universal theory of the flow of bulk materials, including a formalized description of their movement in hoppers, which could be applied to a wide class of bulk materials, has not been created. Moreover, the definition of the subject of research - bulk material - is formulated by different researchers with significant variations regarding their main properties and features, which is due to the difference in the applied tasks faced by the authors of the research.

To describe the process of movement of bulk materials in hoppers, three approaches can be used, on the basis of which mathematical models have been created for specific objects and results acceptable for practical use have been obtained.

The first one is based on the description of the laws of flow of the batch material in the form of geometric dependencies that determine the volume of the zone of active movement of the material ("discharge figures"), the shape of which is determined experimentally, and the volumes of massifs of bulk material, which successively enter the zone of active movement of the material, and then move vertically to the discharge opening of the hopper. At the same time, one of the mandatory conditions is the equality of the volume of material arriving per unit of time in the zone of active movement, and the volume consumption of material being unloaded. In order to take into account the loosening of the material inside the massif in the hopper during the outflow and entry of a certain amount of material into the zone of active movement from the side surface that limits this zone, some authors introduce an empirical constant value [55 - 60].

The content of components in the output flow of charge materials from the BLT hopper can be determined using mathematical models developed by K. Nakano, I. Isei, and K. Sunahara [61, 62] in collaboration with colleagues, which are based on the distribution of the entire volume of the charge in the hopper into arrays, for which a certain sequence of the exit of these arrays from the hopper is specified, repeatedly confirmed experimentally.

At the same time, it should be noted that the considered mathematical models [52 - 62] do not cover the entire complex of processes of moving arrays of charge components and their mixing on the path of the loading system "charge feed - furnace", in particular, they do not take into account the effect of mixing components during unloading from skips to the BLT hopper.

The second approach is an attempt to take into account the kinematic regularities of the movement of particles of bulk material in the zone of active movement in the initial phase of outflow in combination with the determination of the volumes of masses of bulk, which will further enter the zone of active movement of the material, in the form of geometric dependencies [63].

To describe the patterns of movement of bulk material in the zone of active movement, which the authors of the kinematic model call the zone of converging flow, they use the dependence of the speed of particles on their initial and current coordinates [64], which makes it possible to analytically substantiate and determine the shape of the "discharge figure".

According to our evaluation, the dependences proposed by the authors make it possible to obtain a satisfactory convergence with the data of experimental studies of IPM at industrial facilities, only in the converging flow zone (the error in determining the exit time of individual particles does not exceed 9%), however, less reliable results were obtained for the remaining zones of bulk material. A preliminary analysis of the dependencies of the kinematic model of flow of bulk materials showed that if these dependencies are used for three-dimensional modeling of the process, the zone of active movement of the material will be a paraboloid of rotation. As mentioned above, on the basis of the dependencies of the kinematic model of outflow, only the type of curve limiting the zone of active movement is determined, and the mathematical description of the subsequent stages of the process, as during the application of the first approach, is reduced to the determination of the corresponding volumes of bulk material, which successively enter the zone of active movement from the surface of the formed funnel.

The third approach is based on DEM, the mathematical models on the basis of which require the assignment of a number of input data, the acquisition of which causes difficulties in determining, or data, the reliability of which does not have sufficient confirmation.

In [65], modeling with the use of DEM was used to quantify the segregation of charge materials by size during loading of the BLT hopper and changes in the content of individual fractions in the flow of charge material discharged from the hopper. Using this method, R. Kumar, Ch.M. Petelem, A.K. Yana [66], D.K. Chibwe [67] and a number of other researchers have currently developed algorithms that ensure the possibility of determining the sequence of exit of individual components from the hopper and their mass ratio in the flow. In combination with mathematical models of the movement of charge materials through the BLT tray, in the furnace space and their distribution on the backfill surface in the furnace, models of this class can provide calculation characteristics of the distribution of charge components along the radius of the furnace.

ISI has been conducting multi-faceted analytical and experimental studies of the process of loading charge materials and their distribution in the working space of the blast furnace for a long time. Under the leadership of Academician of the National Academy of Sciences of Ukraine V.I. Bolshakov developed a methodology for pre-commissioning studies on blast furnaces with BLT [1, 68]. The research involved determining the main parameters of the flow of charge materials during its movement along the BLT tract and in the furnace space, as well as the characteristics of the distribution of charge materials on the backfill surface. The practical experience acquired in the process of mastering BLT installed on blast furnaces became the basis for the development of a number of calculation methods and mathematical models, in particular: the movement of the charge through the working surfaces of the valve assembly and the tray distributor, the calculation of the trajectories of the movement of the charge materials in the blast furnace space, the determination of the meeting points of the material flow with the backfill surface and the calculation of the distribution of ore loads along the radius of the furnace furnace [1, 45 - 49].

