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MODELING THE LOADING PROCESS OF PNEUMATIC SEPARATION CHANNELS

The object of research is the problem of uniform distribution of bulk materials across the width of the working elements of the separation equipment. Such a problem limits the productivity and quality of the process of separation of bulk materials by aerodynamic and dimensional characteristics. To ensure uniformity of the layer of bulk material across the width, an integrated design of the loading device is proposed, which consists of a gable surface with a variable angle of inclination from the center of the feed to the extreme limits of the device. The working part of the device is made in the form of surfaces of variable width, and the width of each slope of the surface increases proportionally to the distance to the walls of the housing. This allows for controlled distribution of the material across the width. The studies were conducted using analytical and experimental methods. To determine the parameters of the movement of the bulk grain medium along the integrated inclined surface, analytical expressions were obtained that take into account the parameters of the proposed loading device and the properties of the bulk grain material. The patterns of change in the rate of descent of particles of bulk grain material from the inclined surface, as well as the dependence of the velocity of their fall to the hopper bottom, were obtained. Experimental studies were based on high-velocity video recording of the process with identification of dynamic parameters of bulk material and comparison with modeling data. The adequacy of the model was confirmed by experiments with a difference of up to 3.6 %. The influence of the following significant factors on the final velocity of particles of bulk grain material (BGM) was established: the length of the sloping surface at the level of 47.5–116.5 %, then the distance from the surface to the hopper bottom at the level of 76.7–85.6 % and the angle of inclination of the sloping surface at the level of 24.4–41.1 %. The ranges of variation of the BGM particle velocities were established: the initial velocity of particles on the sloping surface 0.82–1.27 m/s, the velocity of particles descending from the sloping surface 0.85–1.43 m/s, the velocity of falling particles 0.68–1.47 m/s. The research results were rational parameters of the integrated loading device, which provides excellent particle movement velocities and leads to uniform distribution of bulk grain material across the width of the separation equipment with an inlet to outlet ratio of (1:5). The results obtained prove the existence and method of scientific and technical solution to the problem, create conditions for further research and design of separation equipment with high technological indicators.

Keywords: *dynamics of bulk material, grain mixture, distribution uniformity, analytical expressions, rational parameters, separation equipment.*

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1. Introduction

The use of separation equipment is a common technological operation in the pharmaceutical [1], agricultural [2, 3], construction [4] and mining industries [5].

The main technological indicators of separation equipment are the productivity and quality of separation of particles of bulk grain material (BGM) by different characteristics: size [6, 7], aerodynamic properties [8], density [9], color [10], surface condition [11], shape [12], electromagnetic properties [13], etc.

The most widespread is separation equipment, the working elements of which are perforated screening surfaces (sieves) and pneumatic separation channels. Existing studies on increasing the efficiency of sieves by using holes of complex geometry [14, 15] or intensifiers [6], improving the efficiency of pneumatic separation channels by preliminary stratification [16] prove their significant potential. However, researchers have proven that the loading conditions and their uniform distribution over the working surface have a significant impact on the efficiency of the separation process [17]. The authors also note the limitation of the thickness of the BGM layer in relation to the required quality of component separation.

This leads to the technological arrangement of the working elements into blocks, increasing their width to ensure the required thickness of the BGM layer. As a result, there is a ratio of the sizes of the inlet pipes and working elements of 1 to 5 (1:5) and more, which requires appropriate scientific and technical solutions.

The efficiency of the separation equipment largely depends on the uniformity of the supply of the source material across the entire width of the working surfaces, and especially the pneumatic separation channels. Changing the thickness of the BGM layer or its absence in areas of the working element (especially pneumatic separators) leads to a redistribution of the air flow movement through them, the absence of the material separation process as a whole [18]. To form a uniform supply, loading devices are installed on the separation equipment.

Loading devices are widely used in grain cleaning machines, which use a hopper with an inclined bottom, in the front part of which a dosing device is installed, made of a spring-loaded valve attached to the bottom, above which a dosing coil with drive mechanisms is installed [19].

When the groove of the coil rotates, which are made parallel to the longitudinal axis of the coil, part of the initial BGM is separated from the hopper and directed to the working bodies of the grain cleaning machines. Such devices provide a uniform supply of BGM across the width of the working bodies, but the supply is formed pulsating, that is, uneven in terms of operation time. This reduces not only the productivity of the machine, but also the quality of cleaning.

A more uniform supply of the initial BGM over time is provided by loading devices, in which the dosing devices include a rotor from a cylindrical brush [20]. But with increasing device productivity, the quality of dosing decreases sharply.

Loading devices are also known in which the hopper bottom is mounted on a vibrator, and a metering valve is installed above the outlet window, which changes the thickness of the BGM layer, and hence the amount of feed of the starting material [21]. Such devices ensure a uniform feed of the starting, even low-flowing material, including small-seeded agricultural crops and medicinal plants, to the working bodies of low-performance separating machines with a small difference in the sizes of the inlet pipe and the working body.

