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DESIGN OF A SHELF PNEUMATIC CLASSIFIER FOR SEPARATING A POLYDISPERSE MIXTURE OF GRANULATED SUPERPHOSPHATE

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The object of this study is a polydisperse mixture of granular superphosphate. It is emphasized that existing technologies of granulation and processing of granules lead to the formation of dusty fractions of small particles. The content of small fractions in the finished product should be minimal and, in connection with this problem, the task is to remove small particles from the mixture. The purpose of the current experimental study is to classify a polydisperse mixture of granular superphosphate in a pneumatic classifier. The device includes an inclined perforated shelf with an unloading space between its end and the wall of the apparatus. It has been experimentally revealed that the maximum efficiency of extraction into the entrainment of small particles is achieved with a width of the discharge space equal to 0.5 of the length of the cross-sectional side of the apparatus; the degree of perforation of the shelf is 5 %; the angle of inclination of the shelf is 25–30°; the speed of the gas flow in the free section of the apparatus is 3.7 m/s. It is shown that the degree of extraction into the entrainment of a small fraction less than 1 mm in size reaches 70–75 %, the content of the small fraction in the carry-over is 96–98 %, and the large fraction is less than 5 %. By processing experimental data, an empirical equation was built that makes it possible to determine the concentration of particles in the gas stream for individual fractions of the material. It is shown that due to the implementation of an active aerodynamic weighing mode, the shelf pneumatic classifier works at specific loads for air flow rate less than the typical designs of fluidized bed separators. It is noted that the effective operation of the shelf pneumatic classifier in the production of granular mineral fertilizers is ensured at a productivity of no more than 10–12 t/h. With greater productivity, there is a need to install several devices in the technological line

Keywords: granular fertilizers, pneumatic classifier, energy consumption, energy efficiency, fine fraction, carryover, energy saving

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1. Introduction

One of the important areas of the chemical industry is the production of granular phosphate fertilizers. Among phosphate fertilizers, various types of granular superphosphates, ammophos, and other complex fertilizers are in high demand by consumers [1, 2].

Technological operations of obtaining granular fertilizers lead to the formation of a product of polydisperse granulometric composition. At the same time, the consumer's requirements for this indicator are quite stringent: the commercial fraction with a granule size of 1–4 mm should be at least 85–90 %, and fractions less than 1 mm – no more than 5 %.

The granulation methods used do not guarantee the production of a product with a specified range of granule sizes. Therefore, any technological line must be equipped with equipment that would limit the granulometric composition. Such equipment includes classifiers and crushers. They should enable the return of large fractions of more than 4 mm for crushing and extraction of small fractions less than 1 mm [3].

To separate granules by size in modern technologies, mechanical classification on screens is used. The most common is mechanical separation. The polydisperse mixture is divided on vibrating screens, thus separating the fraction of more than 4 mm on the upper sieve, and less than 1 mm on the lower one [4]. However, superphosphate granules have a sufficiently high temperature at the outlet of the granulator (about 90 °C), they are prone to agglomeration and adhesion. Therefore, the fine fraction clogs the cells of the lower sieve while reducing the passage section of the holes. This leads to a deterioration in the sifting capacity of the lower sieve. As a result, the fraction content of less than 1 mm in the material is overestimated, which does not meet the requirements for the quality indicators of the finished product. The operational reliability of the screen is also degraded as it must stop to clean the surface of the lower sieve. To partially solve this problem, additional mechanical screens are installed after the fluidized bed coolers. However, this approach complicates the technological scheme and leads to an increase in energy costs for production.

A rational way to solve this problem is to use pneumatic classification in order to remove small fractions from the granular material. The pneumatic classifier is installed after the granulator, which makes it possible to eliminate the need for a mechanical screen in the lower sieve and, accordingly, to avoid the above shortcomings.

Therefore, research aimed at designing effective pneumatic classifiers for the separation of a polydisperse mixture of granular mineral fertilizers is relevant.

2. Literature review and problem statement

Under industrial conditions, granular materials are divided into fractions under the influence of gravitational forces in the upward flow of gas [5]. Separation under the action of inertial and centrifugal forces is also used – in air-passage separators, in separators with a closed gas flow, in devices with rotating elements, etc. [6].

Centrifugal pneumatic classifiers are used to separate finely dispersed materials with a particle size of not more than 50–100 µm [7]. For the separation of granular materials with a particle size of 1–4 mm, these classifiers are not suitable since they require increased energy costs for pumping air flow through the working volume of the device.

The simplest pneumatic classifiers of the gravitational type, with vertical channels of free cross-section [8], are not widely used since they do not provide the required separation efficiency. In such devices, the raw materials are loaded from the dispenser into the working volume by a continuous stream of material. This causes an increase in the density of the gas dispersed flow at the dosing site. A dense jet is not broken mechanically since there are no contact devices in the working volume of the device. Therefore, the dosage mixture has poor contact with the gas flow. Thus, a large fraction, falling down, drags the small fraction along with it. This reduces the effectiveness of fractional separation. A diamond-shaped pneumatic classifier was more effective [9]. However, its effectiveness has been proven for finely dispersed materials of fractions less than 1 mm. Therefore, when processing granular materials with large fractions of more than 1 mm, the efficiency of its separation will be significantly reduced.

A further development of such devices were zigzag pneumatic classifiers [10, 11], in which centrifugal forces arise due to turns in the flow of gas, causing the circulation of particles. This effect reduces the density of the gas dispersed flow and therefore increases the efficiency of the classification process. However, the layer of material moving along the inclined walls is not blown by airflow, so zigzag pneumatic classifiers do not provide a sufficiently complete extraction of the fine fraction from the material.

This pneumatic classifier has been modernized and the new design has a vertical channel with a rectangular cross-section, in which solid shelves are installed at an angle to the gas flow [12, 13]. However, solid shelves significantly increase the hydraulic resistance of the device and turbulize the flow, which increases the carryover of a large fraction into the cyclone. The scope of application of these devices is limited to the dedusting of only powdered products.

