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THE PARAMETERS OF BURDEN FLOW FROM THE BINS OF BELL-LESS TOP CHARGING SYSTEM OF BLAST FURNACES

Purpose. To prove the correspondence of the mathematical description regarding the process of the furnace charge material efflux out of the collecting bin of the bell-less top charging mechanism of a blast furnace as a result of the full-scale modeling of the studied process.

Methodology. Full-scale modeling of mechanical systems based on the Newton number is employed in the research study. Experimental investigation of the process of the burden efflux out of the collecting bin of the bell-less top charging mechanism of a blast furnace is fulfilled at the scale of 1 : 10.6. The correspondence of theoretically-calculated volumetric burden flow rate is tested and compared with the results of the full-scale modeling.

Findings. The volumetric flow rate of the burden is determined both experimentally and theoretically taking into account various degrees of opening sliding charge gate. It is found that the change in the opening angle of the sliding charge gate of the charging feeder bin model from to 1 radian results in the raise of the volumetric burden flow rate from 0 to 0.0014 m^3/s while maintaining the free-dispersed nature of the flow. The integrated effect of granulometric furnace burden characteristics as well as geometric parameters of the bin delivery part on the volumetric furnace burden flow rate out of the bin is outlined. Empirical dependencies for model-sized sinter and coke consumption rates are developed. According to the results, the adequacy of the mathematical description regarding the process of the furnace charge material efflux out of the collecting bin of the bell-less top charging feeder in terms of the blast furnace is proven as a result of the full-scale modeling of the studied process.

Originality. First-ever, complex dependencies of the furnace charge flow rate on the opening angle of the sliding gate, the configuration of the delivery part of the bin, the size of the used furnace charge are established. Thus, the flow rate increases with the rise in the opening angle of the sliding gate, the reduction in the equivalent diameter (average size) of the particles of the furnace charge materials, the angle of the delivery part of the bin.

Practical value. The results can be used for determining the technological parameters of charging a modern blast furnace under various raw materials conditions. This will enable to make the furnace feeding system more automated, which will result in more efficient use of expensive furnace charge materials, reduction in power consumption and decrease in harmful impact on the environment. Recommendations regarding the selection of sizes for both the blast furnace feeding system elements and furnace burden for the corresponding modeling are provided. This makes any furnace feeding system unit modeling as well as various mechanical system design possible.

Keywords: *blast furnace, charging mechanism, collecting bin, structural-mechanical areas, sliding charge gate*

Introduction. Blast-furnace smelting remains the dominant aspect of the pig iron production technology in the world. However, the conditions for its implementation are becoming much more complicated today. This is due to the deterioration in quality and rise in prices of raw materials used [1], higher requirements for the quality of a produced product, as well as more stringent environmental safety requirements [2]. Modern studies of blast furnace charging processes are often performed using the full-scale modeling. Modeling is a method for task solution in which a system under study is replaced by a simpler object, which, in its turn, represents real equipment and is called a model. Both elements of a charging system and an entire system in general are modeled [3]. Modeling makes it possible to obtain qualitative and quantitative values of processes occurring with burden moving along channels of a blast furnace bell-less charging top. Mathematical models of burden flows should be tested experimentally to achieve the necessary accuracy of any process description. The use of models ensures a number of advantages: low cost, time and resources saving, high repeatability, accuracy, visual clarity and versatility.

In the publication [4], experimental studies of dynamic parameters of burden flow in bell-less charging channels were performed. Qualitative regularities of material distribution in a rotating chute and on a stock surface were established. However, modeling criteria (on the basis of which geometrical dimensions of a full-scale charging system model were selected) were not indicated and sizes of experimental burden were not justified.

To date, many researchers are analyzing the dynamics of burden using various application packages based on the finite element method [5]. The simplest relations of a stressed condition and hopper geometry are established. This approach is noteworthy only when taking into account the minimal number of factors that influence the determination of material discharge parameters. With the introduction of recording the influence of more than five factors, models become much more complex and provide results with a rather low accuracy.

One of the main components of blast furnaces bell-less charging tops with rotating chutes are burden hoppers. In a blast furnace design, burden hoppers serve both as receiving hoppers and components that well determine a velocity of blast furnace charging, as well as a nature of the radial and circumferential distribution of burden on a throat.

To date, nevertheless, existing methods for determining basic parameter values of bulk material discharge from hoppers are generalized, which does not allow optimizing the charging process in each particular case and reduces blast furnaces efficiency by 1–3 %.

