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INTEGRATED STUDY OF THE EFFICIENCY OF GRINDING MATERIAL IN AN IMPACT-CENTRIFUGAL MILL

Abstract. The analysis of existing methods of air classification of crushed bulk materials is carried out, priority directions of their development and improvement are identified, the hardware design of these methods and the main approaches to the calculation of air classifiers are studied. The conclusion is made about a rather isolated motion of particles in the working volume of the classifier at optimal performance. The prospects of dry separation methods and the progressiveness of creating multistage gravitational classifiers have been established. Theoretical studies of the separation process in a gravity classifier with overflow shelves have been carried out. The regularities of the process of separation of bulk materials in air classifiers have been established, reliable methods have been developed for calculating their technological and design parameters in order to create highly efficient and productive industrial plants. Theoretical dependencies and differential equations are obtained, which characterize the influence on the separation mechanism of technological and design parameters of the classifier. The results of solving the equations of motion made it possible to determine the main design parameters of the apparatus based on the technological requirements for productivity and the dispersed composition of the final products. On the basis of theoretical research, analytical relationships and differential equations have been developed that describe the separation process in a gravity classifier with overflow shelves. The use of these equations made it possible to simulate the air flow in the classifier, to obtain a field of air flow velocities for any design and technological parameters. This, in turn, shows the direction of movement of particles of different sizes or densities and makes it possible to estimate the boundary size of separation, and also allows you to study the interaction of the air flow with the material being separated in a wide range of technological and design parameters of the classifier, and, ultimately, to determine the boundary size separation and particle size range of the resulting fractions of the finished product. The relationship between technological and design parameters of the apparatus is theoretically determined.

Key words: material, crushing, particle, classification, device, fraction, hydrodynamics, gravitation, flowability, flow.

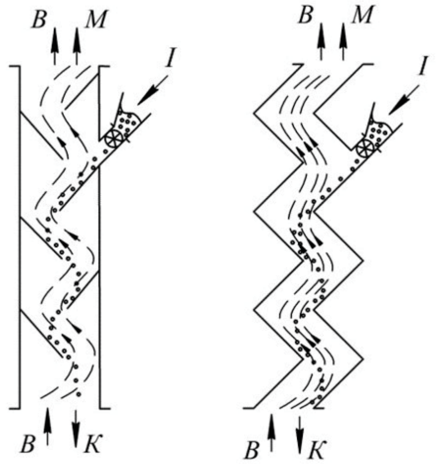
1. Introduction. Modern production places high demands on the quality of powdered materials, at the same time the imperfection of crushing processes does not always allow to obtain a product with desired properties. Therefore, in technological processes for preparation of bulk materials, especially in crushing systems, special devices are often needed – classifiers or separators. The main purpose of the classifier is to divide the material passing through it into two or more fractions with the predominant content in each fraction of particles of the required size or density range.

More progressive are dry methods of separation, carried out, most often, in devices with air flows or, if necessary, flows of inert, flue or other gases. The tendency of transition to the dry methods of production in many branches of domestic and foreign industry shows the promise of air classification.

To obtain dry powders of a given granulometric composition with a particle size of about 1 mm or less, the air classification is the main of all known sorting methods. Currently, various designs of air classifiers are exploited in industry, however most of them are characterized by low efficiency and low, about 60 – 70%, degree of extraction of the target product from polydisperse powder. The low degree of extraction of the target product often adversely affects other technological processes. For example, when crushing the material in mills operating in a closed cycle, due to the low efficiency of the classifier, the finished product is sent to grinding again, which leads to decrease in productivity and high energy consumption of the mill unit.

Therefore, the establishment of regularities in the process of separation of bulk materials in the air classifiers, the development of reliable methods for calculating their technological and design parameters in order to create highly efficient and productive industrial installations is a very urgent task for many industries.