Pneumatic separators with a fluidized bed are known. Fluidized bed machines are designed mainly for separation of bulk product in order to separate small particles less than 0.5 mm from the suspended layer. To remove larger particles up to 3 mm in size from the fluidized bed, separators with an upper pneumatic transport section are offered [14]. This design requires increased gas consumption, which leads to an increase in energy costs. In separators with a vibro-boiling layer [15], the effect of particle separation is improved due to vibration energy. However, vibration leads to intense movement of particles in the layer, which contributes to unwanted abrasion of the particle surface. Work [16] shows that the pulsating supply of air flow to the layer suspended on the gas distribution grate increases the efficiency of separation. However, the authors of [16] note the importance of selecting the optimal range of pulsation frequency. Therefore, this design requires a complex automation system and a control unit.

Works [17, 18] consider the process of pneumatic separation of a polydisperse granular mixture consisting of three fractions (4.75–8 mm, 8–12.7 mm, 12.7–19.1 mm) by purging the air flow of the granular layer. This makes it possible to separate the product into different fractions. Nevertheless, as indicated in these works, after separation, large fractions are contaminated with small particles, and large particles enter the finely dispersed product. Therefore, the resulting products require additional mechanical sifting after pneumatic classification.

Installation of inclined perforated shelves makes it possible to implement an active aerodynamic mode of weighing the granular layer. Under this mode, the layer is intensively blown by an upward gas flow. Consequently, the efficiency of extraction of small fractions in the entrainment increases, and the energy consumption for the pneumatic classification process is reduced. The apparatus of this design with a cascade of shelves in the upper part has proven useful for the separation of finely dispersed mixtures into several fractions [19]. However, it is intended for the multi-product separation of powdered materials and thus cannot be applied to the processing of granular products. The design of the device with a cascade of perforated shelves in the lower part is proposed as a cooler of granular mineral fertilizers and a dryer for granular materials [20]. Therefore, as a pneumatic classifier, this apparatus cannot provide sufficient efficiency. Therefore, additional research is required to determine the optimal design and mode parameters of the pneumatic classification process in the shelf apparatus.

In view of the need to isolate small fractions in technologies for obtaining granular mineral fertilizers, it is necessary to install a pneumatic classifier after the granulator [21]. As the above review shows, the main designs of pneumatic classifiers are apparatuses of the mine type with a free cross-section (such as a pneumatic pipe) and a fluidized layer. Mine-type devices are characterized by low efficiency of extraction of a fine fraction in the entrainment – no more than 20–25 %. In addition, these devices have a low boundary separation size in the range of 0.05–0.1 mm. For fluidized bed apparatus, the boundary size of the separation is acceptable – in the range of 0.5–1.0 mm. However, the separation efficiency remains quite low – no more than 30–40 %.

Therefore, for these purposes, it is most expedient to use a pneumatic classifier of the shelf type. In the shelf apparatus, the granular product is simultaneously cooled on the lower shelf contacts [22]. At the same time, there is no need to install a separate fluidized bed cooler in the technological scheme. This approach reduces capital and operating costs when obtaining granular fertilizers. In addition, energy consumption at the technological stages is reduced and thereby the energy efficiency of the production of granular mineral fertilizers increases.

To choose a rational design of a pneumatic classifier, it is important to analyze the parameters that affect the process of extracting a fine fraction from a layer of material.

The first studies on the generalization of experimental data on the removal of a small fraction from the layer were reported in works [23–25]. It is postulated that under conditions of equilibrium between the concentrations of small particles in the layer and in the entrainment, the rate of removal of small particles is expressed by the following dependence:

$$\frac{dC}{d\tau} = -k_C C. \quad (1)$$

The rate of removal of small particles from the layer is expressed by the following equation:

$$G_C = k_C G_l C, \quad (2)$$

where C is the concentration of fine particles in the layer, kg/kg; τ is the process time, s; G_y is the rate of entrainment, kg/s; G_l is the mass of the particles in the layer, kg; k_y is the constant of the rate of entrainment, s^{-1}.

The constant of the rate of entrainment k_y depends on a number of parameters as a general function [26–28]:

$$k_C = f\left(w, u_s, Fr, \mathrm{Re}, d, D, H_l, H_s, \rho, \rho_p\right), \quad (3)$$

where w is the operating fluidization rate, m/s; u_s is the velocity of particulate matter in the gas flow, m/s; Fr is Froude's criterion; Re – Reynolds criterion; d – average diameter of solid particles, m; D – diameter of the apparatus, m; H_l, H_s – respectively, the height of the suspended layer and the superlayer (separation) space, m; ρ_p, ρ – respectively, the density of solid particles and gas, kg/m^3.

Paper [25] proposes a modified entrainment constant, which depends on such parameters as the cross-section of the fluidized layer, the height of the superlayer space, and several experimental constants. In works [29, 30], the authors propose to take into account the mass fraction of the fine fraction in the layer when determining the constant of the rate of carryover. In work [31] the authors propose to additionally take into account such a difficult parameter as the speed of particles. In works [32, 33], the dependence of the intensity of the entrainment of small particles on the fluidized layer on the concentration of small particles in the layer, the Froude and Reynolds criteria, the densities of solid particles and gas is postulated.

Analysis of those dependences reveals that due to a number of assumptions they are of a particular nature since the quantities included in the equations are selected only within the specified limits of change under the conditions of a particular experiment.

Thus, a complex type of correlation for determining the amount of entrainment is the cause not only of discrepancies in the results of the calculation but also of the inconsistency of the nature of the dependence of the carry-over on the speed of the gas flow, the diameter of the apparatus, the height of the layer, the separation zone, etc. For this reason, some of the equations have not found practical application in engineering calculations. Obtaining a more practical equation for engineering calculations should be based on the study of the regularities of the entrainment of small particles from a layer suspended by a gas flow on a gas distribution grid.

3. The aim and objectives of the study

The aim of this work is to identify the main regularities of the pneumatic classification process of a polydisperse mixture of mineral fertilizer granules in an apparatus with a shelf perforated contact device. This will make it possible to get a finished product with a granulometric composition in accordance with the requirements of the standard.

To accomplish the aim, the following tasks have been set:

– to build a mathematical model of the kinetics of the entrainment of small fractions from the suspended layer;

– to experimentally substantiate the optimal design parameters of the shelf pneumatic classifier;

– to experimentally identify the patterns of carrying away individual fractions of the material from the suspended layer;

– to propose an empirical equation for determining the number of removable fractions of the material from the suspended layer.