Literature review. A great number of works address the determination of rational and optimal parameter values of bulk material discharge from hoppers and describe methods for calculating a flow rate and discharge rate for receiving hoppers of bell-less charging tops.

The following relation is given in the publication [6] for determining a mass flow rate from a hopper outlet

$$Q = \frac{4}{\pi} C \cdot \rho_b \sqrt{g D_h} \cdot A_h, \quad (1)$$

where C is a dimensionless constant; ρ_b is material density; D_h is an average hydraulic diameter; A_h is an outlet area.

The expression (1) does not take into account a number of features of burden discharge from receiving hoppers of blast furnaces bell-less charging tops. First of all, the geometry of a hopper outlet section, discharge chute tilt angle and outlet configuration influence a material flow rate from a hopper. A gate of a bell-less charging top receiving hopper has a complex geometry; therefore, it is not enough to take into account the influence of its change on a flow rate only by a hydraulic radius. In addition, dimensionless coefficient C varies within quite a broad range and there are no recommendations for choosing its rational value for a specific design of a receiving hopper. The advantage of the expression (1) is its simplicity and ease of calculation, however, its application involves a significant difference between theoretical and experimental results.

Quantitative analysis of burden discharge is described in the publication [7]. Based on this analysis, it is possible to determine flow rates from blast furnace charging device hoppers, but no analytical expression was obtained in the publication.

In the publication [8], the influence of shape and size of blast-furnace burden particles on the formation of blast furnace burden ratio was studied. Main factors that influence a throughput capacity of a charging system of a blast furnace equipped with a bell-less charging top are also analyzed here. It is noted that the narrowest place in terms of system throughput capacity is a receiving hopper outlet.

Researchers [9] compared theoretical and experimental results to determine the influence of hopper outlet shape on burden flow dynamic parameters.

In the article [10], computer modeling of processes occurring in a hopper during its discharge was performed. Dependence diagrams of mass discharged from a hopper in time in given. Also the formula to determine a material discharge rate from a hopper of a defined shape is given

$$W = C \cdot \rho_b \sqrt{g} \left(D_0 - kd\right)^{\frac{5}{2}}, \quad (2)$$

where C is a constant, determined by bulk properties, and its value is empirically within the range of $0.55 < C < 0.65$; ρ_b is bulk density; g is gravitation acceleration; D_0 is an outlet diameter; k is a shape factor and is usually taken equal to 1.5 for a spherical particle; d is a particle diameter. In this method (2), particle shape is already taken into account; however, properties of material itself are not reflected in the expression.

Considering the above, the drawbacks of the above methods are the lack of a comprehensive consideration of the influence of physical and mechanical characteristics of the used burden, its grain size composition, receiving hopper outlet shape and configuration of a hopper section adjacent to an outlet on parameters of burden flow along channels of a blast furnace charging device.

Therefore, the creation of an experimentally confirmed analytical method for forecasting the effect of the stated factors interaction on burden flow is an urgent unsolved scientific and technical problem.

The purpose of the study is to assess the appropriateness of the method for forecasting the effect of the stated factors interaction on burden flow based on the results of the full-scale modeling of burden discharge from a blast furnace bell-less charging top receiving hopper model.

Methods. A diagram of a hopper of a bell-less charging top with a burden sliding gate is shown in Fig. 1.

Dashed lines show the trajectories of burden particles in a hopper when it is emptied.

Before performing an experiment, it is necessary to choose variable factors, i.e. establish main and secondary characteristics that influence the process under study, analyze the design diagrams of the process. A correct choice of the main and secondary factors is important for experiment effectiveness, since it involves finding relations between these factors.

A hopper is conventionally divided into three areas. Area I (Fig. 1) features the "piston" motion at low rates and the same kinematic characteristics. In Area II, bulk cargo also moves at a low rate, being in a plastic state, and Coulomb's law is true for its internal stresses. Area III is divided into three structural-mechanical zones, shown in Fig. 2. The flow rate from a hopper model was adjusted by changing the position of a burden gate. Experimental burden was fed through the throat *1*. Due to the gravity effect, burden moved through the main and discharge sections of the hopper.

Model dimensions were chosen taking into account general points of the modeling theory. According to this theory, it is necessary to maintain the equality of similarity criteria made up of parameters of a blast furnace charging device and model of its units.

