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

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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 underestimated, 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.

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, ammonophos, 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 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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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, for 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.
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 return 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 \( L_{cl} / L_{dev} = 0.15 \ldots 0.8 \), the angle of inclination of the shelf within \( \gamma = 25 \ldots 30^\circ \) to the horizontal plane, degrees of perforation of the shelf within \( \psi = 5 \ldots 30 \% \). 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:

<table>
<thead>
<tr>
<th>Size Range</th>
<th>Percentage</th>
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<tbody>
<tr>
<td>+2.5 mm – 10 %</td>
<td>–2.5+1.6 mm</td>
</tr>
<tr>
<td>–1.6+1 mm – 25 %</td>
<td>–1+0.5 mm</td>
</tr>
<tr>
<td>–0.5 mm – 20 %</td>
<td>–2.5+1.6 mm</td>
</tr>
</tbody>
</table>

The true and bulk density of superphosphate granules obtained by rolling in a drum granulator, according to reference data, was taken, respectively, 2250 kg/m³ and 1100–1200 kg/m³ [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](image-url)

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/(m²·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), 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.

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 entainment. 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:
\[
\frac{\partial Y_{sm}(\tau)}{\partial \tau} = \left( U_p \text{grad} Y_{sm} + K_y (Y_{sm} - Y_{sm}(\tau)) \right) = \left( U_p \frac{\partial Y_{sm}}{\partial x} + U_p \frac{\partial Y_{sm}}{\partial y} + U_p \frac{\partial Y_{sm}}{\partial z} \right) - K_y (Y_{sm} - Y_{sm}(\tau)).
\]
where \( U_p, U_p, U_p \) are the velocity of the particulate matter relative to the \( x, y, z \) axes, \( m/s \); \( Y_{sm}(\tau) \) is the 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), \( g/m^3 \); \( Y_{sm} \) is the concentration of fine particles in the layer; \( \tau \) 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:
\[
\frac{\partial Y_{sm}}{\partial x} = 0, \frac{\partial Y_{sm}}{\partial y} = 0.
\]
Since a continuous process is carried out in industrial apparatuses, then \( \frac{\partial Y_{sm}(\tau)}{\partial \tau} = 0 \). Consider that the current coordinate corresponds to the height of the separation space \( h \). Then equation (4) will be written as:
\[
U_p \frac{dY_{sm}}{dh} = -K_y (Y_{sm} - Y_{sm}(\tau)).
\]
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):
\[
\int_{Y_{sm}}^{Y_{sm}} \frac{dY_{sm}}{(Y_{sm} - Y_{sm})} = \frac{K_y}{U_p} \int_0^h dh,
\]
we obtain:
\[
\ln \frac{Y_{sm}}{Y_{sm}} = \frac{k_s h}{U_p},
\]
then, by transforming:
\[
\lg Y_{sm} = \lg (Y_{sm} - Y_{sm}) - 2.3 \frac{k_s h}{U_p}.
\]

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, 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 $\psi = 5 \, \text{kg/m}^3$.

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. 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.

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:

$$\lg y = a - \frac{b}{w}$$

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

<table>
<thead>
<tr>
<th>Characteristics of the gas dispersed system (type of apparatus)</th>
<th>Fraction, mm</th>
<th>C with flow velocity, m/s</th>
<th>Particle hovering velocity, m/s</th>
<th>Particle concentration in the stream, g/m$^3$</th>
<th>Constant</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>experiment</td>
<td>Calculation</td>
</tr>
<tr>
<td>Active fluidized layer (separator)</td>
<td>Less than 1.0</td>
<td>5.1</td>
<td></td>
<td>1.89</td>
<td>124</td>
</tr>
<tr>
<td>Inhibited falling layer (shelf pneumatic classifier)</td>
<td>Less than 1.0</td>
<td>5.1</td>
<td></td>
<td>1.39</td>
<td>199</td>
</tr>
<tr>
<td>Free-falling layer (pneumatic pipe with free channel)</td>
<td>Less than 1.0</td>
<td>5.1</td>
<td></td>
<td>1.39</td>
<td>87</td>
</tr>
</tbody>
</table>
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:

$$ a = m_1 \cdot 10^{-\frac{c}{u_s}}, $$

$$ b = m_2 \cdot u_s^n, $$

(13), (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:

$$ a = 3.46 \cdot 10^{-\frac{0.25}{u_s}}, \quad b = 0.044 \cdot u_s^{1.2}, \quad \text{at} \quad u_s \leq 5.1 \text{ m/s}, $$

(15)

$$ a = 10 \cdot 10^{-\frac{0.15}{u_s}}, \quad b = 0.07 \cdot u_s^{1.2}, \quad \text{at} \quad u_s > 5.1 \text{ m/s}, $$

(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 pneumatic tube one. The following formulas apply to these conditions:

$$ a = 5.0 \cdot 10^{-\frac{0.37}{u_s}}, \quad b = 0.15 \cdot u_s^{0.51}, \quad \text{at} \quad u_s \leq 5.1 \text{ m/s}, $$

(17)

$$ a = 5.1 \cdot 10^{-\frac{0.22}{u_s}}, \quad b = 0.18 \cdot u_s^{0.53}, \quad \text{at} \quad u_s \leq 5.1 \text{ m/s}. $$

(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 pneumatic tube 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 $L_{cl}/L_{dec}=0.8$ to $L_{cl}/L_{dec}=0.3$–0.5, that is, when the length of the shelf $L_{cl}$ 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 $L_{cl}/L_{dec}=0.15$.

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

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 $\approx 0.5$ mm and $\approx 0.5–1$ 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 deducting 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 specified loads of 15–20 kg/m²s, which significantly exceeds the specified loads of 0.1–1.5 kg/m²s 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 experi-
mentally proven [22] that for a shelf pneumatic classifier, the specific air flow rate is 0.45–0.6 m³/kg against 1.1 m³/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 physico-chemical 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 hovering velocities of the gas and the concentration of small particles in the entrainment with 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 physico-chemical 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.

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 distribution of the sizes of the particles of the large fraction is less than 5 %.

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 flow.

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