4. The study materials and methods

The object of our study is the process of pneumatic classification of a polydisperse mixture of fertilizer granules, previously obtained by spraying a suspension on the surface of particles in a granulator of a fluidized bed. A feature of the fluidized layer is the effect of separation of particles in different zones of the layer. This phenomenon significantly affects the nature of the granulation process. Separation in the irrigation zone with a suspension of the fluidized layer leads to the predominant growth of individual granules and, therefore, to an increase in the unevenness of the granulometric composition of the layer. This leads to an increased content of small fractions (less than 1 mm in size) in the finished product. Therefore, the main hypothesis of the study is the application of pneumatic classification of granules after their unloading from the granulator and the subsequent supply of retour to the irrigation zone of the granulator. This will increase the uniformity of the granulometric composition of the finished product.

Experimental studies of the pneumatic classification process were carried out in an apparatus with a cross-section of 50×100 mm and a height of up to 1 m together with a separation space. In the working volume of the device, at the level of the input of the source material, a perforated inclined shelf is installed with the formation of an unloading space between the end of the shelf and the wall of the apparatus (Fig. 1).

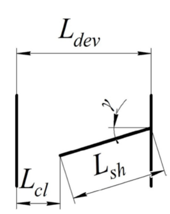

Fig. 1. Basic structural elements of the shelf device

The width of the discharge space is expressed by the ratio L_{cl}/L_{dev}, where L_{cl} is the distance between the end of the shelf and the wall of the device, and L_{dev} is the length of the side of the device. The experiment was carried out at different values of the ratio L_{cl}/L_{dev}=0.15–0.8, the angle of inclination of the shelf within γ=25–30° to the horizontal plane, degrees of perforation of the shelf within ψ=5–30 %. The studies used a polydisperse granular mixture of superphosphate in the form of granules measuring 0.1–5 mm with a shape coefficient of 0.85. The granulometric composition of the polydisperse mixture was determined by sieve analysis using a set of wire sieves with hole sizes (square hole side size): 0.5, 1.0, 1.6, and 2.5 mm. Sieves were folded in the form of a vertical block with decreasing hole sizes from top to bottom and installed on a vibrating table with a control unit. Sieve analysis was carried out within 15–20 minutes, which corresponds to the accuracy of measurements [34]. To assess the accuracy of the measurements performed, several samples were analyzed, according to the methodology in [35]. The deviation of the results for each of the samples did not exceed 1.5–2.0 %. Results of the sieve analysis of the initial polydisperse mixture: +2.5 mm – 10 %; –2.5+1.6 mm – 25 %; –1.6+1 mm – 25 %; –1+0.5 mm – 20 %; – 0.5 mm – 20 %. The true and bulk density of superphosphate granules obtained by rolling in a drum granulator, according to reference data, was taken, respectively, 2250 kg/m^3 and 1100–1200 kg/m^3 [36].

The laboratory installation (Fig. 2) consisted of a pneumatic classifier 2 equipped with a loading hopper 3 with a belt feeder 4 and an unloading hopper 5. There was a centrifugal cyclone 5 with a discharge hopper 7 for capturing small fractions. The high-pressure fan 8 provided air pumping through the apparatus and the cyclone. The air flow rate was regulated and measured by a calibrated manifold with control valve 6. The walls of the device on the front side were transparent for visual observation.

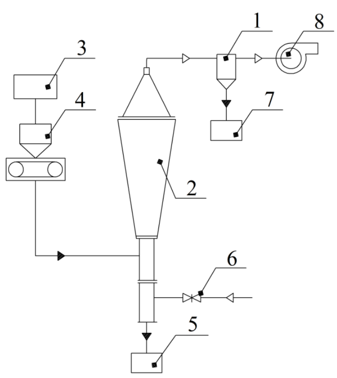

Fig. 2. Diagram of the laboratory installation of pneumatic classification

The initial mixture of granular superphosphate with a weight of 3 kg was weighed on an electronic scale with an accuracy of 0.1 g. Specific productivity for the material was 6–10 kg/(m^2·s). The humidity of the granules was less than 1 % by weight, the temperature of the granules corresponded to the ambient temperature. These conditions do not affect the heat exchange process [37]. The air temperature at the inlet to the device was equal to the air temperature in the laboratory room: under summer conditions, 22–27 °C; under winter conditions, 18–22 °C. The starting material was fed by the feeder to the apparatus, was classified by the air flow, after which a large fraction (particle size more than 1 mm) gravitationally fell down the apparatus and accumulated in the unloading bunker. The fine fraction (particle size less than 1 mm) was carried away by the airflow and captured in the cyclone. When the device operates under stationary conditions (established after 15–20 seconds after switching on the feeder), up to 5–6 samples were taken from the unloading bunkers of the device and the cyclone. In order to eliminate the suction of the outside air during the sampling of the material, the unloading hoppers were made double. Spring-loaded valves were installed on the outgoing pipes of the upper hoppers.

Samples were weighed on an electronic scale with an accuracy of 0.1 g. For sieve analysis, an arithmetic mean value was taken from the weights of the samples taken. To assess the accuracy of the measurements performed, several samples taken during repeated experiments under the same conditions were analyzed. The deviation of the measurement results for each fraction between the samples taken was 1.5–2.0 %. In order to eliminate the influence of random factors on the reliability of the measurement results, six experiments were conducted.

The pressure difference of the device was measured by an alcohol U-shaped manometer, one tube of which was connected to the point of the body under the shelf, and the second – at the outlet of the gas flow after the shelf. The measurement error at the countdown of two levels (on each tube) was ±2 mm at an ambient temperature of 20±5 °C.

The efficiency of separating small particles from the suspended layer was characterized by the degree of extraction of the fine fraction (particle size less than 1 mm) in the entrainment ε_{sm}. This indicator is the ratio of the mass of the fine fraction in the entrainment to its amount in the initial product.

5. Results of studying the process of separation of a polydisperse mixture of granular superphosphate in a shelf pneumatic classifier

5. 1. Construction of a mathematical model of the kinetics of the entrainment of small fractions from a suspended layer

In the separation upper zone of the apparatus of the fluidized or suspended layer, the particles move under a pneumatic transport mode. Their concentration in the stream is a constant value and does not change in height, which slightly exceeds the height of the separation zone. Paper [12] shows the relationship between the averaged concentration of particles in terms of the height of the separation zone and the velocities of the air flow and the hovering of particles. The speed of the air flow determines the intensity of its turbulent effect on the particles, and the rate of hovering takes into account the physical properties of the particles – their size, density, shape, and surface roughness.