Based on the fact that a bell-less charging top is a mechanical system, hopper parameters were taken using the criterion of mechanical similarity. That is, the Newton criterion shall be

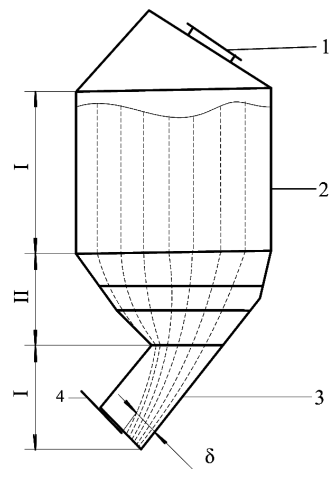

Fig. 1. Diagram of a receiving hopper of a blast furnace bell-less charging top with a sliding gate:

1 – charging throat; 2 – main section of a hopper; 3 – discharge section of a hopper; 4 – sliding gate for burden met for the model being developed and existing blast furnace, which is as follows

$$Ne = \frac{F \cdot \tau^2}{M \cdot l}, \quad (3)$$

where F is force; τ is time; M is batch mass; l is movement by the force.

Since gravity is the moving force, then the value $F = Mg$ can be inserted in (3). Then (3) can be represented as

$$Ne = \frac{g\tau^2}{l}.$$

Burden flow in a throat is proportional to the value $R\frac{h_s + h_c}{h_c + h_p}$, where h_s, h_c, h_p are the geometrical parameters of material dumping profile on models of a charging device in central, middle and peripheral zones of a throat. The authors proposed a geometric outline of a layer in a vertical section as a decisive similarity criterion, which is as follows

$$\sigma_{sh} = \frac{P_p + P_c}{P_c + P_s},$$

where P_p, P_c, P_s are the parameters of a burden layer (layer thickness, mass, etc.) in a peripheral, middle and central chambers of a throat of a bell-less charging top model.

The following dimensionless values can be the modeling criteria

$$\frac{D}{dcp}; \quad \frac{M}{D^3\gamma}, \quad (4)$$

where D is a throat diameter, dcp is an average burden particle size; M is feeding mass; γ is a bulk mass of burden. The modeling criteria should be identical both for a model and real charging device of a blast furnace.

To ensure compliance between a model and real charging device, it is necessary to find an automodeling region, i.e. a region where the change in a ratio of a throat diameter to an average burden particles size $\frac{D}{dcp}$ influences the decisive criterion slightly. An automodeling region occurs at $\frac{D}{dcp} \geq 430$.

To determine the scale of model development, we transform (4)

$$\frac{M_n}{D_n^3\gamma_n} = \frac{M_m}{D_m^3\gamma_m}. \quad (5)$$

The “n” indices mean attribution to real parameters, and the “m” indices mean attribution to model parameters. Since the scale of a model can be calculated as a ratio $C = \frac{D_n}{D_m}$, then (5) can be transformed as follows

$$C = \sqrt[3]{\frac{M_n\gamma_m}{M_m\gamma_n}}. \quad (6)$$

Thus, according to (6), the scale in relation to the actual sizes of the hopper of the blast furnace bell-less charging top No. 9 of PJSC “ArcelorMittal Kryvyi Rih” is taken as 1 : 10.6.

The above approach for determining the necessary sizes of a unit model as a mechanical system is suitable for any charge-conveying component of a modern blast furnace. Using this method, it is possible to model burden flow along tilted spouts, chutes and pipes, as well as in a throat area. This makes it possible to study a wide range of technological parameters of burden flows and recommend the adjustment range of control impacts on a system as a whole based on the results obtained.

The experiment was performed using a mixture of sinter of fractions of 0.5–1; 1.5–2; 3–5 mm with a ratio of 20 : 60 : 20 and coke with a size of 6.5–8 mm. The mass of a single batch was 25 kg. These parameters fully comply with all the modeling criteria of burden flow along channels of a blast furnace bell-less charging top (relations 4, 5, 6).

Let us consider burden discharge from a bell-less charging top hopper model. Fig. 2 shows a diagram with the designation of structural-mechanical state zones [11].

In the zone of the dynamic bridge C, bulk cargo particles form movable bridges moving downward, sliding along walls of a channel, the width of which is equal to the outlet width. A velocity of bulk cargo particles increases significantly, and their trajectories approach vertical lines due to the gravity effect.