On medium and high-performance separating machines, such devices are not effective. Modern trends in the design of separating equipment, especially agricultural ones, are focused on significant productivity, minimizing energy consumption, injury to BGM, etc.

For such machines, loading devices are used, which include a housing with an inclined bottom, in the front side of which a dosing device is installed. The device includes a dosing window made along the entire width of the front side of the loading device, which is covered by a rotary regulating flap with counterweights. In the middle of the upper cover of the loading device, an inlet pipe of the supply device for the initial BGM is installed [22]. During operation of the loading device, the initial BGM enters the device through the inlet pipe and, being distributed automatically across its entire width along the inclined bottom, through the dosing window enters the working bodies of the separating machines.

This design of the loading device is reliable in operation, easy to maintain and provides high-quality dosing when feeding dry, initial BGM. When loading wet, low-flowing BGM, the dosing quality is significantly reduced: firstly, due to insufficient material flow to the side walls of the device, which does not provide the necessary layer to form a given feed. Secondly, due to overloading of the central part of the device, from the bottom in the front part of the device, BGM crypts are periodically formed, which reduce its flow to the dosing device, both as a result of uneven feed and in the central part of the device.

The technical task of the research is to increase the uniformity of the feed of the initial BGM by the loading device to the working bodies of the pneumatic separation equipment due to its preliminary redistribution over the entire plane of the loading device body.

This task is implemented in the developed integrated loading device (Fig. 1) [23, 24].

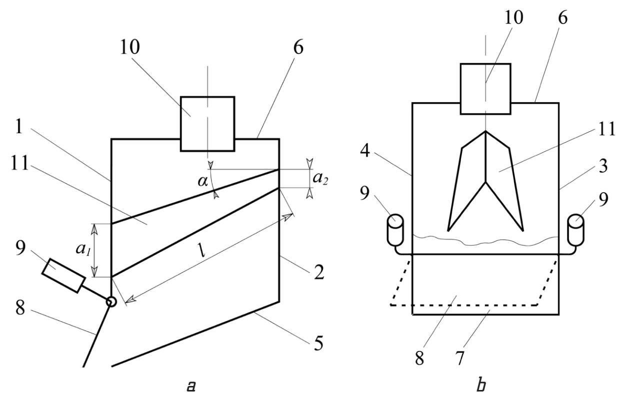


Fig. 1. Structural diagram of the integrated loading device of the pneumatic separation machine: *a* – side view; *b* – front view (width); 1–4 – front, rear, right, left side, respectively; 5 – hollow bottom; 6 – top cover; 7 – dosing window; 8 – regulating valve; 9 – counterweight; 10 – inlet pipe; 11 – distributor of the initial BGM

The proposed design of the integrated loading device of the pneumatic separation machine consists of a housing that includes the front 1, rear 2, right 3 and left 4 sidewalls, hollow bottom 5 and a top cover 6 [24]. A dosing device is installed in the front sidewall 1, which includes a dosing window 7, made in the lower part of the front sidewall 1 along its entire width, which is covered by a rotary regulating valve 8 with counterweights 9. An inlet pipe 10 of the feeding device is installed in the middle of the top cover 6. Under the inlet pipe 10 of the feeding device, inside the hopper, a distributor of the initial BGM 11 is installed with an inclination at an angle α towards the dosing device (dosing window 7). It is made, for example, in the form of a double-slope surface of variable width, and the width of each slope of the surface increases from the value a_1 to a_2, proportional to the distance l to the front side 1 of the loading device housing (i. e., the closer to the front side 1, the greater the width of each slope of the distributor 11). The proposed design works as follows: after the working bodies of the separation machine enter the specified operating mode, the feeding device is turned on and the initial BGM enters the loading device housing through the inlet pipe 10 and most of it immediately enters the distributor 11. Due to its double-slope surface, the output material is divided into two streams along the corresponding slopes. Near the rear sidewall 2 of the housing, the width of the distributor slopes is the smallest and the source material is poured from the distributor to the middle along the width of the inclined bottom 5. The further from the rear sidewall 2 the width of the distributor slopes 11 increases and the layer of the initial BGM is poured from it further from the middle of the width of the hopper, and a layer of a certain thickness is moved under the distributor 11 to the dosing device. Due to the inclination of the distributor at an angle α, the BGM is additionally accelerated along its slopes, due to which the trajectory of its descent becomes flatter, and the magnitude of the descent displacement increases. Thus, the entire initial BGM is distributed across the entire width of the bottom 5 of the hopper and, due to its inclination, is moved to the dosing window 7 in an approximately aligned layer across its entire width. By means of counterweights 9, the position of the dosing valve 8 is regulated, which finally regulates the feed rate and its uniformity across the entire width of the dosing device.

Thus, due to the distributor 11 of the proposed design, the entire initial BGM, entering through the inlet pipe 10, is distributed across the entire width of the bottom 5 of the hopper, which eliminates the reloading of individual parts of the hopper and the formation of vaults, which significantly reduce the uniformity of the feed.