Small particles of the material are carried out of the suspended layer into the superlayer space. Further, small fractions of particles are picked up by the gas stream and carried out of the apparatus. Two types of entrainment can be distinguished:

1) kinetic, in which small particles are carried out by a gas stream, provided that the speed of their hovering in the stream is less than the speed of the gas;

2) dynamic (inertial), in which particles are ejected into the superlayer space.

The first type of entrainment is caused by the kinetic energy of the gas flow and is based on the equilibrium ratio of the velocities of particle hovering and the velocities of the gas flow in the superlayer space. If the hovering velocity is greater than the velocity of the gas, the particle will be carried away, if less, it will sink back into the layer. That is, by expanding the separation space from the bottom up and, accordingly, reducing the speed of the gas flow, it is possible to carry out particles of a given size. At the same time, it is possible to predict the quality of the carryover by the size of particles of the fine fraction. This type of entrainment is characteristic of gravitational pneumatic classifiers.

The second type of entrainment is due to the kinetic energy of the particles due to their collision with the walls of the apparatus and the surface of the contact elements, the collision with each other (occurs in gravitational pneumatic classifiers). It is possible to eject particles from the surface of the layer due to the destruction of gas bubbles on the surface of the layer, the destruction of which forms a plume of particles, which by inertia flies into the superlayer space (takes place in the separators of the fluidized layer). In this case, large particles can also be carried away, the hovering velocity of which is greater than the speed of the gas flow. At the same time, the quality of the entrainment decreases since large fractions fall into the entrainment.

The mechanism of carrying away small fractions of material from the layer to the superlayer space is expressed by a differential equation of the following form:

$$\frac{\partial Y_{sm}(\tau)}{\partial \tau} = \left(U_p \operatorname{grad} Y_{sm}\right) + K_y\left(Y^*_{sm} - Y_{sm}(\tau)\right) =$$
$$= \left(U_{px}\frac{\partial Y_{sm}}{\partial x} + U_{py}\frac{\partial Y_{sm}}{\partial y} + U_{pz}\frac{\partial Y_{sm}}{\partial z}\right) - K_y\left(Y^*_{sm} - Y_{sml}(\tau)\right), \quad (4)$$

where U_{px}, U_{py}, U_{pz} is the velocity of the particulate matter relative to the x, y, z, axes, m/s; $Y_{sm}(\tau)$ is the current concentration of fine particles in the gas stream (in the superlayer (separation) space), g/m^3; Y^*_{sm} – boundary concentration of fine fraction particles in the gas flow (in the superlayer (separation) space), g/m^3; $Y_{sml}(\tau)$ is the concentration of fine particles in the layer; τ is time, s; K_y is the constant of the rate of entrainment, s^{-1}.

Given that the carrier pneumatic transport flow in the separation space is directed vertically and the change in the concentration of the fine fraction in the flow also occurs in the vertical plane, we assume:

$$\frac{\partial Y_{sm}}{\partial x} = 0, \quad \frac{\partial Y_{sm}}{\partial y} = 0.$$

Since a continuous process is carried out in industrial apparatuses, then $\partial Y_{sm}(\tau)/\partial \tau = 0$. Consider that the current z coordinate corresponds to the height of the separation space h. Then equation (4) will be written as:

$$U_p \frac{dY_{sm}}{dh} = -K_y\left(Y^*_{sm} - Y_{sml}\right). \quad (5)$$

Equation (5) characterizes the kinetic removal due to the removal of small particles from the layer, the hovering velocity of which is less than the velocity of the gas flow, and dynamic (inertial), due to the kinetic energy of small particles that are carried out from the surface of the suspended layer.

Integrating equation (5):

$$\int_{Y_{sm}}^{Y^*_{sm}} \frac{dY_{sm}}{\left(Y^*_{sm} - Y_{sml}\right)} = -\frac{K_y}{U_p}\int_0^h \mathrm{d}h, \quad (6)$$

we obtain:

$$\ln \frac{Y_{sm}}{\left(Y_{sm} - Y_{sml}\right)} = -\frac{k_C \cdot h}{U_p}, \quad (7)$$

then, by transforming:

$$\lg Y_{sm} = \lg\left(Y^*_{sm} - Y_{sml}\right) - 2.3\frac{k_C \cdot h}{U_p}. \quad (8)$$

The boundary concentration of fine particles in the gas stream Y^*_{sm} corresponds to the limit concentration of particles of this size (Y_{lim}), which can occur in the stream when it is completely «saturated» with suspended particles, that is, $Y^*_{sm} = Y_{lim}$. Ideally, with the complete extraction of small particles from the layer $Y_{sml}=0$. For a stationary section of the separation space, the particle velocity (U_p) is close to the flow rate (w), therefore, in equation (8), $U_p=w$. Then:

$$\lg Y_{sm} = \lg Y^*_{sm} - 2.3\frac{k_C \cdot h}{U_p} = \lg Y_{\lim} - \frac{k}{w}. \quad (9)$$

Replacing $a=lgY_{lim}$ and $k=2.3$ k·h, we obtain an equation for determining the concentration (g/m^3) of particles of a single mono fraction in the gas stream at the outlet of the separation zone of the apparatus:

$$\lg Y_{sm} = a - \frac{b}{w}. \quad (10)$$

In work [12] it is shown that between the constants «a» and «b» in equations (10) and the hovering velocity there are functional relationships in the form of dependences:

$$a = m_1 \cdot 10^{-\left(\frac{n_1}{u_s}\right)}, \quad b = m_2 \cdot u_s^{n_2}, \quad (11)$$

which cannot be expressed by a single equation for the studied interval of change in the magnitude of the velocity of the particles. The reason for this is the complex nature of the phenomena occurring when particles of different sizes interact with turbulent flow in the channels. When the particle size changes, the mode of flow around the particles with the gas flow changes and, consequently, the intensity of turbulization of the boundary layer at the surface of the particles.

5. 2. Experimental substantiation of optimal design parameters for a shelf pneumatic classifier

Fig. 3, *a* shows dependences of the concentration of small particles smaller than 1 mm in size on the width of the discharge space.