In the collapse (mixing) zone D, due to velocity increase, links between bulk cargo particles are disrupted, a free-dispersed motion begins, and the particles are in a continuous chaotic motion, colliding with each other, and their velocity increases due to the gravity effect. Zone D is of the greatest interest for the research, since it is located at the end of the hopper discharge section and kinematic parameters of material discharge from the hopper are determined in it.

Zone E is the area of immovable burden.

The volume flow rate of burden can be calculated by the formula [11]

$$Q = \eta b a^{1.5}\sqrt{g}, \quad (7)$$

where η is a dimensionless coefficient of bulk cargo flow rate from the hopper; b is the length of the hopper slotted opening; g is gravitational acceleration; a is the height of the hopper discharge section.

The coefficient η in equation (7) is determined by the formula

$$\eta = \frac{\delta\eta_0 \sin\alpha}{\sqrt{\delta^2 \sin^2\alpha + k^2 K_1 K_2}}. \quad (8)$$

In expression (8), the values δ, K_1 and η_0 are determined as follows

$$\delta = \frac{a}{d}; \quad (9)$$

$$K_1 = \frac{1}{2}\left(f + \sqrt{1+f^2}\right); \quad (10)$$

$$\eta_0 = \frac{2\sqrt{2}}{3}\sin(\varphi_c + \beta)B\sqrt{A + \chi}\left(\frac{\operatorname{tg}\alpha}{1 + K_1\operatorname{tg}\alpha}\right)^{1.5}, \quad (11)$$

where $\chi = f + \frac{1}{f} - \sqrt{1+f^2}$.

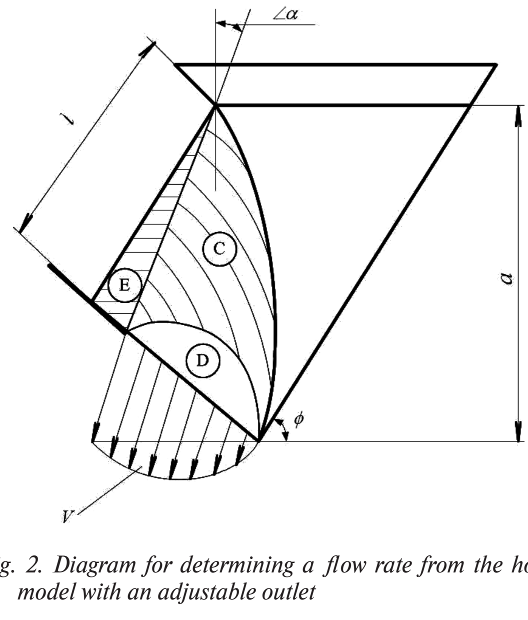

Fig. 2. Diagram for determining a flow rate from the hopper model with an adjustable outlet

In expressions (8–11), d is an average size of burden; f is the coefficient of internal friction of burden as bulk cargo; β is an inclination angle of an outlet section of bulk cargo from the hopper with an adjustable gate; φ_c is an inclination angle average value of a velocity vector V of cargo particles discharge from the hopper to the horizontal, K_2 is the coefficient taking into account outlet shape (for a rectangular outlet $K_2 = 1$, for a circular outlet $K_2 = 3$).

In the equation (11), coefficients A and B are calculated by the formulas

$$A=\frac{\mathrm{tg}\varphi_c(K_1-\mathrm{tg}\beta)}{\mathrm{tg}\beta+\mathrm{tg}\varphi_c};\quad B=\frac{\left(K_1+\mathrm{tg}\varphi_c\right)\sqrt{1+\mathrm{tg}^2\beta}}{\mathrm{tg}\beta+\mathrm{tg}\varphi_c}.$$

The extent of sliding gate opening is determined by the angle α. In this case, the angle β is determined by the formula

$$\mathrm{tg}\beta=\frac{a/l-\cos\alpha}{\sin\alpha}\quad(0\le\alpha\le0.5\pi).$$

The average value of the angle φ_c is

$$\varphi_{\tilde{n}}\approx\frac{(0.5\pi-\alpha)+\varphi_0}{2}\quad\left(0.5\pi-\alpha\le\varphi_c\le0.5\pi\right).$$

In the real blast furnace charging system, the receiving hopper has a sector burden sliding gate. It is designed in a way that the maximal gate opening coincides with an opening angle of 60°. In this regard, dependence diagrams below are designed for gate opening angle within 0–60°.