2. Literature data analysis and problem definition. Currently, the most common are air gravitational classifiers with transfer shelves (Fig. 1, a) and Zigzag classifiers (Fig. 1, b) [1, 2].



a – classifier with transfer shelves;
b – Zigzag classifier.

Fig. 1. Schemes of multistage gravitational classifiers

Many researchers were engaged in the creation of multistage gravitational classifiers, the literature presents experimental data and results of industrial operation of many structures of this type, indicating their high efficiency [1-6]. At the same time, the results of theoretical studies do not allow to fully calculate such devices. As a rule, calculation methods are tied to a specific technological process or a product of the same type [4, 5]. This hinders the introduction of cascade and shelf classifiers in other technologies and indicates the relevance of research in this direction.

Deterministic and stochastic models are among the main approaches to modeling and calculating the aerodynamic classification.

The stochastic models are based on the use of probability theory to calculate the dynamics of material flow. The most significant results in this direction were obtained by M.D. Barsky [1] and S.G. Ushakov [6] in the study of gravitational and centrifugal classifiers. By now, the stochastic models were further developed in the works of many scientists [5, 7, 8], and various approaches to modeling the classification of disperse systems were developed. One of the promising approaches is an approach based on the theory of Markov chains, which was used in the works of Yu.I. Makarov [9-11], and is now widely used in modeling many physicochemical processes [7]. The main advantage of the stochastic models is to obtain formulas for constructing a separation curve (Tromp curve), which reflects the probability of a particle of a certain size falling into a large or small product and is the main technological characteristic of the classifier [1].

The deterministic models are based on differential equations of the granular medium motion in a carrying flow. Some researchers consider this direction unpromising due to the many assumptions made in modeling [7]. The most significant of them are that, firstly, the particle moves under the action of not only deterministic, but also numerous random forces (collision, turbulence, etc.), which are difficult to take into account even in a generalized form, and secondly, the constraint of particle motion is not taken into account [7]. However, many believe that these assumptions are not critical in creating engineering methods for calculating real structures, when the model is presented not only with requirements for accuracy and reliability, but also for availability of use for a wide range of specialists of the relevant profile [4, 5, 12-14]. For example, experimental data indicate an effective classification with a mass ratio of solid and gas phase of approximately 1:1 [2]. Taking into account the difference in densities, it can be concluded that particles are quite separate in the working volume of the classifier with optimal performance. In addition, the deterministic models allow, based on the analysis of the results of solving the equations of motion, to determine many design parameters of the devices, based on the technological requirements for performance and dispersion composition of the final products. Therefore, methods of deterministic modeling are common and evolving at present, the same approach was used in the theoretical study of the multistage shelf classifier design.

3. Research objectives and tasks. The objective of the work is to study the process of fractionation of crushed material in the gravitational classifier.

To achieve this objective, it is necessary to solve the following tasks:

- simulate the motion of a continuous carrying medium in the device;
- investigate the interaction of the air flow with particles of the material to be separated;
- based on the obtained data, determine the patterns of motion of these particles and the possibility of their falling into a small or large fraction.

4. Methods of modeling the process of fractionation of crushed material in the gravitational classifier. To model the motion of air in the classifier, the Navier – Stokes equation was used for viscous media, which is written in the vector form as

$$\rho\ dc/dt=M-\mathrm{grad}p+\mu\Delta c, \qquad 1)$$

where ρ – density of the medium, kg/m^3; c – velocity vector; M – vector of bulk forces; p – pressure, Pa; μ – dynamic viscosity, Pa · s; Δ – Laplace operator.

The Navier – Stokes equation was supplemented with the flow continuity equation

$$\partial\rho/\partial t+\mathrm{div}(\rho\bar{c})=0, \qquad 2)$$

and the equation of state

$$\rho=pM/RT, \qquad 3)$$

where M – molar gas mass, g/mole; R – universal gas constant; T – absolute temperature, K.