The proposed design is technologically suitable for use in separation equipment, belongs to the gravitational type, and also meets the requirements for minimizing energy consumption and material trauma.

Among the methods of modeling the BGM dynamics, it should be noted: traditional dynamic models of the motion of a single particle [25], the motion of a pseudo-fluid medium according to rheological models [16], models according to hydroanalogies [26, 27], analogy with a bubbling liquid [28].

The use of simulation modeling methods, for example, DEM [29, 30], can also be an effective research tool in the presence of experimental clarifying data.

Taking into account the design features of the loading devices, the absence of vibration, and the small range of variation of the BGM properties, it is possible to adopt the methodology of modeling the dynamics of a material point with experimental verification of the adequacy of the results.

For experimental identification of the parameters of the movement of BGM particles, it is possible to use high-velocity video recording and image processing, which has repeatedly proven its effectiveness [30, 31].

Therefore, *the aim of research* is to develop a scheme and justify the parameters of the integral loading device of the separation equipment. This will create variations in the velocity of descent of particles of bulk material to the hopper bottom and ensure their uniform distribution across the width of the working bodies.

2. Materials and Methods

2.1. Modeling the dynamics of bulk grain material

To model the BGM movement, it is possible to consider individual subtasks: the fall of particles onto the inclined surface of the device, their movement and descent from the inclined surface with given parameters, their fall from the inclined surface to the hopper bottom.

As an efficiency criterion, let's take the variation level of the values of the final velocity of the fall of BGM particles onto the hopper bottom, which will ensure their distribution across the width of the working elements of the separation equipment, and will also allow to implement the possibility of controlling the distribution process.

The work will identify the design parameters of the proposed device, the properties of the bulk material, etc.

Let's consider the fall of BGM particles onto inclined surfaces in the central zone (Fig. 2). For modeling, let's make the following simplifications and assumptions: leveling of air resistance and elastic properties of particles, particles are solids with the same size and mass.

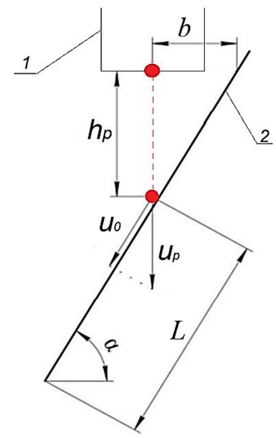


Fig. 2. Fall scheme of BGM particles:
1 – inlet pipe; 2 – working surface of the device

Let's adopt the following notations (Fig. 2): α – angle of inclination of the working surface to the horizon; b – distance from the inlet pipe to the inclined working surface; h_p – height between the inlet pipe and the inclined working surface of the device; L – distance traveled by BGM particles along the working surface.

To determine the initial velocity of movement of the BGM particle u_0 on the working surface, which is inclined at an angle α, let's use the formula:

$$u_0 = u_p \sin\alpha, \tag{1}$$

where u_p – fall velocity of BGM particles:

$$u_p = \sqrt{2gh_p}, \tag{2}$$

where g – acceleration of free fall; h_p – fall height of BGM particles.

Analyzing expressions (1) and (2), it is obvious that varying the distance b (Fig. 2) from the inlet pipe to the working surface leads to a change in the initial velocity of the BGM particles u_0.

The final expression for determining the initial velocity:

$$u_0 = \sqrt{2gh_p}\sin\alpha.$$

Let's assume that the distance of the BGM particles (L) (Fig. 2) is equal to the segment from the place of their fall to the extreme point of the working inclined surface.

The BGM movement along the working inclined surface can be considered as the movement of particles with sliding, due to their insignificant and minimal rolling.

Then the dynamics of a solid particle (BGM) along the inclined surface can be described by differential equations (Fig. 3) [16]:

$$m_p\frac{d^2L}{dt^2} = m_p\frac{du}{dt} = m_p g(\sin\alpha - \mu\cos\alpha), \tag{3}$$

where m_p – the mass of the BGM particle; t, μ – the time of movement and the coefficient of friction of the BGM particle along the working surface, respectively.

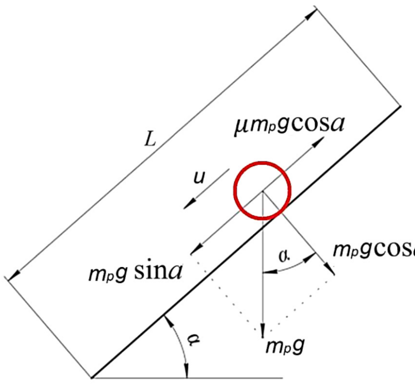


Fig. 3. Scheme of the movement of a BGM particle along the working surface of the device

Dividing both sides of equation (3) by m_p, let's obtain:

$$\frac{du}{dt}=g(\sin\alpha-\mu\cos\alpha). \quad (4)$$

Let's represent:

$$\mu=\tan\varphi=\frac{\sin\varphi}{\cos\varphi}, \quad (5)$$

where φ – the friction angle of the BGM particle along the working surface of the device.