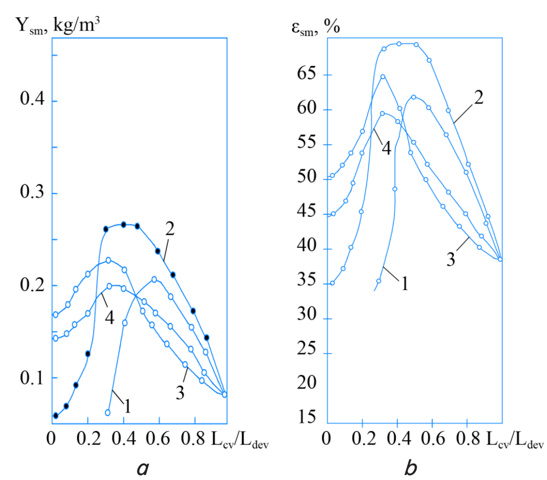

Fig. 3. The influence of the design parameters of the shelf on the carry-away of the fine fraction from the layer: *a* – the dependence of the amount of carryover on the width of the unloading space; *b* – the dependence of the extraction efficiency on the width of the discharge space; the degree of perforation of the shelf: 1–4 – respectively, 0, 5, 15, and 30 %; the angle of inclination of the shelf is 30°; material – granular superphosphate; material consumption – 6 kg/(m^2·s)

Fig. 3, *b* shows the dependences of the efficiency of extraction of a fraction of less than 1 mm per carryover on the width of the discharge space. Each curve corresponds to a certain degree of perforation of the shelf contact.

As the functional dependences show, the maximum values of the indicators are achieved with the width of the discharge space L_{cl}/L_{dev}=0.5 and the degree of perforation ψ=5 %, kg/m^3.

5. 3. Patterns of carrying away of individual fractions of material from a suspended layer

Fig. 4 shows the dependence of the concentration of individual fractions in the entrainment on the speed of the gas flow in the working volume of the apparatus in the form of the function lg$y$=f(1/w). The nature of the dependences confirms the increase in the concentration of particles in the carried-away stream with an increase in the speed of the gas flow in the free section of the apparatus.

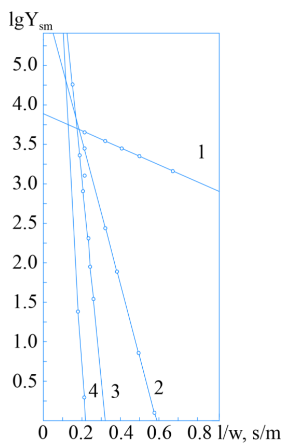

Fig. 4. Dependence of the concentration of particles in the gas stream on the speed of the air flow: 1 – fraction – 0.5 mm; 2 – fraction + 0.5–1 mm; 3 – fraction + 1–1.6 mm; 4 – fraction + 1.6–2.5 mm; material – polydisperse mixture of granular superphosphate; consumption – 6 kg/(m^2·s)

Fig. 5 shows the size distribution curves of superphosphate particles. Dependences show that particles of a certain size have a maximum percentage in the samples analyzed.

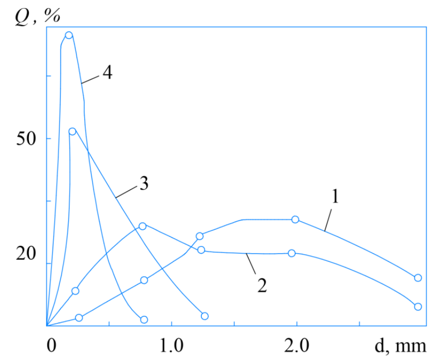

Fig. 5. Distribution curves of superphosphate particles by size: 1 – failure in the shelf pneumatic classifier; 2 – failure in the separator of the fluidized bed; 3 – entrainment in the separator of the fluidized layer; 4 – entrainment in a shelf pneumatic classifier

Table 1 gives experimental and calculated results on the entrainment of fraction particles smaller than 1 mm for various hydrodynamic regimes.

The values of the parameters (Table 1) were obtained in the experimental apparatus during the implementation of various hydrodynamic weighing modes. The active fluidized bed was implemented when installing a horizontal gas distribution grid along the entire cross-section of the apparatus. The inhibited falling layer was realized by installing an inclined perforated shelf (Fig. 1). The free-falling layer was an apparatus with a free cross-section.

5. 4. Empirical equations for determining the concentration of particles in the separation space of the apparatus

The experimental data (Fig. 4) for each fraction were processed in the form of dependences lg y=f(1/w), which correspond to an equation of the following form:

$$\lg y = a - \frac{b}{w}, \qquad (12)$$

where a, b are experimental constants; y is the concentration of particles in the separation space of the apparatus carried by the gas flow, g/m^3; w is the gas flow rate, m/s.

Table 1

Basic parameters of gas dispersed flow

Characteristics of the gas dispersed system (type of apparatus)	Fraction, mm	Cwith flow velocity, m/s	Particle hovering velocity, m/s	Particle concentration in the stream, g/m^3		Constant			
						a		*b*	
				experiment	Ccalculation	eexperiment	ccalculation	experiment	pcalculation
Active fluidized layer (separator)	Less than 1.0	1.89	5.1	124	239	2.50	2.51	0.18	0.24
		2.57		178	261				
		2.8		191	266				
		3.29		198	275				
Inhibited falling layer (shelf pneumatic classifier)	Less than 1.0	1.39	5.1	199	309	2.67	2.73	0.195	0.33
		2.4		331	389				
		3.1		398	417				
		3.7		447	437				
		4.2		501	447				
Free-falling layer (pneumatic pipe with free channel)	Less than 1.0	1.39	5.1	87	263	2.6	2.63	0.19	0.29

The ordinate of the point of intersection of each line with the axis of the ordinate corresponds to the value of the constant *a*, which is the logarithm of the value of the concentration of particles in the stream to which it tends with an increase in the flow rate. The tangent of the angle of inclination of the lines to the abscissa axis is a constant *b*. The values of the experimental and calculated data of the parameters of the gaseous flow are given in Table 1.

