Original scientific paper
Journal of Central European Agriculture, 2025, 26(2), p.383-393
DOI: /10.5513/JCEA01/26.2.4301

Mathematical modeling of grain movement dynamics in the processes of air-centrifugal separation of grain material

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Received: March 5, 2024; accepted: April 6, 2025

ABSTRACT

The article is devoted to increasing the efficiency of the process of cleaning the grain of cereal crops by intensifying the release of garbage impurities from the grain material. Using the proposed mathematical models, the trajectories of movement of the components of the grain mixture along the working surface of the spreading disc and in the space of the annular air flow are determined, depending on the physical and mechanical properties of the mixture components and separator parameters. The effect on the components of the grain mixture of the lateral lifting force, which occurs due to the air flow's unevenness with the air channel's width, is considered when developing computational models. The dependences of the grain mixture components separation on the frequency of rotation of the spreading disc, the average value of the air flow in the channel, and the supply of material to the separator are established. The design and parameters of the scatter disc of the vibrating sieve grain separator are substantiated. The rational regime characteristics of the aspiration chamber were experimentally established, at which the efficiency of pneumatic separation of grain materials is 76-78% with the output of the grain fraction to waste less than 2%.

Keywords: cleaning processes, grain, spreading disc, pneumatic distribution channel

INTRODUCTION

The need for quick processing of a freshly harvested grain crop, in many cases wet and clogged with small and light impurities (e.g. chaff, straw), determines the specific requirements for separators for pre-cleaning of grain materials. This is several times increased productivity of the primary and secondary cleaning machines, the ability to clean grain material with high humidity and clogging up to 50%.

One of the widely used pre-cleaning machines is air-sieve separators, designed to clean the grain of the main crop from the impurities. The basis of their use is the difference in the physical and mechanical properties of grain, size and aerodynamic properties. Cleaning of the grain and seeds on such machines is associated with a significant ingress of the grain into the waste, and its injury. Machines are characterized by complexity, high material and energy intensity. It should be noted that such machines function much more efficiently after preliminary cleaning of the grain material (Aliiev et al., 2019; Rogovskii et al., 2020; Sheychenko et al., 2017).

The use of air flows for grain cleaning is based on the difference in the aerodynamic properties of the material of the main crop and the impurities (Bulgakov et al., 2020). This principle of separating the grain material is used in the air separators, which are simpler both in design and operation (Kharchenko et al., 2021).

The existing designs of grain separators with pneumatic systems using horizontal, vertical and inclined separation channels (Olshanskii et al., 2016; Shapiro et al., 2005) have low productivity, both as independent pneumatic separators and as part of combined grain separators.

The disadvantages of existing designs that significantly complicate the operation of pneumatic separating channels (Kharchenko et al., 2021) are: an uneven velocity field in the cross section of the channel, the supply of grain in a dense flow into the channels, the similarity of the aerodynamic characteristics of the culture and impurities (Vasylkovskyi et al., 2019).

The existing ways to improve the efficiency of air separating channels (Bredykhin et al., 2021; Stepanenko et al., 2022a) are aimed at the structural improvement of the air separating systems by using multi-jet, multi-level introduction of the material, preliminary stratification of the material by air or vibrations (Piven et al., 2018), the use of an electric field (Mykhailov et al., 2021), the use of a multi-channel device (Nesterenko et al., 2017). However, such techniques significantly complicate the design of machines for separating grain materials and do not solve the problem of a significant increase in the productivity of the grain separating equipment, but only increase the energy costs (Bazaluk et al., 2022). Loosening of the grain material in a fluidized bed (Bracacescu et al., 2016) is used to improve the introduction of the grain material into the vertical aspiration channel of an existing plant, but its independent use as a pneumatic separating unit is limited by the vertical channel width.

A promising way to improve the productivity and quality of the cleaning process of grain material in vertical air flows is the introduction of a thin layer of material by using the centrifugal formation of a circular layer of grain when it is introduced into an annular air channel, that is, the use of centrifugal-pneumatic separation (Adamchuk et al., 2021; Stepanenko et al., 2022b). The technology of this process is implemented by the following course of operations: grain supply by a jet to a disc or plate rotary spreader, movement of the grain flow along the disc with a layer whose thickness decreases in the direction of movement and the introduction of material into the air flow of the annular channel (Olshanskyi et al., 2022). Rotary spreaders have the shape of a disc in the form of a conical or plate surface with or without radial partitions (Bakum et al., 2022). The blades inside the conical or disc spreader, when it rotates, give the grains a rotational (around the axis of the spreader) movement, and the grain material acquires different speeds in the process of moving along the rotary surface. When leaving the spreader-feeder, the grains and the impurities acquire various speeds when they enter the aspiration channel with a forced air flow, which underlies the separation of a two-phase medium into its constituent components.