Fractions of experimental bulk material for a hopper model are given in [10]. Material particle size was determined as an arithmetic average of sizes of all fractions found in it. Such an approach does not ensure a sufficiently accurate account of the influence not only of the fraction size, but also of its content in the entire volume of the experimental bulk material. Therefore, in this work, the average burden particle size was calculated taking into account the following relation

$$d=\sum d_i\psi_i, \tag{12}$$

where ψ is a portion of material with the appropriate size. Values of (12) were inserted in (8 and 9).

Experimental studies were performed as follows. Material of a defined mass and grain size composition was fed into the hopper model. The necessary gap was ensured using the sliding gate 4 (Fig. 1) and the process of burden discharge was started. After dumping completion, batch discharge time was recorded. The flow rate was calculated as a ratio of charged material volume to time of its discharge. The volume was determined as a ratio of batch mass to its bulk mass. 20 tests were performed for each extent of hopper model gate opening. The authors chose ten gate positions.

Using the experimental data, a single-factor regression analysis was performed. A regression relationship with a determination coefficient of 0.99 for sinter and 0.98 for coke was obtained as a result of the analysis. The expression of the sinter flow rate from the hopper is as follows

$$Q=1.457\cdot10^{-3}\cdot\alpha^{1.196}-1.146\cdot10^{-4}, \tag{13}$$

where α is an extent of sliding gate opening of the blast furnace charging device receiving hopper model.

For the coke it was respectively

$$Q=1.14\cdot10^{-3}\cdot\alpha^{1.565}+7.3\cdot10^{-6}. \tag{14}$$

Fig. 3 shows dependences of a burden flow rate on an extent of hopper model sliding gate opening.

Points *1* show the average values of the experimental flow rates for one position of the sliding gate for model burden in the form of sinter. The values *2* for coke are marked in the same manner. Curves *3* and *4* represent theoretical dependences for the flow rate, obtained using the expression (7) for iron ore materials and coke, respectively. In this case, the determination coefficients for the experimental and theoretical dependences were 0.95 and 0.97 for coke and sinter. Curves *5, 6* represent regression dependences for sinter and coke (expressions (13) and (14)). As we can see, the theoretical and regression curves represent the process of burden discharge from the blast furnace bell-less charging top hopper model with quite a high precision (absolute deviations are less than 2 %).

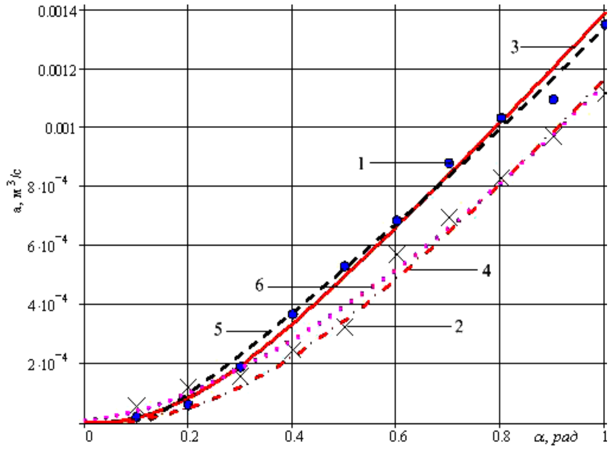

Fig. 3. Dependence of burden flow rate on an opening angle of the blast furnace bell-less charging top hopper model sliding gate

To assess the correctness of the regression curves, the authors chose the least squares method as the most effective method in the case under consideration. Using a simple mathematical technique, this method allows quickly assessing the convergence of two dependences – experimental-regression and theoretical ones – with a high accuracy. The sum of squared deviations, calculated using this method, for iron ore materials was $1.152\cdot10^{-8}$ and $1.661\cdot10^{-8}$ for the regression and theoretical curves, respectively. Deviations for the coke flow rate curves are $5.26\cdot10^{-9}$ and $1.482\cdot10^{-8}$. The obtained deviation values are significantly less than 1 %; therefore, the dependences can be successfully applied in practice. The calculations and visual analysis of the curves performed by the authors prove good convergence of the experimental and theoretical results. Thus, types of mathematical dependences are proposed, which can replace the formula (7) for burden with specific grain size and physical and mechanical parameters.