Then:

$$\frac{du}{dt}=g\left(\sin\alpha-\frac{\sin\varphi}{\cos\varphi}\cos\alpha\right),$$

or

$$\frac{du}{dt}=g\frac{\sin(\alpha-\varphi)}{\cos\varphi}. \quad (6)$$

Let's assume the following initial conditions: $u=u_0$; $L=0$ at $t=0$.

Let's integrate equation (6) and there is an expression for identifying the velocity of movement (s) and the distance (L) of the BGM particle along the working surface of the developed device:

$$u=u_0+\frac{\sin(\alpha-\varphi)}{\cos\varphi}gt, \quad (7)$$

$$L=u_0t+\frac{\sin(\alpha-\varphi)}{2\cos\varphi}gt^2. \quad (8)$$

For convenient calculation, let's assume:

$$j=\frac{\sin(\alpha-\varphi)}{\cos\varphi}g. \quad (9)$$

A significant factor characterizing the BGM dynamic parameters is the angle φ or the friction coefficient μ, which depend on the properties of the particles. The angle of friction of particles is one of the conditions that limits the minimum angle of inclination of inclined surfaces, i. e. $(\alpha>\varphi)$. In this case, let's exclude the BGM stopping on inclined surfaces, but there is an acceleration of particles along.

Taking into account this condition and the design features of the proposed device, there is a rarefied layer of BGM in the final zone of unloading from the inclined surface.

BGM particles are fed to the working surface of the device sequentially with time t_0.

The distance that the next BGM particle will travel, according to (8), is:

$$L_d=u_0(t-t_0)+\frac{j}{2}\cdot(t-t_0)^2. \quad (10)$$

Taking into account equations (8)–(10), let's find the distance between BGM particles L_{dp}:

$$L_{dp}=L-L_d,$$

or

$$L_{dp}=t_0\left(u_0+j\left(t-\frac{t_0}{2}\right)\right). \quad (11)$$

The integrated change in the angle of the inclined surface (α) directly affects both the variation of the velocity of movement (s) and the interval between the BGM particles. This proves the possibility of controlling the distribution of BGM particles on the proposed integral loading device.

Let's proceed to the analytical determination of the BGM productivity on the developed device under the condition of continuous movement of the medium. It should be noted that when a multilayer medium moves along inclined working surfaces, variability in the velocity of movement of the BGM sublayers will be observed [8]. This will cause chaotic movement, mixing and changes in the trajectories of the convergence of BGM particles. The only solution to this is the implementation of continuous single-layer BGM movement along the working surfaces.

Let's assume the appropriate conditions that ensure the BGM appropriate movement:

$$L_{d0}=d_p,\ t=t_0, \quad (12)$$

where L_{d0} – the distance traveled by the BGM particle along the working surface before the next particle hits it; d_p – the equivalent diameter of the BGM particle.

Substituting equations (9), (12) into (8), let's obtain:

$$u_0\cdot t_0+\frac{j\cdot t_0^2}{2}-d_p=0. \quad (13)$$

From equation (13), let's find the time t_0 between the fall of BGM particles onto the working surface:

$$t_0=\frac{\sqrt{u_0^2+2\cdot j\cdot d_p}-u_0}{j}. \quad (14)$$

Then, from (8), let's find the time t_{ed} of the movement of BGM particles from the place of their fall onto the sloping surface to its extreme point:

$$t_{ed}=\frac{\sqrt{u_0^2+2\cdot j\cdot L}-u_0}{j}. \quad (15)$$

Let's proceed to solving the third subproblem: determining the velocity of descent of BGM particles from the sloping surface u_s.

Taking into account expressions (7), (9) and (15), the expression for determining the velocity of descent of BGM particles has the form:

$$u_s = u_0 + j \cdot t_{ed}. \quad (16)$$

The BGM distribution across the width occurs in the lower zone of the accumulation hopper (Fig. 1). Between the lower edge of the working inclined surface and the hopper bottom hopper there is a distance L_s (Fig. 4), which also affects the distribution uniformity.

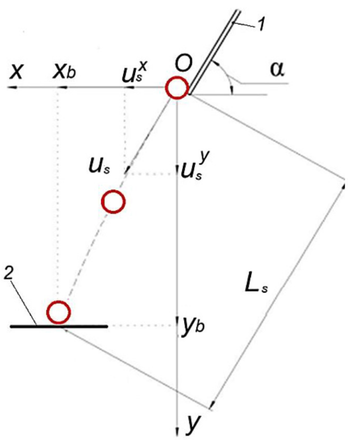


Fig. 4. Scheme of the subprocess of the descent of BGM particles from the inclined surface of the device: 1 – inclined working surface; 2 – hopper bottom

Let's assume the coordinate system xOy and the following notations (Fig. 4): x_b, y_b – coordinates of the hopper bottom; L_s – distance from the inclined surface to the hopper bottom.