Analysis of experimental data showed that there are functional relationships in the form of correlations between the constants *a* and *b* from equation (12) and the rate of hovering:

$$a = m_1 \cdot 10^{-\left(\frac{n_1}{u_s}\right)}, \qquad (13)$$

$$b = m_2 \cdot u_s^{\,n_2}, \qquad (14)$$

where m_1, m_2, n_1, n_2 are experimental constants; u_s is the hovering velocity of particles, m/s.

Having established on the basis of experimental data the values of the constants m_1, m_2, n_1 and n_2 in equations (13) and (14), we come to the formulas:

$$a=3.46\cdot 10^{-\left(\frac{0.25}{u_s}\right)},\ b=0.044\cdot u_s^{2.2},\ \text{at } u_s\leq 5.1 \text{ m/s}, \qquad (15)$$

$$a=10\cdot 10^{-\left(\frac{3.5}{u_s}\right)},\ b=0.07\cdot u_s^{2.2},\ \text{at } u_s>5.1 \text{ m/s}. \qquad (16)$$

(15), (16) are used for the conditions of classification of granular materials in the shelf apparatus.

For the purpose of comparative analysis, experimental studies were conducted on pneumoseparation of a polydisperse mixture of granular superphosphate in the apparatus of the fluidized bed and a pneumotube one. The following formulas apply to these conditions:

$$a=5.0\cdot 10^{-\left(\frac{0.75}{u_s}\right)},\ b=0.15\cdot u_s^{0.51},\ \text{at } u_s\leq 5.1 \text{ m/s}, \qquad (17)$$

$$a=5.1\cdot 10^{-\left(\frac{0.72}{u_s}\right)},\ b=0.18\cdot u_s^{0.53},\ \text{at } u_s\leq 5.1 \text{ m/s}. \qquad (18)$$

Formula (17) is applicable for the conditions of classification of granular materials in the fluidized bed apparatus, and formula (18) is applicable in the pneumotube apparatus.

6. Discussion of results of the study of the regularities of the entrainment of small particles from the suspended layer in the shelf pneumatic classifier

As follows from Fig. 3, the installation of an inclined shelf pneumatic classifier in the working volume has a characteristic effect on the concentration of small particles in the carry-off and the efficiency of fine fraction extraction. The lines of functional dependence have characteristic maxima of these values. At the same time, the amount of small particle entrainment and the efficiency of fine fraction extraction naturally increase with a decrease in the width of the discharge space from L_{cl}/L_{dev}=0.8 to L_{cl}/L_{dev}=0.3–0.5, that is, when the length of the shelf L_{sh} increases (Fig. 1). After reaching the maximum values of these indicators, their values decrease with a further decrease in the width of the discharge space to L_{cl}/L_{dev}=0.15.

As the functional dependences show, the maximum values of the indicators are reached with the width of the discharge space L_{cl}/L_{dev}=0.5 and the degree of perforation ψ=5 %.

In experiments, the operating speed of the gas flow in the free section of the apparatus was maintained in the range of 3.5–3.7 m/s. At these speeds, small fractions of –0.5 mm and +0.5–1 mm from a polydisperse mixture of granular superphosphate are completely removed into the entrainment. At the same time, a large fraction with a particle size of more than 1 mm is practically not carried away.

Sieve analysis for granulometric composition (Fig. 5) showed that in the material removed from the shelf pneumatic classifier, the content of the fine fraction is 96–98 %, and the coarse fraction is less than 5 % (Fig. 5, line 4). The granulometric composition of the fall (Fig. 5, line 1) shows that the commercial product consists of granules 1–4 mm in size. The content of the fine fraction in this product is not more than 5 %, which meets the requirements of the standards for granular fertilizers produced by the industry.

Among the known designs of pneumatic classifiers, fluidized bed separators and pneumatic tube separators have found the greatest application in industry [8, 14–16]. Therefore, it was important to conduct a comparative analysis of these separators with a shelf pneumatic classifier in terms of their effectiveness.

For comparison, experimental studies were carried out during the installation of a failed gas distribution grating in the apparatus, on which the active fluidization mode was implemented. At the same time, a fraction of less than 0.5 mm was mainly present in the entrainment (Fig. 5, line 3), and in the fall (Fig. 5, line 2) there was an increased fraction content of +0.5–1.0 mm. That is, the fluidized bed apparatus mainly works on dedusting the granular material and cannot provide an effective classification.

As follows from the data in Table 1, the concentration of fine particles in the carried away stream for a shelf pneumatic classifier is on average 25–50 % higher than for a fluidized bed separator and a pneumatic tube apparatus. The values of constants *a* and *b* for the modes of fluidized, free, and inhibited falling layers are of the same numerical order. Experimental and calculated values differ from each other by 10 % for the constant *a* and up to 12–28 % for the constant *b*.

Therefore, with a sufficient degree of accuracy for different hydrodynamic modes of weighing particles of the same size, it is possible to offer equations (23) to (26) of approximately the same form. This fact confirms the validity of the proposed hypothesis that the intensity of the removal of small particles depends primarily on the speed of the gas flow and the velocities of the hovering of these particles. Therefore, the conditions for weighing small particles of the same size and shape in layers with the same polydispersity will be similar under various hydrodynamic modes.

In the shelf pneumatic classifier, pulsating unloading of the material is provided during the cyclic flow of the air flow between the perforation of the shelf and the unloading space. This enables intense phase contact. At the same time, a clear classification is provided in shelf pneumatic classifiers at specific loads of 15–20 kg/m^{2}s, which significantly exceeds the specific loads of 0.1–1.5 kg/m^{2}s for fluidized bed separators. Work [38] shows that in the production of granular superphosphate at the stages of pellet processing, energy losses are 5–10 % of the total energy consumption. It has been experimentally proven [22] that for a shelf pneumatic classifier, the specific air flow rate is 0.45–0.6 m^3/kg against 1.1 m^3/kg for fluidized bed separators. Therefore, the use of a shelf pneumatic classifier operating at lower air consumption is one of the directions for the development of energy-saving technologies for obtaining granular fertilizers. The shelf pneumatic classifier is characterized by a boundary separation size of 0.05–7.0 mm at the efficiency of extraction of the fine fraction in the entrainment of 70–80 %. These indicators exceed those similar for typical devices of the fluidized bed and pneumatic tubes.