Since direct numerical simulation in solving equations (1) - (3) requires substantial time resources in calculating turbulent flows, there was used the standard turbulence model k-ε [15-17]. Here, the Navier – Stokes equation is transformed into a form in which the influence of the average velocity fluctuation (in the form of turbulent kinetic energy) and the process of reducing this fluctuation due to viscosity (dissipation) are added.

In the adopted model, the viscous shear stress tensor is defined as [18–19]

$$\tau_{ij}=\mu\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}-\frac{2}{3}\frac{\partial u_k}{\partial x_k}\delta_{ij}\right)-\frac{2}{3}\rho k\delta_{ij}, \quad (4)$$

where μ – dynamic viscosity, Pa · s; u – velocity, m/s; x – coordinate, m;   – Kronecker delta function; k – turbulent kinetic energy.

The dynamic viscosity μ is calculated as the sum of the coefficients of dynamic viscosity μl and turbulent viscosity μt.

The coefficient of turbulent viscosity is calculated by the dependence [10]

$$\mu_t=f_\mu\frac{C_\mu\rho k^2}{\varepsilon}, \qquad (5)$$

where fμ, Cμ – coefficients; ε – turbulence energy dissipation.

Cμ coefficient is recommended to be taken equal to 0.9 [18]. fμ coefficient is found by the formula

$$f_\mu=\left(1-e^{-0{,}025R_y}\right)^2\left(1+\frac{20{,}5}{R_T}\right), \quad (6)$$

where R_y, R_T- variables defined by the expressions

$$R_y=\frac{\rho\sqrt{k}y}{\mu_l}, \quad R_T=\frac{\rho k^2}{\mu_l\varepsilon}, \quad (7)$$

where y – distance from the local averaged flow volume to the wall of the computational domain, m.

The turbulent kinetic energy k and the dissipation of this energy ε are found by solving two equations:

$$\frac{\partial\rho k}{\partial t}+\frac{\partial}{\partial x_k}(\rho u_k k)=\frac{\partial}{\partial x_k}\left(\left(\mu_l+\frac{\mu_l}{\sigma_k}\right)\frac{\partial k}{\partial x_k}\right)+S_k, \quad (8)$$

$$\frac{\partial\rho\varepsilon}{\partial t}+\frac{\partial}{\partial x_k}(\rho u_k\varepsilon)=\frac{\partial}{\partial x_k}\left(\left(\mu_l+\frac{\mu_l}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_k}\right)+S_\varepsilon, \quad (9)$$

where S_k, S_ε- characteristics of the kinetic energy pulsations and dissipation of this energy, calculated by the expressions:

$$S_k=\tau_{ij}\frac{\partial u_i}{\partial x_j}-\rho\varepsilon-\mu_l\left(\frac{g_i\partial\rho}{\sigma_B\rho\partial x_i}\right), \quad (10)$$

$$S_\varepsilon=C_{\varepsilon1}\frac{\varepsilon}{k}\left(f_1\tau_{ij}\frac{\partial u_i}{\partial x_j}+\mu_l C_B\left(\frac{g_i\partial\rho}{\sigma_B\rho\partial x_i}\right)\right)-C_{\varepsilon2}f_2\frac{\rho\varepsilon^2}{k}, \quad (11)$$

where $C_{\varepsilon1}$=1,44, $C_{\varepsilon2}$=1,92, σ_ε=1,3, σ_k=1 – empiric coefficients; *f1, f2* – variables depending on the coefficients of dynamic and turbulent viscosity, determined by the following formulas:

$$f_1=1+\left(\frac{0{,}05}{f_\mu}\right)^3, \quad f_2=1-e^{-R_T^2}. \quad (12)$$

Using the above equations allows to simulate the air flow in the classifier, to obtain the air flow velocity field with any design and technological parameters.

5. The results of computer experiment based on mathematical models. The equations obtained were solved using computational hydrodynamics in the SWFlowSimulation software [18]. One of the typical air flow patterns is shown in Fig. 2.