Analytical and experimental studies of the last decade, carried out at the ICH, made it possible to clarify previously developed mathematical models and carry out a series of developments to create a complex mathematical model of blast furnace loading, which describes as fully as possible the processes of forming multi-component portions of charge materials at the charge feed, delivering these portions to the furnace, loading them into BLT hoppers and unloading them, the movement of charge materials in a tray that rotates, and in the blast furnace space, their fall on the backfill surface and distribution on this surface. The main purpose of developing such a model was to ensure the possibility of determining the characteristics of the distribution of each of the components of the charge along the radius of the blast furnace and, accordingly, the composition of mixtures of charge materials formed in different zones of the blast furnace.

The solution of this urgent task, in turn, made it possible to determine the high-temperature properties of mixtures of charge components, the composition and properties of the formed melts, and also made it possible to get an idea of the nature of their distribution along the cross-section of the furnace.

The results of research and development work.

The general block - diagram of the algorithm for modeling the process of loading multicomponent portions of charge materials into the blast furnace is shown in Fig. 1. The components of a complex mathematical model of the process of loading a multicomponent charge into a blast furnace are as follows.

A model of the formation of multi-component portions of the charge in bell less blast furnace top charging systemand with skip delivery of the charge to the furnace.

The structure of the portion in loading systems with conveyor delivery of the charge to the furnace is unambiguously specified by assigning the components the corresponding indices, assigning the masses of the doses of the components, and determining the leading component (which go first to the hopper of the loading device), assigning the offset values of the beginning of the dose of other (known) components, relative to the beginning of the dose of the leading component (Fig. 2). The displacement is expressed in units relative to the mass of the portion. During conveyor loading into the BLT hopper, each part of the portion on the conveyor, which differs in the composition of components, forms a separate layer in the hopper, in which the input masses of the components and their ratio are stored.

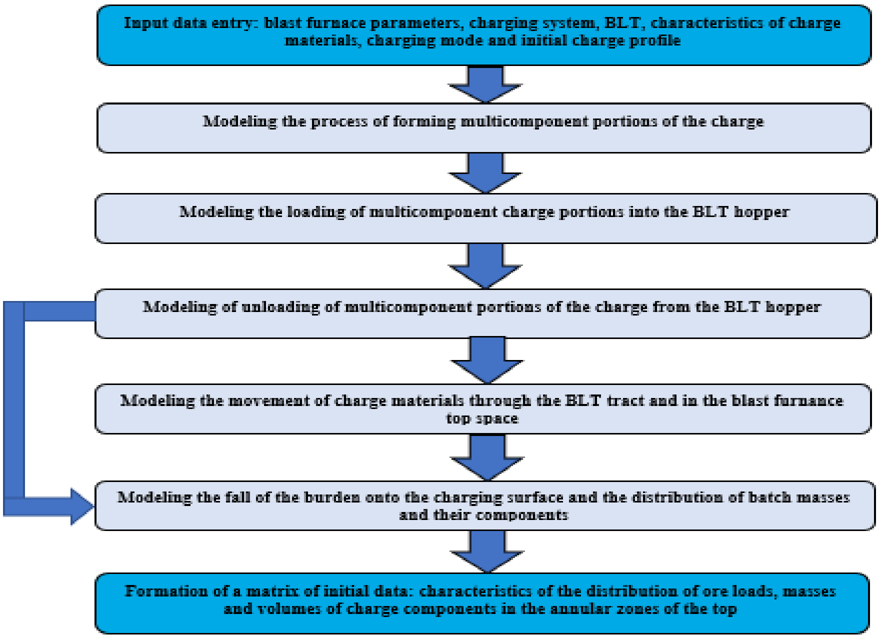
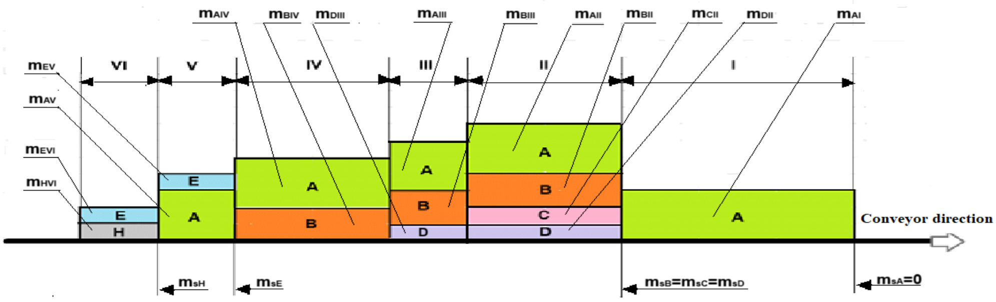