It should be noted that the proposed empirical equations (12), (15) to (18) depend only on two parameters – the velocities of the gas flow and the hovering of particles. These parameters are unambiguously specified or can be determined. Therefore, these equations are simpler than existing equations, which may include hard-to-determine quantities. However, the applicability of equations (12), (15) to (18) is limited within the limits of particle sizes, their physicochemical properties and the polydispersity of the mixture of coarse-grained materials. Such are granular phosphate fertilizers, such as superphosphate and ammophos. For powdered products, which will be various inorganic salts, metal powders, etc., these equations will not be applicable. The study of the regularities of the entrainment of small fractions from a polydisperse mixture of powdered materials will be the task of further research.

The effective operation of the shelf pneumatic classifier in the production of granular mineral fertilizers is enabled at a productivity of not more than 10–12 t/h. With greater productivity, there is a need to install several devices in the technological line.

7. Conclusions

1. A mathematical model of the removal of small fractions from a suspended layer has been built, confirming the kinetic and inertial mechanism of removal of small particles. The model makes it possible to derive an equation relating the concentration of small particles in the entrainment with the hovering velocities of the particles and the gas flow.

2. The maximum value in terms of the degree of extraction of small particles from a polydisperse mixture of granular superphosphate into the entrainment was experimentally revealed. At the same time, the width of the discharge space is 0.5 of the length of the cross-section of the device, the degree of perforation of the shelf is 5 %; the angle of inclination of the shelf is 25–30°; the speed of the gas flow in the free section of the device is 3.7 m/s.

3. The efficiency of the pneumatic classification process of polydisperse mixture of granular superphosphate in the shelf apparatus has been experimentally substantiated. At the same time, the degree of extraction into the entrainment of a small fraction smaller than 1 mm in size reaches 70–75 %, the content of the small fraction in the carryover is 96–98 %, and the large fraction is less than 5 %.

4. By processing experimental data, an equation was built in the form of a logarithmic-linear dependence of the concentration of particles in the stream on the velocity of the gas.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

All data are available in the main text of the manuscript.

References

1. Giroto, A. S., do Valle, S. F., Guimarães, G. G. F., Molina, A., Reis, H. P. G., Fernandes, D. M. et al. (2020). Tailoring Efficient Materials for NPK All-in-One Granular Fertilization. Industrial & Engineering Chemistry Research, 59 (41), 18387–18395. doi: https://doi.org/10.1021/acs.iecr.0c02985
2. Sherkuziev, D. (2021). Simple superphosphate by two-stage acid treatment of phosphate raw materials. IOP Conference Series: Earth and Environmental Science, 939 (1), 012057. doi: https://doi.org/10.1088/1755-1315/939/1/012057
3. Fazullin, R. K., Khalitov, R. A., Khuziahmetov, R. K., Matuhin, E. L., Fazullina, A. A. (2020). Granular nitrogen and nitrogen-potassium fertilizers containing sulfur from the spent acid mixture of nitrocellulose production. IOP Conference Series: Materials Science and Engineering, 862 (6), 062034. doi: https://doi.org/10.1088/1757-899x/862/6/062034
4. Erro, J., Urrutia, O., Baigorri, R., Fuentes, M., Zamarreño, A. M., Garcia-Mina, J. M. (2016). Incorporation of humic-derived active molecules into compound NPK granulated fertilizers: main technical difficulties and potential solutions. Chemical and Biological Technologies in Agriculture, 3 (1). doi: https://doi.org/10.1186/s40538-016-0071-7
5. Otwinowski, H., Krzywanski, J., Urbaniak, D., Wylecial, T., Sosnowski, M. (2021). Comprehensive Knowledge-Driven AI System for Air Classification Process. Materials, 15 (1), 45. doi: https://doi.org/10.3390/ma15010045