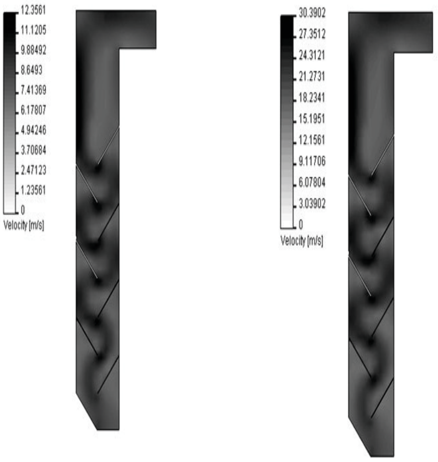
To study the motion of particles of the material along inclined shelf of the classifier, a design scheme was drawn up (Fig. 3).

The following basic forces act on the particle moving along the inclined shelf.

The force of gravity

$$G=mg, \quad (13)$$

where m-mass of the particle, kg; g-free fall acceleration, m/s^2.



a) b)

a) – air velocity per classifier section 2 m/s;

b) – air velocity per classifier section 5 m/s

Fig. 2. Air flow velocity profiles in the shelf classifier

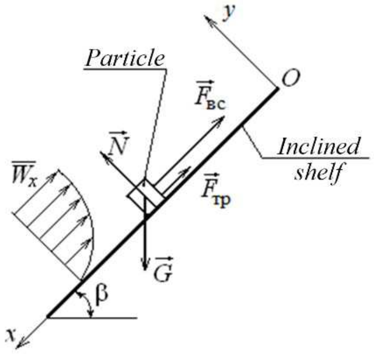


Fig. 3. Scheme of forces acting on the particle locatedon the inclined shelf classifier

The force of friction

$$F_{тр} = fN, \quad (14)$$

where f- coefficient of friction of the particles on the blade surface; N-supporting force, H.

The supporting force N is equal in our case, based on the condition of non-motion with respect to the axis y (Fig. 4), to the expression

$$N = G\cos\beta. \quad (15)$$

The force of aerodynamic resistance to the motion of the particle from the medium is determined by the dependence

$$F_{BC} = \xi S \frac{v_{rel}^2}{2} \rho_g, \quad (16)$$

where ξ – aerodynamic resistance coefficient; S – midsection of the particle, m2; v_rel– relative velocity (ambient velocity of the particle with the flow), m/s; ρ_g– gas (air) density, kg/m3.

The relative velocity v_relcan be found as the difference between the velocities of the particle along the inclined shelf and the air flow (Fig. 4):

$$v_{rel} = \frac{dx}{dt} - W_x, \quad (17)$$

where W_x- air velocity around the particle, m/s.

In the turbulent flow regime, the gas velocities profile in the channels with a sufficiently high accuracy is described by the dependence

$$\frac{W_x}{W_{max}} = \left(\frac{y}{R}\right)^{\frac{1}{7}}, \quad (18)$$

where W_max - maximum velocity on the channel axis, m/s; y – current coordinate (Fig. 2), m; R – conditional radius of the channel, m.

The maximum velocity along the channel axis, i.e. with y=R is determined by the expression

$$W_{av} = 0{,}85W_{max}, \quad (19)$$

where W_av - average gas velocity along the channel section, m/s, is calculated as the ratio of the gas flow to the cross sectional area of the channel.

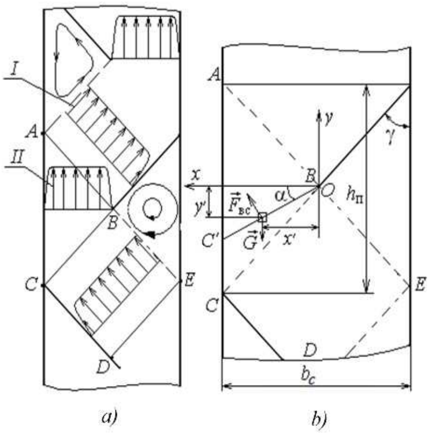
Thus, the equation for the particle motion along the inclined shelf surface relative to the axis x can be written as

$$\frac{d^2x}{dt^2} = g(1 - f\cos\beta) - \xi S \frac{v_{rel}^2}{2m} \rho_g. \quad (20)$$

The equation (20) was solved by the numerical method in the mathematical package Matlab 6.0 [20]. The obtained data on the velocity of the material particles' falling from the inclined shelf, depending on their properties, size, shelf length, were used as initial conditions for subsequent equations of motion.