Figure 1 - General block - scheme of the algorithm for modeling the process of loading multicomponent portions of charge materials into a blast furnace



A, B, C, D, E, H – component indices; mon = 0, msB, msS = msD = mwith E, msH – the value of the total mass of the bulk materials unloaded on the conveyor until the start of the unloading of the corresponding component, t; I, II, III, IV, V, VI – indices of the layers of materials formed when loading a portion into the BLT hopper; mAI, mAII, mIII, mAIV, mOF,mKIND OF, mBIII, mBIV, mCII, mDII, mDIII, mTHIS, mHOUSE, mWHI – masses of components in layers of materials formed when loading a portion into a BLT hopper, i.e.

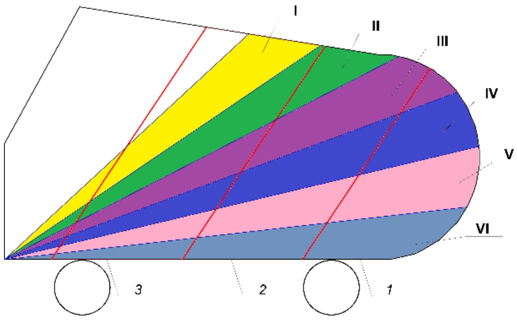
Figure 2 – The structure of a mixed multicomponent batch of charge materials on a conveyor

In systems with skip delivery of the charge to the furnace, a portion of the charge materials in the finished form is formed in the hopper of the loading device. In this regard, along with the loading sequence of feed skips, the location of the layers of components and their mixtures for each feed skip should be specified in the form of a layer index, which corresponds to the order of arrival of the component or mixture of components in the skip with the indication of the mass of charge materials in each layer.

The unloading of materials from the skip to the BLT hopper is carried out during the movement of the skip in the unloading curves, starting from the moment when the angle of inclination of the free surface of the material in the skip to the horizontal exceeds the angle of resistance to the shear of the material. During the unloading of the skip, the layers of the charge formed during its loading are intensively mixed. The layout of the loaded and unloaded layers of bulk materials in the skip is shown in Fig. 3. The output data of the model are the mass, volume and component composition of the charge layers loaded into the BLT hopper.

The model of loading multi-component portions of the charge into the BLT hopper, which takes into account, among other things, the redistribution of components in the volume of the skip when turning it in the unloading curves.

Determination of the mass distribution of the components and their mixtures in the volume of the portion loaded into the BLT hopper is carried out identically for the options of skip and conveyor loading of the hopper.



1 – 3 – layers of bulk materials formed during skip loading; Ⅰ - Ⅵ – layers of bulk materials unloaded from the skip (loaded into the BLT hopper)

Figure 3 - Diagram of the location of loaded layers of bulk materials in the skip and layers unloaded from the skip.

Based on the known volume of the layer of bulk materials loaded into the BLT hopper and its component composition, the coordinates of the points of intersection of the straight lines bounding the surface of the bulk materials formed after loading this layer with the lines of the internal contour of the BLT hopper are determined. Thus, it becomes possible to imagine the structure of the portion in the BLT hopper in the form of a series of layers of different shapes with the known volume and composition of the components of each layer, which, in the presence of the index of each layer, uniquely characterizes the structure of the multicomponent portion in the hopper (Fig. 4).

The model of unloading multi-component portions of the charge from the BLT hopper, which provides a calculated determination of the content of each component in the output stream.