After the descent of BGM particles from the edge of the working surface, they move in free fall to the point of contact with the bottom of the storage hopper.

To determine the dynamics of the fall of BGM particles, taking into account the closed space inside the hopper and small distances L_s (Fig. 1), let's neglect air resistance.

The dynamics of BGM particles as they descend from the working surface, in the form of velocity u, distances L and acceleration a, is determined by the following expressions:

a) relative to the x-axis:

$$L_x = x_0 + u_s \cdot \cos\alpha \cdot t_f,$$
$$u_x = u_s^x = u_s \cdot \cos\alpha,\ a_x = 0; \quad (17)$$

b) relative to the y-axis:

$$L_y = y_0 + u_s \cdot \sin\alpha \cdot t_f + \frac{g \cdot t_f^2}{2},$$
$$u_y = u_s^y + g \cdot t_f = u_c \cdot \sin\alpha + g \cdot t_f,\ a_y = g, \quad (18)$$

where x_0, y_0 – coordinates of BGM particles at the moment of their descent from the working surface of the device; t_f – time of fall of BGM particles from the inclined surface to the hopper bottom.

The value of the distance L_s is a variable parameter (Fig. 4) and depends on the given coordinate along the width of the device.

Then, there is an expression for determining the time of fall of BGM particles when they descend to the hopper bottom:

$$t_f = \frac{L_s \cdot \cos\alpha}{u_s \cdot \cos\alpha} = \frac{L_s}{u_s}. \quad (19)$$

Let's find the rate of fall of BGM particles from the expression:

$$u_f{}^2 = \left(u_s^x\right)^2 + \left(u_s^y\right)^2. \quad (20)$$

Let's transform equation (20) taking into account (17), (18) and (19), which will allow to obtain an equation for determining the rate of fall of BGM particles:

$$u_f = \sqrt{(u_s \cos\alpha)^2 \left(u_s \sin\alpha + \frac{g \cdot L_s}{u_s}\right)^2}. \quad (21)$$

Thus, the developed mathematical model describes the movement of BGM particles from the moment of their fall onto the inclined tray to the place of descent to the hopper bottom.

2.2. Experimental studies

To determine the dynamic parameters of the environment on sloping surfaces, it is necessary to have a clear idea of the BGM properties.

The task of experimental studies was to determine the physical and mechanical properties of the BGM (dimensions, weight, friction coefficients), as well as to verify the obtained analytical expressions.

For the studies, BGM corn seeds of the Khortytsya variety with the following properties were used: maturity group – medium early, yield potential – 13.0–13.5 t/ha, FAO – 240, manufacturer – National Academy of Agrarian Sciences of Ukraine, weight of 1000 grains – 260–270 g.

The unit presented in Fig. 5 was used for experimental studies.

The main elements of the unit are the base 1, to which the stand 2 is mounted. The rack is equipped with a hopper 3, a goniometer 4, an inclined surface 5 and a device 6 with a tray 7. A high-velocity camera 8 was used to determine the dynamic characteristics.

The following parameters were identified on the device: the angle of friction of particles, the velocity of movement of BGM particles along the inclined surface and the velocity of their fall.

To determine the friction coefficients of BGM, an inclined surface connected to a goniometer was used. The method consisted in setting the corresponding angle α at which the BGM material moved along the steel surface. The number of repetitions was 5, and then the arithmetic mean value was determined.

To determine the velocity of movement of BGM particles, a high-velocity camera Miro M120 (Germany) [32] was used. The camera allows shooting at a velocity of up to 1380 frames/s with a resolution of 1920×1080 pixels. The camera uses a CMOS matrix, the pixel size is 10 microns, and the dynamic range is 12 bits.

The process was as follows: BGM particle from a hopper raised to a given height fell onto a sloping surface. Next, the particle moved along a surface of a given length L_s and inclined at an angle α (Fig. 5).

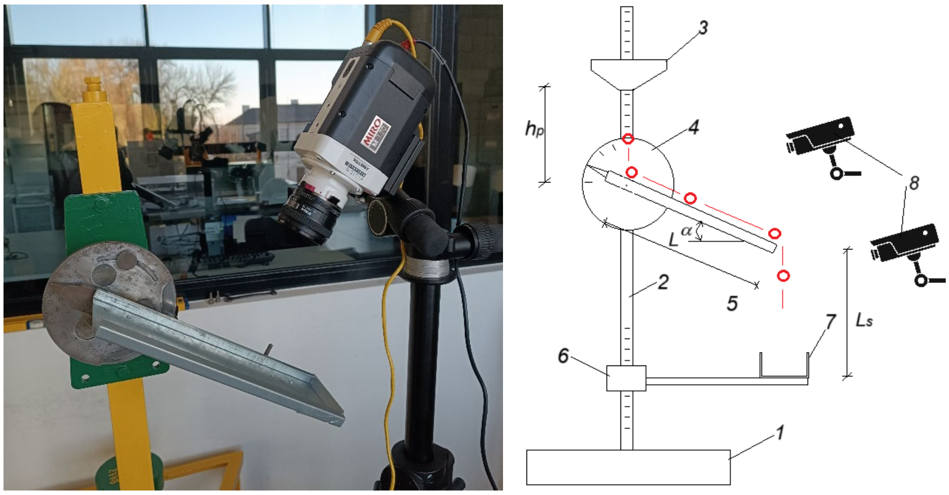


Fig. 5. Unit for experimental determination of BGM dynamic characteristics: *a* – general view; *b* – diagram; 1 – base; 2 – stand; 3 – hopper; 4 – goniometer with a clamp; 5 – inclined surface; 6 – device for changing height; 7 – tray; 8 – high-velocity camera