In the existing methods of air centrifugal cleaning of grain, the various schemes of rotary distributors are used: disc, conical, a flat disc continuing with a cone; dish-shaped with a curved surface, with radial and radially inclined blades (Derevjnko et al., 2017).

In the pneumatic-centrifugal separators for various purposes, the pneumatic separating channels of cylindrical, conical and conically annular sections are used (Mircea et al., 2020).

The substantiation of the design and mode parameters of the specified material cleaning process requires the construction of appropriate mathematical models and their investigation.

As the analysis of literature publications showed, many theories and methods for calculating the coordinate positions of grains on the surfaces of rotary distributors and in channels are devoted to investigating the movement of grains in various designs of the separating units.

In work (Adamchuk et al., 2021), the mathematical models of particle movement along the surface of a disc with a cone and blades, along the blade of an inclined sector, and in the air flow of an annular channel were developed and analyzed. The proposed models do not take into account the action of air resistance forces, both in the radial and tangential directions, and the angle of convergence of the grain from the spreader. The model of the grain movement as a material particle in an air channel does not take into account the distribution of air velocity in the channel section.

Investigation (Kharchenko et al., 2021) is also aimed at creating a mathematical model of the movement of impurity particles along the surface of a disc spreader, but the resistance force is determined by the Stokes law, which is characteristic of the laminar mode of the air movement. The real speeds of movement of grains correspond to Newton's quadratic law. In the equations of motion of the grain mixture along the plate, the air resistance is not taken into account. In earlier works (Kotov et al., 2023), the resistance forces were not taken into account in the models of grain movement along the surface of the spreader.

In the analyzed publications, there are no data on the experimental determination of the efficiency of grain cleaning depending on the parameters of the spreader and the operating modes of the pneumatic channel.

The purpose of the research is to increase the efficiency of grain cleaning by intensifying the separation of impurities from the grain material.

MATERIALS AND METHODS

A centrifugal-pneumatic separator is considered, which combines a conical-shaped rotary spreader-feeder with an annular ascending-accelerated air flow; the schematic diagram is shown in Figure 1. The separator can function as a stand-alone unit or as a unit with a vibrocentrifugal sieve separator, having a seeding and sorting grid. To determine the efficiency of grain cleaning, we used the method of trajectory analysis.

The trajectories of movement of the components of the grain material in the separating zone of the air annular-conical channel are determined, which depend on the structural and kinematic parameters of the spreader and the air channel, as well as the modes of operation. The angle and speed of grain introduction depend on the angle of inclination of the spreader cone and the frequency of its revolutions.

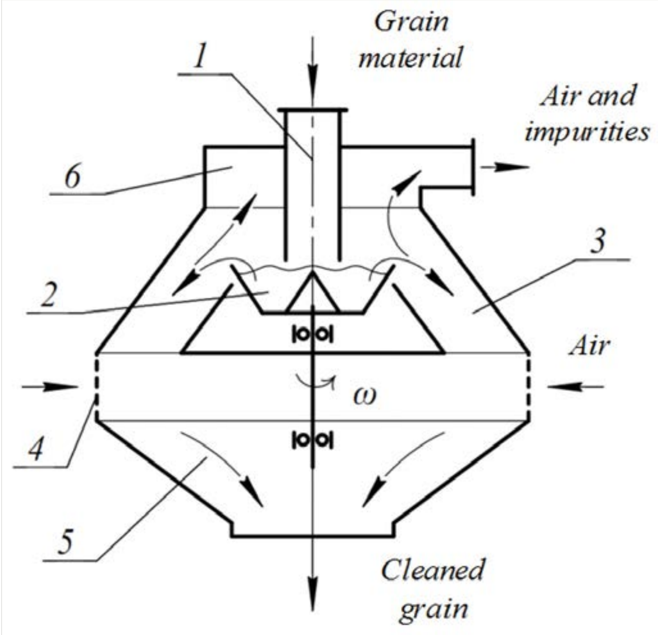


Figure 1. Schematic diagram of a pneumatic centrifugal separator (where 1 – grain pipeline; 2 – rotary spreader of the grain mixture; 3 – air channel; 4 – louvered cylinder; 5 – sloping cone; 6 – air collector)

The movement trajectories of the grain material components are determined by mathematical modeling of the grain movement as a material point with mass m in an annular-conical air flow and along the conical surface of a rotary spreader.