The pattern of curves *3, 4* and *5, 6* is very similar to the dependence diagrams in the publication [10]. However, the formula (2) provides values which are comparable with the experimental ones only with the maximal opening of the hopper model sliding gate. This may be due to the fact that, when the burden gate is fully open, hopper outlet shape is close to the correct one and the coefficient C selected in [10] corresponds to actual flow rate values. Rise of the coefficient C results in that, with small gate opening, the flow rate coincides with the experimental flow rate, but when the gate opens by more than 60 % of the maximal opening, the values are significantly higher. Similar results are obtained by analyzing methods described in [6].

The correctness of a mathematical model of burden discharge from the receiving hopper outlet rather strongly influences the determination of actual values of dynamic parameters of burden flow along channels of a charging device of a blast furnace equipped with a bell-less charging top. Taking that burden flow rate in all the components of the charging system at the blast furnace throat is a constant value for each corresponding opening of a burden sliding gate, it becomes possible to analytically determine the geometry and kinematics of burden flow anywhere in the channel of the charging device. To ensure a burden ratio at the blast furnace throat, it is important that an iron-containing materials layer is uniformly covered with a coke layer. This is possible only in case of coincidence of intersection points of iron ore portion and coke trajectories with a burden stock surface on the throat. Since coke and iron ore fractions have different grain size composition, physical and mechanical properties, so, to ensure trajectory coincidence during the charging, it is necessary to adjust a volume flow rate and, as a consequence, material discharge rate from a hopper, which directly influences a rate of burden discharge from a chute. Change of initial conditions of burden flow in a blast furnace throat area by changing a flow rate from a receiving hopper is an important factor for controlling the operation of a blast furnace and ensuring its effective running.

Thus, using the method in [11] allows extending the range of parameters taken into account, which have a significant influence on burden discharge from a hopper. Using this method does not stipulate the use of numerical coefficients, value of which is chosen empirically. It is important that a ratio of an outlet slot width and bulk material portion size is taken into account when calculating a volume flow rate. For certain sizes, some zones of an outlet section do not operate, which should be taken into account when calculating a flow rate. The method proposed by the authors takes into account the change in sizes of structural-mechanical zones with the change in sliding gate opening.

To use (7) in an automatic charging control system of a modern blast furnace, it is possible to plot a variety of curves for various equivalent diameters of iron ore portion of burden and coke and subsequently approximate them using simpler mathematical expressions. They can be of type (13, 14).

Conclusions. According to the full-scale modeling results, it was established that the dependence of a volume flow rate of burden from a charging device receiving hopper outlet on a gate opening angle can be described as a power-law dependence $Q(\alpha) = \lambda \cdot \alpha^{\xi} + \psi$, where the values λ, ξ and ψ depend on a type, physical and mechanical properties of burden. The obtained modeling criteria are valid for the entire system of charging device components of a modern blast furnace. Grain size composition and type of burden have the greatest influence on a volume flow rate. Rise of the parameter α within the range of 0 to 1 radian increases a volume flow rate of burden by 0 to 0.0014 m^3/s. The results of the full-scale modeling confirmed a high degree of conformity of the method described in the publication [11] to real data, which provides reasons to recommend it for use in engineering calculations. The method described in the publication [11] can be recommended for high-accuracy calculations and forecast of possible process situations for any configurations and capacities of receiving hoppers, when using burden of different quality (type of material) and with different physical and mechanical (grain size composition, friction coefficients, and others) parameters, and any burden charging systems of modern blast furnaces. This method can be successfully applied in modernizing automated blast furnace charging control systems, which will increase the efficiency of blast-furnace smelting and make it easier for process personnel to make decisions.

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Параметри випуску шихтових матеріалів із бункерів безконусних завантажувальних пристроїв доменної печі

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Мета. Встановити адекватність математичного опису процесу витікання шихтових матеріалів із накопичувального бункера безконусного завантажувального пристрою доменної печі результатами натурного моделювання досліджуваного процесу.

Методика. У роботі використано натурне моделювання механічних систем на основі критерію подібності Ньютона. Проведені експериментальні дослідження процесу витікання шихтових матеріалів на моделі накопичувального бункера безконусного завантажувального пристрою доменної печі, виконаної в масштабі 1 : 10,6. Адекватність теоретично розрахованих об'ємних витрат шихти оцінювали їх зіставленням з результатами натурного моделювання.