The camera recorded the movement of the BGM particle along the sloping surface and when falling from it. The recording was carried out at 300 frames per second with the possibility of reduction during further processing.

The resulting recording of the movement of the BGM particles was processed in the Phantom Cine Toolkit program, where it was decomposed frame by frame into separate photos (Fig. 6).

With a known number of frames (N_k) per unit time (t_k) and the path traveled by the particle in the photo, the experimental determination of the velocity was carried out:

$$u_e = \frac{S_p}{t_k} = \frac{S_p \cdot N_k}{\Delta N}, \qquad (22)$$

where $S_p = S_f - S_0$ – the path traveled by the BGM particle (Fig. 6); ΔN – the number of frames to be studied.

To check the adequacy of the obtained analytical expressions, the results were compared with the experimental data.

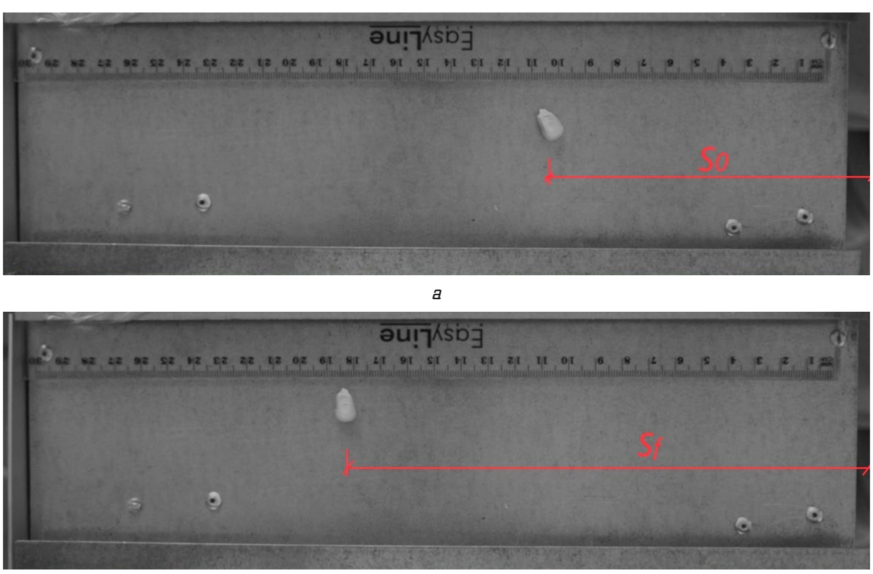


Fig. 6. Photographic frames of the movement of a BGM particle (h_p=0 mm, α=30°, L=300 mm): *a* – image with the initial distance of the particle; *b* – image with the final distance of the particle

The numerical evaluation was carried out using the deviation in the form of a relative error:

$$\delta = \frac{u_e - u}{u_e} 100\ \%, \qquad (23)$$

where u_e – the experimentally determined velocity of the BGM particle; u – depending on the definition is the velocity u_s or u_f.

3. Results and Discussions

3.1. Modeling results

Numerical calculation of the obtained mathematical expressions, carried out with the following parameters: height of fall on the sloping surface h_p=0.1–0.2 m, length of the sloping surface L=0.1–0.2 m, distance from the sloping surface to the hopper bottom L_s=0.05–0.15 m, angle of inclination of the sloping surface α=36–40 degrees, angle of BGM friction on the sloping surface φ=35 degrees (determined experimentally).

The modeling result was the regularity of change: velocity of fall of BGM particles on the sloping surface (Fig. 7), velocity of descent of particles from the sloping surface (Fig. 8) and final velocity of fall of particles on the hopper bottom (Fig. 9). The given dependencies take into account the design parameters of the proposed integral loading device of the separation equipment. The analysis of dependencies (Fig. 8) has established that an increase in the height of the fall h_p in the range under study leads to an intensive increase in the initial velocity of the BGM particles by 54.6 %. At the same time, an increase in the angle of inclination of the sloping surface reduces the initial velocity much less by 6.2–9.4 %.