At the second stage of calculations using the scheme shown in Fig. 4, the material particles' motion in the upward air flow was considered.

The material's particle after its separation from the inclined shelf is affected by two main forces: the force of gravity, constant in magnitude and direction, and the air resistance force.



a – air motion scheme; b – scheme of forces acting on the material particle

Fig. 4. Motion of the material particles and air flow in the classifier's space

In the course of the air motion between the inclined shelves, two characteristic sections can be distinguished: section I, limited with BCDE contour, where the average velocity and direction of the air motion are constant (Fig. 4, a); and section II, limited with ABC contour, where the air flow turns around 90° (Fig. 4, a) and during this turn the average air velocity constantly changes, since the free section area changes.

Note that in the classifier construction under the study, the working columns have a square shape, and the inclined shelves overlap a half of the cross section. Such a design allows to obtain the highest quality separation, as evidenced by the experimental studies [1].

In the fixed coordinate system Oxy, the equations of the particle motion can be written as

$$m\frac{d^2x}{dt^2} = (F_{BC})_x,$$
$$m\frac{d^2y}{dt^2} = (F_{BC})_y - m \cdot g, \quad (21)$$

where (F_"вс")_x,(F_"вс")_y– projections of the air resistance force on the coordinate axis.

The projections of the air resistance force on the coordinate axis are determined from the expressions

$$(F_{вс})_x = \xi S \frac{(v_{rel})_x v_{rel}}{2} \rho_g,$$

$$(F_{вс})_y = \xi S \frac{(v_{rel})_y v_{rel}}{2} \cdot \rho_g. \quad (22)$$

Based on this equation of motion, the material particles in section I (Fig. 3, a) will be written as

$$\frac{d^2x}{dt^2} = \xi S \frac{(v_{rel})_x v_{rel}}{2m} \rho_{г},$$

$$\frac{d^2y}{dt^2} = \xi S \frac{(v_{rel})_y v_{rel}}{2m} \cdot \rho_{г} - g. \quad (23)$$

The projections of the relative velocity with (9) will be equal

$$(v_{rel})_x = \frac{2Q \sin\gamma \cos\ \gamma}{b_c^2} - \frac{dx}{dt},$$

$$(v_{rel})_y = \frac{2Q \sin^2\gamma}{b_c^2} - \frac{dy}{dt}. \quad (24)$$

The full magnitude of the relative velocity

$$v_{rel} = \sqrt{\left(\frac{2Q \sin\gamma \cos\ \gamma}{b_c^2} - \frac{dx}{dt}\right)^2 + \left(\frac{2Q \sin^2\gamma}{b_c^2} - \frac{dy}{dt}\right)^2} \quad (25)$$

If the material particle is carried away by the air flow to section II (ABC contour, Fig. 5, a), then its motion is calculated using the same differential equations (23), which are supplemented by the dependence, taking into account the flow turn

$$\alpha = \mathrm{arctg}\left(\frac{y^{\square}}{x^{\square}}\right) \quad (26)$$

The empiric relationship was used to calculate the aerodynamic resistance coefficient ξ over the entire range of Reynolds numbers [10]

$$\xi = 0{,}386 \cdot 1{,}325^{\left(lg\, Re_{\square}^{2} - 3{,}87\right)^2}. \quad (27)$$

The solution of the obtained equations by the numerical methods using previously established data on the distribution of the air flow velocities allows to simulate the material particles' motion in the classifier's working area with its various technological and design parameters. This, in turn, shows direction of motion of particles of different size or density and makes it possible to estimate the boundary size of the separation.