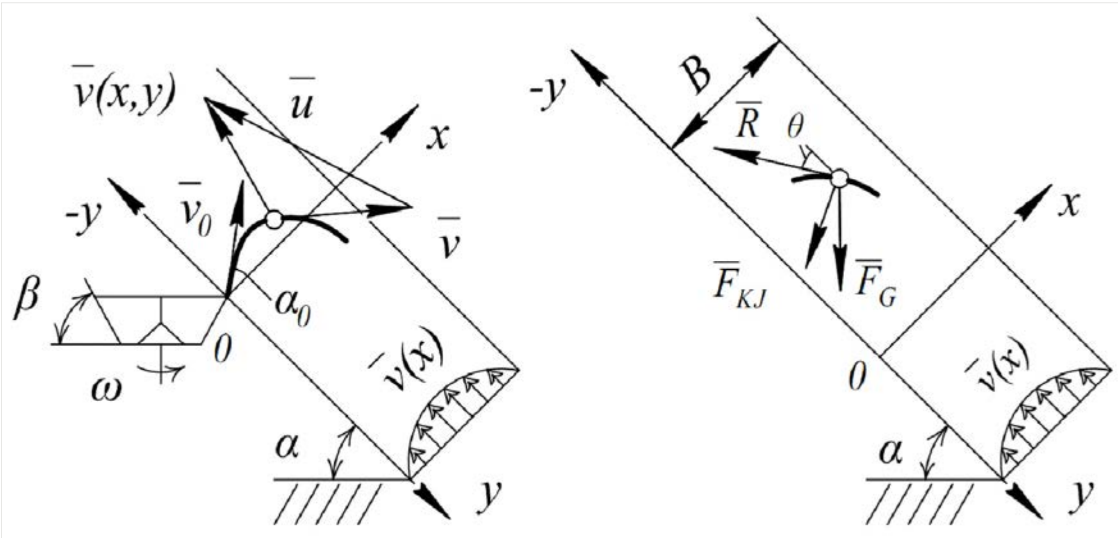
The existing models do not take into account the air speed change in the direction of movement.

The mathematical model of grain movement in the air flow is formulated on the basis of subsequent references and simplifying assumptions.

The speed of the ascending air flow increases both in the direction of movement, due to the conical shape of the annular channel, and in the cross section of the channel due to air friction on the walls of the channel, i.e. $v_A = v(x, y)$.

A grain moving in an uneven air flow is affected by such forces (Figure 2).

The analysis of the force interaction scheme leads to the determination of the most influential forces on the grain in the process of movement of the grain material.



(a) (b)

Figure 2. Scheme of the speeds (a) and the force interaction (b) of a grain with an air flow with a variable speed in the sections of the channel

To study the mechanism of the grain movement in the pneumatic channel, we use the model of its force interaction with the air flow, restricting ourselves to the movement of a spherical grain in the *x*0*y* plane passing through the axis of the pneumatic channel (Figure 2).

The equation of grain motion can be written in vector form:

$$m\frac{\mathrm{d}\bar{v}}{\mathrm{d}t} = \bar{R} + \bar{F}_{\mathrm{G}} + \bar{F}_{\mathrm{KJ}} \quad (1)$$

where

- m is the mass of the grain;
- $\bar{R}$ is an aerodynamic resistance force;
- $\bar{F}_G$ is a gravitational force;
- $\bar{F}_{KJ}$ is a lateral force.

Since the air velocity in the channel changes (in our case, increases) in the direction of its movement, the value of the relative velocity must be clarified:

The change in air flow velocity with the 0*y* coordinate can be determined by the formula:

$$v_a(y) = \frac{Q}{a-b\cdot y} \quad (2)$$

where

- *a* and *b* are constants determined by the geometrical parameters of the channel (*B*, *α*);
- *Q* is a volumetric air flow;
- v_{max} is the maximum speed on the channel axis.