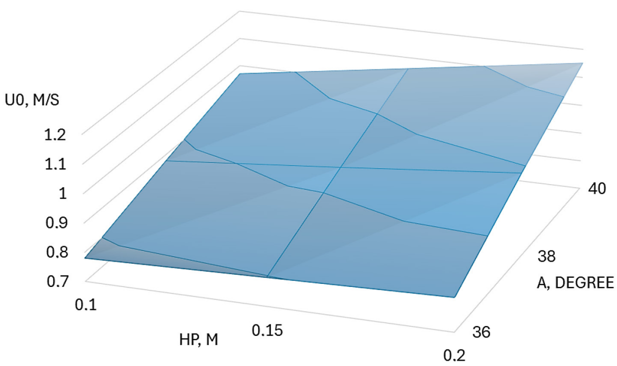
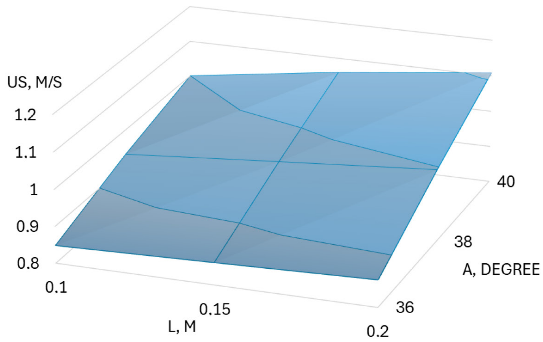
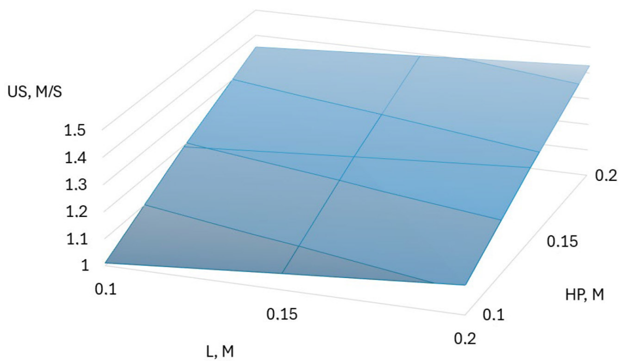


Fig. 7. Dependence of the initial velocity of BGM particles on the inclined surface on the height of fall (h_p) and the angle of inclination of the inclined surface (α)



a

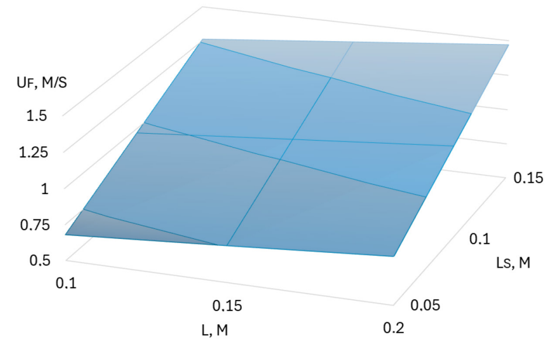


b

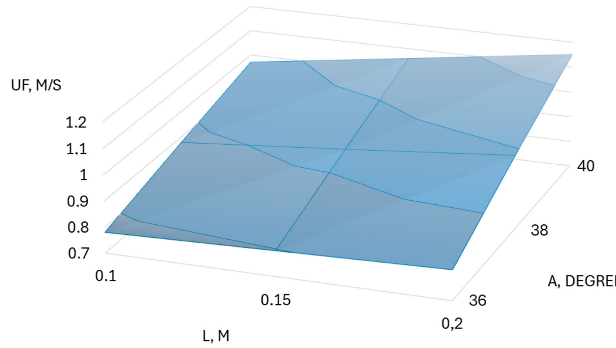
Fig. 8. Dependence of the velocity of descent of BGM particle from the inclined surface on: *a* – the length of the inclined surface (L) and its angle of inclination (α); *b* – the length of the inclined surface (L) and the height of fall (h_p) (φ=35)

The analysis of dependencies (Fig. 9) of the velocity of the descent of BGM particles from the sloping surface proves the influence of its length (L) on the change in values by 30.7–41.4 %. At the same time, an increase in the angle of inclination of the sloping surface leads to an increase in the velocity of the particles by 17.9–26.9 %, and from an increase in the height of the fall there is an increase in the values by 28.8–33.9 %.

The analysis of dependencies (Fig. 9) of the velocity of the fall of BGM particles proves that an increase in the length of the sloping surface increases the value by 47.5–116.49 %. It was also found that changing the distance L_s in the range under study leads to an increase in the falling velocity of BGM particles by 76.7–85.6 %. The smallest impact on the value of the falling velocity of particles is exerted by an increase in the angle of inclination of the sloping surface – by 24.4–41.1 %.



a



b

Fig. 9. Dependences of the velocity of fall of BGM particles to the hopper bottom on: *a* – the length of the inclined surface (L) and the distance from the surface to the hopper bottom (L_s); *b* – the length of the inclined surface (L) and its angle of inclination (α) (h_p=0.1 m; φ=35 degrees)

The ranges of variation of the velocities of BGM particles are established: the initial velocity of particles on the sloping surface is 0.82–1.27 m/s, the velocity of descent of particles from the sloping surface is 0.85–1.43 m/s, the velocity of falling particles is 0.68–1.47 m/s.