6. Discussion of the research results. Based on the performed modeling, it was possible to determine the zigzagging of air motion in the classifier, which allows to make a conclusion about a diverse cross-flow classification. In addition, it was found that, unlike the average flow velocity, its value in the core of the flow is several times higher, and, consequently, a higher intensity of impact on the incoming material.

The initial polydisperse material is fed, as a rule, into the middle part of the classifier to the supply shelf. In this case, the material particles move along the inclined shelf, then fall into the upward air flow and, depending on various factors, either fall onto the underlying shelf or are carried up with the air. Thus, the material particles' motion was studied in two stages: at the first, the material particles' motion along the inclined shelf was studied, and at the second, the particles' motion in the air flow before contact with the next shelf (according to the scheme in Fig. 1, a). The results of the first stage of research were the initial conditions for the next stage and so on up to the border of the classifier's working area.

The results of the study of the air flow interaction with the material particles to be divided and determination of the regularity of motion of these particles possibly falling into the fine or coarse fraction, carried out by the calculation hydrodynamics methods, based on the results obtained on the distribution of the air flow velocities, allowed to simulate the particles' motion in the classifier taking into account various technological and design parameters. The data obtained allow to determine the direction of motion of particles of both different size and density, which, in turn, makes it possible to estimate the boundary size of the separation.

It should be noted that the research results will also be valid for Zigzag type classifiers, since the mechanism of motion of the upward air flow and its interaction with the material particles is similar to that observed in classifiers with the transfer shelves.

6. Conclusions. 1. The study of the process of fractionation of the crushed material in the gravitational classifier using the simulation method allows to describe the air flow in the classifier using equations, to obtain the air flow velocity field for any design and technological parameters.

2. In the course of the research, the equations of the material particles' motion in the air classifier with the transfer shelves were developed, which solution using computer numerical methods allows to investigate the interaction of the air flow with the material to be divided in a wide range of technological and design parameters of the classifier, and, ultimately, to determine the boundary size of the separation and the particle size range of the finished product's resulting fractions.

3. The modeling showed that in the classifier the air moves in a zigzag manner, therefore, there is a multiple cross flow classification. The velocity in the core of the flow can be many times higher than the average flow velocity, which allows to intensively affect the source material.

4. Solving the obtained equations of the material particle's motion in the classifier and the aerodynamic resistance coefficient by the numerical methods using the obtained data on the distribution of the air flow velocities, allows to simulate the material particles' motion in the working area of the classifier with its various technological and design parameters. The information obtained makes it possible to determine the direction of motion of particles of different size or density, as well as to estimate the boundary size of the separation.

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ГРАВИТАЦИЯЛЫҚ ЖІКТЕУІШТЕ ҰСАҚТАЛҒАН МАТЕРИАЛДЫ ФРАКЦИЯЛАУ ПРОЦЕСІН МОДЕЛЬДЕУ