One of the approaches (analyzed above) was used to describe the process of movement of bulk materials in hoppers, based on which mathematical models for specific objects have been created and results acceptable for practical use have been obtained [78]. This approach is based on the description of the laws of the flow of the batch material in the form of dependencies that determine the volume of the zone of active movement of the material ("discharge figures"), and the volumes of massifs of bulk material that successively enter the zone of active movement of the material and move vertically to the discharge opening of the hopper (Fig. 4).

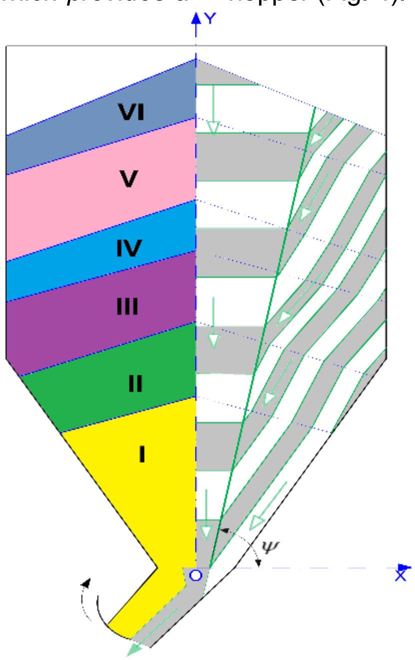


Figure 4 - Diagram of the location of the loaded layers of charge materials in the BLT hopper and the layers unloaded from it.

In the model, the shape of the zone of active movement of the material and the sequence of the output of elementary volumes of the material from the hopper are specified, which have been repeatedly confirmed by the research of the ISI experimentally. The output data of the model are the masses of the components in each elementary volume of the unloaded material.

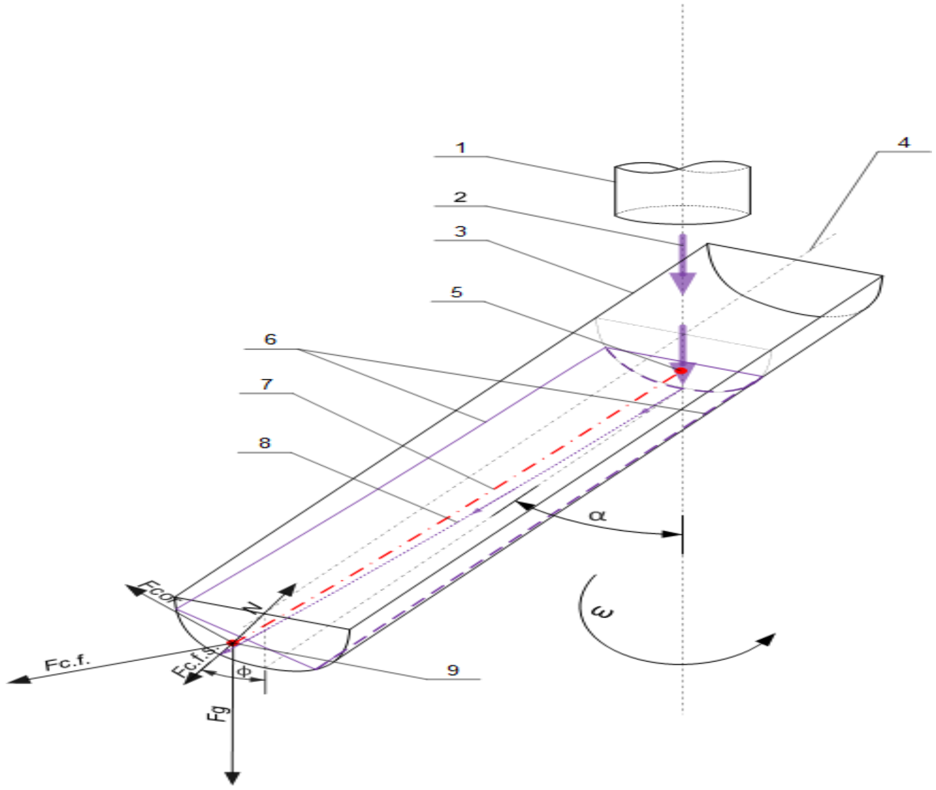
The model of the movement of charge materials along the BLT (in the valve assembly, the central pipe and along the tray distributor).

The model contains a mathematical description of the process of movement of charge materials from the plane of the discharge opening of the BLT hopper to their exit from the rotating tray. A system of differential equations is used to describe the complex movement of charge particles on the surface of a rotating tray (Fig. 5).