Thus, the greatest impact on the final velocity u_f is exerted by the length of the sloping surface L, the distance L_s and the angle of inclination of the sloping surface α. The obtained mathematical expressions allow, depending on the width of the separation equipment, by varying the parameters of the proposed device to determine the required velocity and trajectory of BGM particles, to ensure their uniform distribution.

3.2. Experimental results

As a result of using the unit (Fig. 5), the friction angle of BGM on the sloping surface was determined. The average value of five repetitions of the experiments was 35 degrees. The friction angle depends on the size and weight of BGM particles, which is determined mainly by their humidity and density, as well as the material from which the sloping surface is made.

As a result of using the unit (Fig. 5) and high-velocity recording of the movement of BGM particles, experimental values were established: initial particle velocity (u_0), particle descent velocity from the sloping surface (u_s) and particle fall velocity (u_f).

The experiments were carried out with the following parameters: drop height h_p=0.1 m, slope angle α=40 degrees, slope length L=0.2 m, distance from the surface to the hopper bottom L_s=0.1 m, material friction angle φ=35 degrees, 300 frames per second.

The results of the studies, their comparison with analytical ones, are presented in Table 1.

Table 1

Average values of dynamic characteristics of BGM particles on a sloped surface

Parameters	Data type				Deviation Δ, %
	analytical	experimental			
		S_p, mm	t_k, s	u_e, m/s	
Initial velocity of particles on the inclined surface u_0, m/s	0.9	46	0.05	0.92	2.17
Velocity of descent of particles from the inclined surface u_s, m/s	1.108	107	0.1	1.07	3.55
Velocity of falling particles u_f, m/s	1.151	112	0.1	1.12	2.77

The presented data indicate an acceptable relative deviation of the experimental and modeling data, which is 2.17–3.55 % and does not exceed 5 %. This indicates the adequacy of the obtained equations, the presence of particle velocity variation by the proposed design solutions and the possibility of the final uniform distribution of BGM particles across the width of the separation equipment.

3.3. Discussions

The results obtained in the form of a new technical solution, mathematical expressions of the dynamics of BGM particles, research methods, allow to increase the technological efficiency of the separation equipment by ensuring the uniformity of BGM distribution across the working bodies and improving the quality of the process of their separation, reducing energy consumption. The research results are useful for technological equipment intended for transportation, mixing, separation, dosing of BGM in various industries.

The research was conducted on BGM – corn seeds with specified properties, which imposes certain restrictions in relation to other materials. However, the developed methodology is universal and can be used for other values of BGM properties and initial parameters of loading devices. The obtained mathematical expressions allow to perform with the necessary accuracy the determination of BGM particle dynamics and to predict the technological efficiency of the equipment.

The importance of the study on the improvement of separation equipment for post-harvest grain processing adds to the need to restore the partially destroyed material and technical base of agricultural enterprises of Ukraine in war conditions.

Successful solution of the tasks of this work opens the way to justify the parameters of the working zone of pneumatic separation channels taking into account multiple separation. A comprehensive solution of the tasks set will allow to obtain pneumatic separation equipment with high technological indicators (productivity and quality of the BGM separation process), low energy consumption and particle damage.

4. Conclusions

A method for ensuring the uniformity of the distribution of bulk material across the width of the separation equipment is proposed, which has technical solutions and was investigated using analytical and experimental methods.

A scheme has been developed and the parameters of an integral loading device have been substantiated, which is capable of providing variation in the velocity of BGM particles in the gravitational type of their movement and realizing uniformity of their distribution across the width of the working elements of the separation equipment.

Analytical expressions for determining the velocity of BGM particles have been obtained, taking into account the parameters of the proposed device and the properties of the bulk material.

The use of a high-velocity camera and subsequent image analysis allowed to confirm the adequacy of the obtained mathematical expressions for identifying the BGM dynamic characteristics in the form of an allowable value of the relative deviation, which does not exceed 3.6 %.

The ranges of variation in the velocities of BGM particles have been established: the initial velocity of particles on the inclined surface is 0.82–1.27 m/s, the velocity of particles ascending from the inclined surface is 0.85–1.43 m/s, the velocity of particles falling is 0.68–1.47 m/s.

The ranking of factors by the significance of the impact on the dynamic characteristics and further distribution of BGM was determined: the greatest impact is exerted by the length of the sloping surface at the level of 47.5–116.5 %, the subsequent distance from the surface to the hopper bottom – 76.7–85.6 % and the angle of inclination of the sloping surface – 24.4–41.1 %.

The results obtained allow to increase the technological efficiency of the separation equipment by ensuring the uniformity of the BGM distribution across the working bodies and improving the quality of the process of their separation, reducing energy consumption.

Conflict of interest

The authors declare that they have no conflicts of interest, in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

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

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the presented work.

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