Аннотация. Ұсақталған сусымалы материалдарды әуеде жіктеудің қолданыстағы әдістеріне талдау жасалады, оларды дамыту мен жетілдірудің басым бағыттары анықталады, осы әдістердің аппараттық рәсімделуі және ауа жіктеуіштерін есептеудің негізгі тәсілдері зерттеледі. Қорытынды оңтайлы өнімділік кезінде жіктеуіштің жұмыс көлеміндегі бөлшектердің жеткілікті оқшауланған қозғалысы туралы жасалады. Құрғақ бөлу әдістерінің болашағы және көп сатылы гравитациялық жіктеуіштерді құрудың прогрессивтілігі анықталды. Толтырғыштары бар гравитациялық жіктеуіштерді бөлу процесінің теориялық зерттеулері жүргізілді. Ауаның жіктеуіштерінде сусымалы материалдарды бөлу процесінің заңдылықтары анықталды, жоғары тиімді және өнімді өндірістік кәсіпорындар құру үшін олардың технологиялық және жобалық параметрлерін есептеудің сенімді әдістері жасалды. Жіктеуіштің технологиялық және есептік параметрлерінің бөлу механизміне әсерін сипаттайтын теориялық тәуелділіктер мен дифференциалдық теңдеулер алынады. Қозғалыс теңдеулерін шешу нәтижелері өнімділікке технологиялық талаптарға және соңғы өнімдердің дисперсті құрамына сүйене отырып, аппараттың негізгі құрылымдық параметрлерін анықтауға мүмкіндік берді. Теориялық зерттеулер негізінде толып жатқан сөрелер мен ауырлық күшін жіктеуіште бөлу процесін сипаттайтын аналитикалық байланыстар мен дифференциалдық теңдеулер жасалды. Осы теңдеулерді қолдану жіктеуіштегі ауа ағынын модельдеуге, кез-келген жобалық және технологиялық параметрлерге ауа ағынының жылдамдықтарының өрісін алуға мүмкіндік берді. Бұл өз кезегінде әртүрлі көлемдегі немесе тығыздықтағы бөлшектердің қозғалу бағытын көрсетеді және бөлінудің шекара өлшемін бағалауға мүмкіндік береді, сонымен қатар ауа ағынының кең ауқымында бөлініп жатқан материал мен өзара әрекеттесуін зерттеуге мүмкіндік береді. Аппараттың технологиялық және жобалық параметрлерінің ара қатынасы теориялық тұрғыдан анықталған.

Түйін сөздер: материал, ұсақтау, бөлшек, жіктеу, аппарат, фракция, гидродинамика, ауырлық күші, ағындылық, ағын.

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МОДЕЛИРОВАНИЕ ПРОЦЕССА ФРАКЦИОНИРОВАНИЯ ИЗМЕЛЬЧЕННОГО МАТЕРИАЛА В ГРАВИТАЦИОННОМ КЛАССИФИКАТОРЕ

Аннотация. Проведен анализ существующих способов воздушной классификации измельченных сыпучих материалов, выявлены приоритетные направления их развития и совершенствования, изучено аппаратурное оформление этих способов и основные подходы к расчетам воздушных классификаторов. Сделан вывод о достаточно обособленном движении частиц в рабочем объеме классификатора при оптимальной производительности. Установлена перспективность сухих способов разделения и прогрессивность создания многокаскадных гравитационных классификаторов. Выполнены теоретические исследования процесса разделения в гравитационном классификаторе с пересыпными полками. Установлены закономерности процесса разделения сыпучих материалов в воздушных классификаторах, разработаны надежные методики расчета их технологических и конструктивных параметров с целью создания высокоэффективных и производительных промышленных установок. Получены теоретические зависимости и дифференциальные уравнения, характеризующие влияние на механизм разделения технологических и конструктивных параметров классификатора. Результаты решения уравнений движения позволили определить основные конструктивные параметры аппаратов исходя из технологических требований к производительности и дисперсному составу конечных продуктов. На основании теоретических исследований разработаны аналитические зависимости и дифференциальные уравнения, описывающие процесс разделения в гравитационном классификаторе с пересыпными полками. Использование данных уравнений позволило смоделировать течение воздуха в классификаторе, получить поле скоростей воздушного потока при любых конструктивных и технологических параметрах. Это, в свою очередь, показывает направление движения частиц различного размера или плотности и дает возможность оценить граничный размер разделения, а также позволяет исследовать взаимодействие воздушного потока с разделяемым материалом в широком диапазоне технологических и конструктивных параметров классификатора, и, в конечном итоге, определить граничный размер разделения и диапазон размеров частиц получаемых фракций готового продукта. Теоретически определена взаимосвязь технологических и конструктивных параметров аппарата.

Ключевые слова: материал, измельчение, частица, классификация, аппарат, фракция, гидродинамика, гравитация, сыпучесть, поток.

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