The output data of the model are the magnitude and direction of the speed of movement of the charge particles at the time of exit from the tray.

The model of the fall of a multi-component charge on the backfill surface and distribution on it in the form of formation of layers, which provides a calculated determination of the component composition of the charge in a given area of the blast furnace.

The model contains the equations of movement of the charge in the furnace space of the blast furnace and dependencies that describe the process of formation of the backfill surface on the furnace in the form of a gradual increase and distribution of the volume of discharged charge materials until the BLT hopper is completely emptied.



1 - the central pipe of the BLT; 2 - the direction of movement of the charge material; 3 - distribution tray; 4 - longitudinal axis of the tray; 5 - the center of gravity of the flow at the beginning of movement along the tray; 6 - the limits of the flow of charge materials on the tray; 7 - trajectory of the center of gravity of the flow; 8 - the trajectory of the movement of the material point along the tray; 9 - position of the center of gravity of the flow on the unloading end of the tray; α - angle of inclination of the tray to the vertical, degrees; ω - angular speed of tray rotation, rad/s; φ - the angle of lifting (deposition) of materials on the tray, degrees; F_g - gravitational force, N; $F_{c.f.}$ - centrifugal force from tray rotation, N; F_{cor} - Coriolis force, N; $F_{c.f.s.}$ - centrifugal force from lifting (carrying) materials onto the side of the tray, H; N is the normal component of the reaction force, N.

Figure 5 – Diagram of the forces acting on a charge particle during movement along the tray.

The model takes into account the peculiarities of the formation of the backfill surface in the wall and axial zones of the blast furnace, as well as the influence of the processes of redistribution of the coke layer when the iron ore portion is unloaded onto it. The model provides a calculated determination of the characteristics of the distribution of masses and volumes of charge materials discharged in different angular positions of the tray, in the annular zones of the furnace. The content of the components of the charge and the composition of mixtures of charge materials in the annular zones of the furnace is determined on the basis of the data on the content of the components in the flow of the charge in the specified angular positions of the tray, which are the initial data of the model of unloading portions of the charge from the BLT hopper. An example of a fragment of a table with output data of a complex mathematical model of the process of loading a multi-component charge into a blast furnace, as well as the distribution of component masses along the radius of the furnace according to the results of the simulation of the loading cycle consisting of 10 passes, is given below (Table 1, Fig. 6).

On the basis of the synthesis of mathematical models describing the processes of loading multi-component bulk materials, their unloading from the BLT hopper, movement along the distribution tray of the loading device and distribution on the backfill surface, which were developed in ISI earlier [79] and improved, a complex mathematical model of the formation of multi-component portions of bulk materials, their loading into the BLT hopper, unloading from the hopper and distribution on surface of the backfill [80].

The model provides determination of the current component composition of the flow formed during unloading of multi-component portions from the BLT hopper, and the full composition of mixtures of charge components

in different ring zones of the furnace. Mathematical and algorithmic support of the model was developed on the basis of the established fundamental dependences of the flow of charge materials from hoppers and their movement along the BLT path, as well as the results of numerous experimental studies performed by ICH at blast furnace production facilities in industrial conditions.

Table 1 – Fragment of a table with output data of a complex mathematical model of the process of loading a multicomponent charge into a blast furna

Parameter, characteristic	**No. of the ring zone of the blast furnace top**									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
	Values (relative)									
Zone boundary radius	0,316	0,447	0,548	0,632	0,707	0,775	0,837	0,894	0,949	1,000
Zone mid-radius	0,158	0,382	0,498	0,590	0,670	0,741	0,806	0,866	0,922	0,974
Sinter mass	0,059	0,088	0,116	0,111	0,100	0,089	0,091	0,103	0,115	0,128
Mass of pellets	0,021	0,041	0,077	0,110	0,136	0,160	0,145	0,119	0,104	0,088
Mass of coke	0,156	0,131	0,097	0,087	0,085	0,082	0,088	0,092	0,092	0,091
Mass of scrap	0,020	0,040	0,076	0,109	0,145	0,180	0,137	0,113	0,099	0,081
Mass of anthracite	0,018	0,038	0,076	0,110	0,130	0,145	0,152	0,125	0,111	0,096
Mass of nut coke	0,026	0,047	0,083	0,116	0,130	0,141	0,146	0,119	0,104	0,089
Ore mass	0,050	0,079	0,117	0,129	0,111	0,087	0,099	0,103	0,108	0,117
Mass of ore part	0,045	0,070	0,101	0,111	0,114	0,117	0,111	0,109	0,111	0,112
Mass of coke part	0,149	0,125	0,097	0,090	0,089	0,087	0,093	0,093	0,090	0,088
Ore load	0,300	0,557	1,046	1,229	1,289	1,342	1,200	1,172	1,227	1,279
Ore part volume	0,046	0,071	0,103	0,111	0,113	0,115	0,109	0,108	0,111	0,113
Coke part volume	0,152	0,127	0,097	0,090	0,088	0,086	0,091	0,092	0,090	0,088