The relative airflow velocity is determined by the equation:

$$\bar{u}(x,y) = \left[\frac{Q}{a-b\cdot y}\cdot\left[\frac{x}{B}\right]^{0,1}\cdot\bar{i} - \bar{v}(x,y)\right] \quad (3)$$

where $\bar{i}$ is the unit vector of the *y* axis.

By projecting equation (1) on the 0x and 0y axes, we obtain a system of differential equations for the planar movement of grains in an uneven air flow in the coordinate form:

$$\begin{cases} m\dfrac{d^2x(t)}{dt^2} = -R_x - F_{\mathrm{KJ}(x)} - m\cdot g\cdot\cos\alpha \\ m\dfrac{d^2y(t)}{dt^2} = R_y - F_{\mathrm{KJ}(y)} - m\cdot g\cdot\sin\alpha \end{cases} \quad (4)$$

where R_x, Ry, $F_{KJ(x)}$, $F_{KJ(y)}$ are projections of acting forces on the coordinate axes, the absolute values of which are determined in paper (Kotov et al., 2023).

The equation of grain movement along the rotational surface of the spreader, which has the shape of a horizontal disc and a truncated cone, is formulated on the basis of the general differential equation of motion of a material point. In vector form, it looks like:

$$m\cdot\bar{\omega} = \bar{F}_{\Sigma} + N\cdot\bar{n} + f\cdot|N|\cdot\bar{\tau} \quad (5)$$

where

- $\bar{n}$ is the unit vector of the normal to the surface;
- $\bar{\tau}$ – the unit vector touching the trajectory of motion of a material point;

- $\bar{F}_{\Sigma}$ – the resultant forces applied to the grain from the outside;
- N – the normal reaction;
- f is the coefficient of friction.

The mathematical dependences of these forces are known and given in paper (Kotov et al., 2023), therefore we will use the determined force equationsn $\bar{F}(t)$, $\bar{F}_C$, $\bar{R}$, $\bar{F}_f$ and substitute them into equation (4).

The direction cosines for designing the normal reaction and the friction force are determined depending on the chosen Cartesian or spherical coordinate system. The polar coordinate system is chosen for the rotating disc.

The constraint equation (arbitrary surface of rotation) around the vertical axis is given by the function $\Phi(x,y,z) = 0$, which in a rectangular reference system is $0xyz$, for a conical surface is given by the function:

$$\Phi(x,y,z) = z \cdot \tan\theta - \sqrt{x^2 + y^2} = 0 \quad (6)$$

The method of compiling the differential equations is as follows. Based on certain forces (5) acting on the grain and the values of the direction cosines, equation (3) is projected onto the axes of the accepted coordinate system, and a system of differential equations is formulated in coordinate form that determines the movement of the grain along the conical surface.

The direction cosines of the velocity in spherical coordinates take the form:

$$\cos(v_r, v) = \frac{\dot{r}}{v}; \cos(v_\varphi, v) = \frac{r \cdot \dot{\varphi} \cdot \sin\theta}{v}; \cos(v_\theta, v) = \frac{r \cdot \dot{\theta}}{v} \quad (7)$$

As for the choice of a coordinate system for compiling and studying the parameters of grain movement along the cone, characterizing the parameters of movement at the inlet to the air channel. An analysis of the structure of the equations of the grain movement along a conical surface, carried out in previous studies, showed that when using spherical coordinates, the differential equations are more rational for research, as they allow you to immediately determine the equation for the normal reaction N. Therefore, to determine the optimal parameters of the grain material spreader, it is advisable to use spherical coordinates.

In addition, the design features of the studied rotary spreaders, namely the combination of the disc and conical surfaces, as shown in Figure 1, determines the use of the polar coordinate system for moving the grain along the horizontal disc, and the spherical coordinate system when the grain moves to the conical surface of the disc. The equations of movement of grain in Cartesian coordinates are used for a comparative analysis of the functioning of the various designs of spreaders with certain parameters.

An experimental investigation was conducted by planning factorial experiments. The design of the experimental unit is shown in Figure 3.