Результати. Експериментально й теоретично для різних ступенів відкриття шихтового затвора визначена об'ємна витрата шихти. Встановлено, що зміна кута відкриття шихтового затвора на моделі бункера завантажувального пристрою в межах від 0 до 1 радіана призводить до збільшення об'ємної витрати шихти від 0 до 0,0014 $м^3$/с за збереження

вільно-дисперсного характеру руху. Виявлено комплексний вплив гранулометричних характеристик шихтового матеріалу й геометричних параметрів випускної частини бункера на об'ємну витрату шихтових матеріалів з бункера. Розроблені емпіричні залежності витрати для агломерату й коксу модельного розміру. На основі отриманих результатів зроблено висновок щодо адекватності математичного опису процесу витікання шихтових матеріалів із накопичувального бункера безконусного завантажувального пристрою доменної печі результатам натурного моделювання досліджуваного процесу.

Наукова новизна. Уперше встановлені комплексні залежності витрати шихти від кута відкриття шиберного затвора, форми випускної частини бункера, розміру шихти, відповідно до яких витрата зростає при збільшенні кута відкриття шибера, зменшенні еквівалентного діаметра (середніх розмірів) частинок шихтових матеріалів, кута нахилу випускної частини бункера.

Практична значимість. Отримані результати можуть бути використані для визначення технологічних параметрів завантаження сучасної доменної печі в різних сировинних умовах. Це дозволить збільшити ступінь автоматизації системи шихтоподачі, що призведе до більш ефективного використання дорогих шихтових матеріалів, зниження споживання енергоресурсів і зниження шкідливого впливу на навколишнє середовище. Сформульовані рекомендації щодо вибору розмірів моделі елементів систем завантаження доменної печі та шихти для моделювання. Це дозволяє моделювати будь-який агрегат системи шихтоподачі печі як механічну систему.

Ключові слова: *доменна піч, завантажувальний пристрій, бункер, структурно-механічні зони, шихтовий затвор*

Параметры истечения шихтовых материалов из бункеров бесконусных загрузочных устройств доменной печи

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Цель. Установить адекватность математического описания процесса истечения шихтовых материалов из накопительного бункера бесконусного загрузочного устройства доменной печи результатами натурного моделирования исследуемого процесса.

Методика. В работе использовано натурное моделирование механических систем на основе критерия подобия Ньютона. Проведены экспериментальные исследования процесса истечения шихтовых материалов на модели накопительного бункера бесконусного загрузочного устройства доменной печи, выполненной в масштабе 1 : 10,6. Адекватность теоретически рассчитанных объемных расходов шихты оценивали их сопоставлением с результатами натурного моделирования.

Результаты. Экспериментально и теоретически для различных степеней открытия шихтового затвора определен объемный расход шихты. Установлено, что изменение угла открытия шихтового затвора на модели бункера загрузочного устройства в пределах от 0 до 1 радиана приводит к увеличению объемного расхода шихты от 0 до 0,0014 м^3/с при сохранении свободно-дисперсного характера движения. Выявлено комплексное влияние гранулометрических характеристик шихтового материала и геометрических параметров выпускной части бункера на объемный расход шихтовых материалов из бункера. Разработаны эмпирические зависимости расхода для агломерата и кокса модельного размера. На основе полученных результатов сделан вывод об адекватности математического описания процесса истечения шихтовых материалов из накопительного бункера бесконусного загрузочного устройства доменной печи результатам натурного моделирования исследуемого процесса.

Научная новизна. Впервые установлены комплексные зависимости расхода шихты от угла открытия шиберного затвора, формы выпускной части бункера, размера шихты, в соответствии с которыми расход возрастает при увеличении угла открытия шибера, уменьшении эквивалентного диаметра (средних размеров) частиц шихтовых материалов, угла наклона выпускной части бункера.

Практическая значимость. Полученные результаты могут быть использованы для определения технологических параметров загрузки современной доменной печи в различных сырьевых условиях. Это позволит увеличить степень автоматизации системы шихтоподачи, что приведет к более эффективному использованию дорогостоящих шихтовых материалов, снижению потребления энергоресурсов и снижению вредного воздействия на окружающую среду. Сформулированы рекомендации по выбору размеров модели элементов систем загрузки доменной печи и шихты для моделирования. Это позволяет моделировать любой агрегат системы шихтоподачи печи как механическую систему.

Ключевые слова: *доменная печь, загрузочное устройство, бункер, структурно-механические зоны, шихтовый затвор*

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