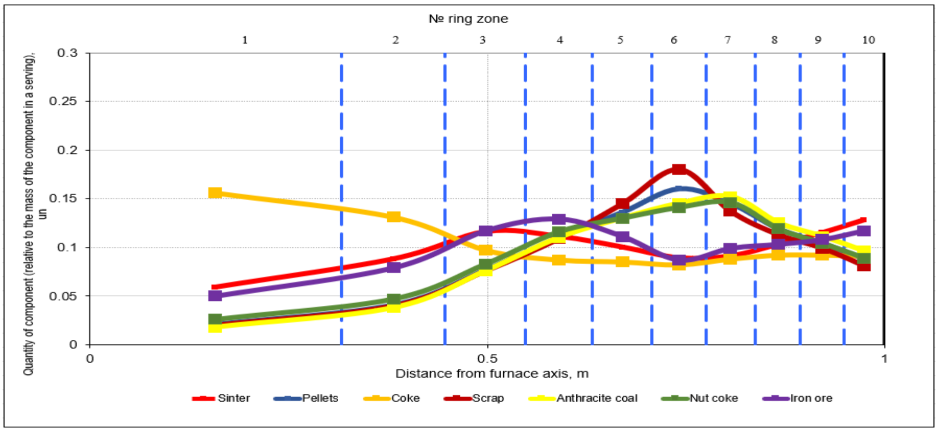


Figure 6 – Mass distribution of charge components along the radius of the to

The model takes into account the influence of the complex of processes of moving mass of charge materials and mixing components in the process of movement and overloading of multi-component portions of the charge, starting from the stage of unloading them on the blast conveyor, or loading them into skips before unloading them on the surface of the backfill on the formation of the characteristics of the distribution of the components of the charge on the surface of the backfill, including the redistribution of components in the volume of the skip when it is turned in unloading curves.

The developed mathematical model contains databases of structural parameters of blast furnaces, loading devices of various types, skips, as well as databases of loading programs and characteristics of charge materials. It is possible to introduce different velocities in the ring zones of the blast furnace if there is a profiler on the blast furnace. One of the most important results that can be obtained with the help of the model is the quantification of the mass of each component of the charge entering the considered annular zone during the unloading of the charge materials during the discharge of the charge materials in each involved angular position of the BLT tray.

This makes it possible to analyze the influence of the quantitative characteristics of the applied program for the distribution of charge materials on the indicators of the distribution of individual components, both the iron ore and fuel parts of the charge, as well as the ore loading, and creates the possibility of selecting and adjusting the program based on the results of predictive calculations before introducing it into the loading control system, which significantly reduces the duration of the development of rational charge loading programs and reduces the risk of making ineffective decisions.

The research carried out in recent years has shown the possibilities of using a complex model of the distribution of charge components in solving various technological problems. In particular, based on the results of mathematical modeling of the distribution of charge components in the annular zones of the blast furnace, it is possible to determine the parameters of the plastic zone in the blast furnace, which largely determines the parameters of blast furnace melting [81].

The results of modeling with the help of a complex model make it possible to evaluate the possibility of implementing the requirements for the distribution of charge materials and gas flow during the operation of blast furnaces in various technological conditions [82].

It is known that the properties of primary slags significantly affect the operation of the blast furnace and furnace heating, and the position of the zone of primary slag formation in the furnace depends primarily on the composition of the charge. In this regard, one of the problems that can be solved by predicting the properties of primary slag melts is the justification of the choice of the composition of the charge. Methods of optimizing the composition of the blast furnace charge, which are known and used at present, do not take into account the uneven distribution of its component composition in the working volume of the blast furnace and the related features of the processes of heating, recovery and melting of the charge materials in its various zones. Accordingly, the specificity of the properties of the melts formed in different zones of the working space of the blast furnace is not taken into account. The ability to assess the properties of primary slag melts in different zones of the furnace will allow predicting the state and parameters of the plastic zone, which largely determines the efficiency of the melting process.