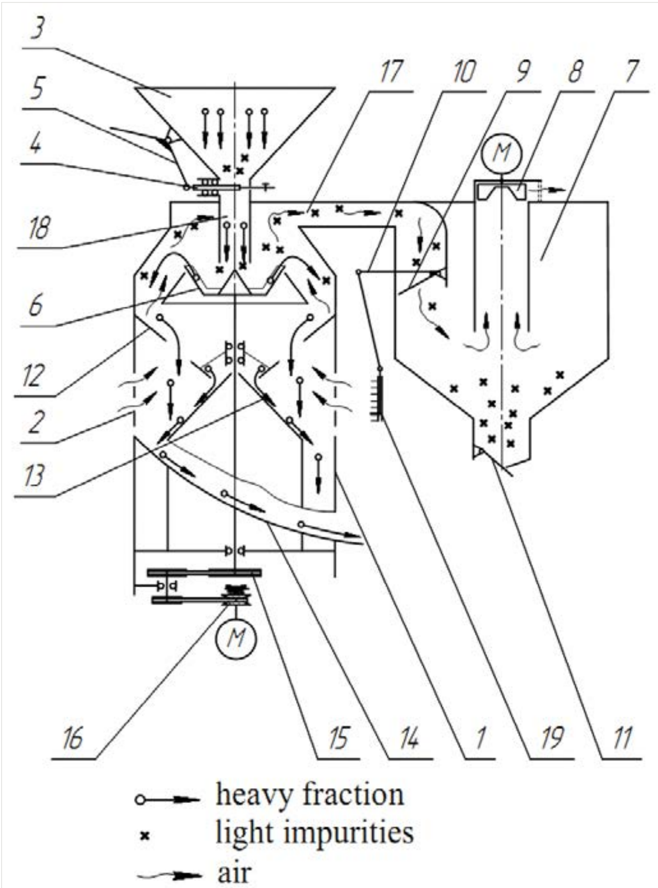


Figure 3. Design and technological scheme of the experimental unit of the pneumatic centrifugal separator (where 1 – housing; 2 – holes for air intake; 3 – hopper; 4 – valve; 5 – valve adjustment mechanism; 6 – spreading disc; 7 – sedimentary chamber; 8 – fan; 9 – valve; 10 – valve adjustment mechanism; 11 – vacuum valve; 12 – slope cone; 13 – distribution cone; 14 – output channel; 15 – drive mechanism; 16 – belt variator; 17 – air duct; 18 – grain pipeline; 19 – scale)

The experimental unit includes a housing 1, in the middle part of which there are holes for air intake 2, to the upper part of which a hopper 3 is attached. In the lower part of the hopper 3, there is a valve 4 and a mechanism for adjusting the valve 5. The sedimentary chamber 7 is also connected to the upper part of the housing 1 through the air duct 17, in which the valve 9 and the valve adjustment mechanism 10 are placed. A fan 8 is attached to the upper part of the settling chamber 7. A vacuum valve 11 is placed in the lower part of the settling chamber 7 for sealing during operation. A sloping cone 12 is attached to the inner wall of the housing 1 for transporting the heavy fraction. Under the inclined cone 12 in the inner wall of the housing 1, there are windows for air intake with a size of 2 x 20 mm. The distribution cone 13 is located below and parallel to it. Between it and the inner wall of housing 1, the outlet channel 14, forming a helical line, is tangentially connected. Inside the case, in its upper part, there is a spreading disc 6.

In the design of the experimental unit, air intake windows of size 2 x 20 mm were located under the inclined cone 12 in the inner wall of the housing 1 to create an additional cascade of blowing the grain material and cleaning it from dust impurities.

On the experimental unit, the valve regulates the supply of grain material from 0 to 40 t/h. With valve 9, it is possible to adjust the speed of the air flow in the aspiration channel in the range from 2 to 9.5 m/s. With the belt variator 16, it is possible to adjust the rotation frequency of the spreading disc in the range from 100 rpm to 180 rpm by changing the distance between the cheeks of the pulley of belt variator 16.

The investigation was planned and carried out according to the methodology of a three-factor experiment. The variable factors were the frequency of rotation of the spreading disc, the velocity of the ascending air stream and the supply of grain material. Level values and variation intervals for variable factors are given in Table 1.

Table 1. Value and coding of factor levels in experimental studies of air-centrifugal separation of grain material

Level of variation	Independent factors		
	$x_1 = n$, rpm	$x_2 = q$, t/h	$x_3 = v$, m/s
Lower (-1)	100	5	5
Medium (0)	130	20	7
Upper (+1)	160	35	9
Variation interval	30	15	2

The study was conducted according to Box's plan (B3). To exclude random processes, each experiment was performed three times. In the study, an uncleaned grain mixture of barley was used, with light impurities of 5% and relative humidity of 14%.

The efficiency and accuracy of separation were adopted as optimization criteria expressing the quality of pneumatic centrifugal separation.