6. Yu, Y., Wang, L., Liu, J. (2022). Analysis of numerical simulation models for the turbo air classifier. Materialwissenschaft Und Werkstofftechnik, 53 (5), 644–657. doi: https://doi.org/10.1002/mawe.202100130
7. Jia, F., Mou, X., Fang, Y., Chen, C. (2021). A New Rotor-Type Dynamic Classifier: Structural Optimization and Industrial Applications. Processes, 9 (6), 1033. doi: https://doi.org/10.3390/pr9061033
8. He, Y., Duan, C., Wang, H., Zhao, Y., Tao, D. (2010). Separation of metal laden waste using pulsating air dry material separator. International Journal of Environmental Science & Technology, 8 (1), 73–82. doi: https://doi.org/10.1007/bf03326197
9. Pavlenko, I. V., Yukhymenko, M. P., Lytvynenko, A. V., Bocko, J. (2019). Solving the Nonstationary Problem of the Disperse Phase Concentration during the Pneumoclassification Process of Mechanical Mixtures. Journal of Engineering Sciences, 6 (1), F1–F5. doi: https://doi.org/10.21272/jes.2019.6(1).f1
10. Banjac, V., Pezo, L., Pezo, M., Vukmirović, Đ., Čolović, D., Fišteš, A., Čolović, R. (2017). Optimization of the classification process in the zigzag air classifier for obtaining a high protein sunflower meal – Chemometric and CFD approach. Advanced Powder Technology, 28 (3), 1069–1078. doi: https://doi.org/10.1016/j.apt.2017.01.013
11. Mann, H., Roloff, C., Hagemeier, T., Thévenin, D., Tomas, J. (2017). Model-based experimental data evaluation of separation efficiency of multistage coarse particle classification in a zigzag apparatus. Powder Technology, 313, 145–160. doi: https://doi.org/10.1016/j.powtec.2017.03.003
12. Yukhymenko, M., Ostroha, R., Litvinenko, A., Bocko, J. (2017). Estimation of gas flow dustiness in the main pipelines of booster compressor stations. IOP Conference Series: Materials Science and Engineering, 233, 012026. doi: https://doi.org/10.1088/1757-899x/233/1/012026
13. Shapiro, M., Galperin, V. (2005). Air classification of solid particles: a review. Chemical Engineering and Processing: Process Intensification, 44 (2), 279–285. doi: https://doi.org/10.1016/j.cep.2004.02.022
14. Liu, Z., Xie, Y., Wang, Y., Yu, J., Gao, S., Xu, G. (2012). Tandem fluidized bed elutriator – Pneumatic classification of coal particles in a fluidized conveyer. Particuology, 10 (5), 600–606. doi: https://doi.org/10.1016/j.partic.2012.03.005
15. Zhou, E., Shan, Y., Li, L., Shen, F., Byambajav, E., Zhang, B., Shi, C. (2021). Study on the Fluidization Quality Characterization Method and Process Intensification of Fine Coal Separation in a Vibrated Dense Medium Fluidized Bed. ACS Omega, 6 (22), 14268–14277. doi: https://doi.org/10.1021/acsomega.1c01034
16. Aziz, M. A. A., Isa, K. Md., Miles, N. J., Rashid, R. A. (2018). Pneumatic jig: effect of airflow, time and pulse rates on solid particle separation. International Journal of Environmental Science and Technology, 16 (1), 11–22. doi: https://doi.org/10.1007/s13762-018-1648-4
17. Ambrós, W. M., Sampaio, C. H., Cazacliu, B. G., Conceição, P. N., dos Reis, G. S. (2019). Some observations on the influence of particle size and size distribution on stratification in pneumatic jigs. Powder Technology, 342, 594–606. doi: https://doi.org/10.1016/j.powtec.2018.10.029
18. Ambrós, W. M. (2020). Jigging: A Review of Fundamentals and Future Directions. Minerals, 10 (11), 998. doi: https://doi.org/10.3390/min10110998
19. Varukha, D. A., Smirnov, V. A., Edl, M., Demianenko, M. M., Yukhymenko, M. P., Pavlenko, I. V., Liaposhchenko, O. O. (2018). Modelling of Separation and Air Classification Processes of Aerodisperse Systems in the Shelving Device. Journal of Engineering Sciences, 5 (1), F5–F9. doi: https://doi.org/10.21272/jes.2018.5(1).f2
20. Yukhymenko, M., Artyukhov, A., Ostroha, R., Artyukhova, N., Krmela, J., Bocko, J. (2021). Multistage Shelf Devices with Fluidized Bed for Heat-Mass Transfer Processes: Experimental Studies and Practical Implementation. Applied Sciences, 11 (3), 1159. doi: https://doi.org/10.3390/app11031159
21. Ostroha, R., Yukhymenko, M., Yakushko, S., Artyukhov, A. (2017). Investigation of the kinetic laws affecting the organic suspension granulation in the fluidized bed. Eastern-European Journal of Enterprise Technologies, 4 (1 (88)), 4–10. doi: https://doi.org/10.15587/1729-4061.2017.107169
22. Yukhymenko, M., Ostroha, R., Lytvynenko, A., Mikhajlovskiy, Y., Bocko, J. (2020). Cooling Process Intensification for Granular Mineral Fertilizers in a Multistage Fluidized Bed Device. Lecture Notes in Mechanical Engineering, 249–257. doi: https://doi.org/10.1007/978-3-030-50491-5_24
23. Leva, M. (1951). Elutriation of Fines from Fluidized Systems. Chem. Eng. Prog., 47 (1), 39–45.
24. Osberg, G. L., Charlesworth, D. H. (1951). Elutriation in a Fluidized Bed. Chem. Eng. Prog., 47 (11), 566–570.
25. Kunii, D., Levenspiel, O. (1969). Entrapment and elutriation from fluidized beds. Journal of Chemical Engineering of Japan, 2 (1), 84–88. doi: https://doi.org/10.1252/jcej.2.84
26. Davidson, J. F., Harrison, D. (Eds.) (1985). Fluidization. Academic Press, 733.
27. Pemberton, S. T., Davidson, J. F. (1986). Elutriation from fluidized beds – I. Particle ejection from the dense phase into the freeboard. Chemical Engineering Science, 41 (2), 243–251. doi: https://doi.org/10.1016/0009-2509(86)87005-1
28. Pemberton, S. T., Davidson, J. F. (1986). Elutriation from fluidized beds – II. Disengagement of particles from gas in the freeboard. Chemical Engineering Science, 41 (2), 253–262. doi: https://doi.org/10.1016/0009-2509(86)87006-3

29. Liu, Y.-D., Kimura, S. (1993). Fluidization and entrainment of difficult-to-fluidize fine powdermixed with easy-to-fluidize large particles. Powder Technology, 75 (2), 189–196. doi: https://doi.org/10.1016/0032-5910(93)80081-k
30. Rodríguez, J. M., Sánchez, J. R., Alvaro, A., Florea, D. F., Estévez, A. M. (2000). Fluidization and elutriation of iron oxide particles. A study of attrition and agglomeration processes in fluidized beds. Powder Technology, 111 (3), 218–230. doi: https://doi.org/10.1016/s0032-5910(99)00292-2
31. Monazam, E. R., Breault, R. W., Weber, J., Layfield, K. (2017). Elutriation of fines from binary particle mixtures in bubbling fluidized bed cold model. Powder Technology, 305, 340–346. doi: https://doi.org/10.1016/j.powtec.2016.09.046
32. Zenz, F. A., Weil, N. A. (1958). A theoretical-empirical approach to the mechanism of particle entrainment from fluidized beds. AIChE Journal, 4 (4), 472–479. doi: https://doi.org/10.1002/aic.690040417
33. Fournol, A. B., Bergougnou, M. A., Baker, C. G. J. (1973). Solids entrainment in a large gas fluidized bed. The Canadian Journal of Chemical Engineering, 51 (4), 401–404. doi: https://doi.org/10.1002/cjce.5450510402
34. Malewski, J. (2017). On accuracy of sieve analysis. In Proceedings of the Annual Conference on Aggregates KruszMin'17. Wroclaw, 103–111.
35. Sieve analysis. Taking a Close Look at Quality (2009). Retsch GmbH Haan: Haan, 52.
36. Green, D. W., Southard, M. Z. (2019). Perry's Chemical Engineers' Handbook. McGraw Hill Professional.
37. Hartnett, J. P. (Ed.) (1968). Analytical Heat Diffusion Theory. Academic Press. doi: https://doi.org/10.1016/b978-0-12-459756-3.x5001-9
38. Yukhimenko, N., Vakal, S. (2016). The exergy analysis of energy efficiency of the technology of granulated phosphorus-potassium fertilizers. Eastern-European Journal of Enterprise Technologies, 5 (6 (83)), 4–10. doi: https://doi.org/10.15587/1729-4061.2016.77182