The developed complex mathematical model of the distribution of a multi-component charge on the furnace of a blast furnace in combination with physicochemical models of high-temperature transformations of iron ore components of the charge makes it possible to calculate the properties of primary slag melts in different zones of the blast furnace. The use of these models made it possible to improve the method of estimating the composition and indicators of high-temperature properties of iron ore materials and primary slag melts, which are formed in selected zones of the blast furnace as a result of the distribution of the charge components during loading. With the help of this ICM method, predictive and analytical studies of the properties of primary slag melts in different zones of blast furnaces during their operation in different technological conditions have been carried out in recent years. Based on the forecast of the properties of the primary slag melts and their comparison with the characteristics set by the technological requirements, an assessment of the effectiveness of the applied loading modes and slag modes is performed, based on which well-founded decisions are made on management and adjustment of their parameters.

Conclusions.

1. Analysis of well-known calculation methods and mathematical models for the distribution of charge materials on the crucible of a blast furnace, which are used in technological and research practice, showed that mathematical modeling using the results experimental studies remain the main way of obtaining information about the distribution of charge materials. There are currently no instrumental means of controlling the distribution of charge components.

2. It is also shown that the distribution of components on the surface of the backfill is the result of the interaction of a number of processes occurring at all stages of the formation of portions of charge materials, their delivery to the furnace and unloading into the furnace. In the process of forming multi-component portions and loading them into the blast furnace, as a result of repeated overloads, the location of the components in the volume of the portion changes significantly, the components are mixed, and masses of unmixed materials and mixtures with different compositions are formed. As a result of the redistribution of components in the volume of the portion, the sequence of unloading components from the BLT hopper is significantly different from the sequence of their loading into the hopper. At the same time, the distribution of charge components and the composition of their mixtures formed in different zones of the blast furnace largely determine the formation and development of the gas flow, its characteristics and their distribution in the volume of the furnace, the condition of the lining and the possibility of risks of violation of its integrity, the formation of fields of primary slag formation, the gas permeability of the zone of slow moving materials, the parameters of the plastic zone and a number of other processes and factors that determine the course and indicators of blast furnace melting.

3. Three approaches to modeling one of the more complex processes that take place on the path of the loading system - the unloading of multi-component portions from the BLT hopper - are highlighted. The first - in the form of geometric dependencies, determines the volume of the zone of active movement of the material, the shape of which is determined experimentally, and the volumes of massifs of loose material,

which in a given sequence will further reach the zone of active movement of the material, and then move vertically to the outlet of the hopper. The second approach is an attempt to take into account the kinematic laws of movement of bulk material in the zone of active movement in combination with the provisions of the first approach to describe the behavior of bulk material outside the active zone. The third approach is based on DEM, the mathematical models on the basis of which require input data, the acquisition of which is difficult to determine, or whose reliability is sufficiently confirmed.

4. On the basis of the synthesis of mathematical models describing the processes of loading multicomponent bulk materials, their unloading from the BLT hopper, movement along the distribution tray of the loading device and distribution on the backfill surface, which were developed and improved in the ICH, a complex mathematical model of the formation of multicomponent portions of batch materials, their loading into the BLT hopper, unloading from the hopper and distribution on the backfill surface was developed. The model provides determination of the current component composition of the flow formed during the unloading of multicomponent portions from the BLT hopper, and the full composition of mixtures of charge components formed in different annular zones of the blast furnace.

5. Over the past 15 years, the developed complex model has been successfully used by the ISI to solve a number of technological tasks regarding the selection of rational loading modes of operating blast furnaces operating on a multicomponent charge, including for the selection of parameters of special loading modes that provide the necessary conditions for the formation of garnish or washing depending on the current requirements of the smelting process. Information on the distribution of charge components across the cross-section of the furnace, which can be obtained using the developed complex model, is also necessary for conducting analytical studies of physico-mechanical and physico-chemical processes in the blast furnace, in particular the conditions of slag formation and the distribution of properties of melts in the volume of the blast furnace.

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