The separation efficiency was determined as the ratio of the light fraction separated by the unit to the amount of light impurities in the initial grain mixture. The accuracy of the pneumatic centrifugal separation was characterized by the content of whole grains in the waste.

RESULTS AND DISCUSSION

The input parameters of grains into the air channel, namely the speed and angle of input, have a significant impact on the conditions for separating the components of the grain material. In the practice of grain cleaning, angles of material supply to the air flow are used from 10 degrees in the direction of air movement to 45 degrees against the movement of air flow. In accordance with this, the rotary spreaders of various shapes and geometries are used. With regard to universal vibrocentrifugal separators, the grain material is fed into a conical-annular air channel, where the air flow is directed at an angle near to 45 degrees, both in the horizontal direction and at an angle of 45 degrees towards the flow. A conical spreader with an inclination of the generating cone 45 degrees to the horizon ensures the introduction of material perpendicular to the air flow. In addition, most of the spreader designs have a combined design: a horizontal disc is associated with a cone, with radial blades to give the grain material an initial angular velocity. A conical spreader with an inclination of the generating cone 45 degrees to the horizon ensures the introduction of material perpendicular to the air flow. In addition, most of the spreader designs have a combined design: a horizontal disc is associated with a cone, with radial blades to give the grain material an initial angular velocity.

For a mathematical description of the grains' movement with resistance, we can use classical differential equations (5), adding to them the components that determine the force of resistance to the air environment according to the quadratic law:

$$\begin{cases} \ddot{r} - r \cdot [\omega - \dot{\varphi}]^2 = -f \cdot g \cdot \frac{\dot{r}}{\sqrt{(\dot{r})^2 + (r \cdot \dot{\varphi})^2}} - k_V \cdot \dot{r} \cdot \sqrt{(\dot{r})^2 + (r \cdot \dot{\varphi})^2} \\ r \cdot \ddot{\varphi} - 2 \cdot \dot{r} \cdot [\omega - \dot{\varphi}] = f \cdot g \cdot \frac{r \cdot \dot{\varphi}}{\sqrt{(\dot{r})^2 + (r \cdot \dot{\varphi})^2}} - k_V \cdot r \cdot \dot{\varphi} \cdot \sqrt{(\dot{r})^2 + (r \cdot \dot{\varphi})^2} \end{cases} \quad (8)$$

$$\dot{r} = \frac{dr}{dt}; \; \ddot{r} = \frac{d^2 r}{dt^2}; \; \dot{\varphi} = \frac{d\varphi}{dt}; \; \ddot{\varphi} = \frac{d^2 \varphi}{dt^2} \quad (9)$$

where $\dot{r}$ and $\dot{\varphi}$ are the radial and angular components of grain velocity; f is the coefficient of friction.

Initial conditions are:

$$t = 0; \; \varphi = 0; r = r_0; \; \dot{\varphi} = 0; \; \dot{r} = 0; \; r_0 = \frac{f \cdot [g + 2 \cdot \omega \cdot v]}{\omega^2} \quad (10)$$

If there are radial blades on the surface of a rotating disc, the grain movement in the radial direction will be described by a second-order nonlinear differential equation in the form:

$$\ddot{r} + 2 \cdot f \cdot \omega \cdot \dot{r} - r \cdot [\omega]^2 - k_V \cdot (\dot{r})^2 - f \cdot k_V \cdot [\omega \cdot r]^2 = -f \cdot g \quad (11)$$

A feature of the movement is that the grain is affected by the components of the air resistance force directed against its movement, and the resistance force is perpendicular to the blade, i.e.

$$t = 0; \dot{r} = 0; \; r = r_0 = \frac{f \cdot [g + 2 \cdot \omega \cdot v]}{\omega^2} \quad (12)$$

The solution of the system of nonlinear differential equations was obtained by numerous methods in the MathCad software in the form of trajectories of movement of grain (Figure 4).

The trajectories of movement of grains on the surface of a flat disc are logarithmic spirals, the curvature of which is greater, the greater the resistance coefficient. This is possible due to the fact that with a small value of the resistance coefficient, the value of the relative speed of movement of the grain on the surface of the disc increases, thereby giving the opportunity to leave the surface of the disc faster. This means that at the same angular speed of rotation of the disc, the grain with a higher relative speed will reach the periphery of the disc at a smaller angular coordinate (Figure 4).

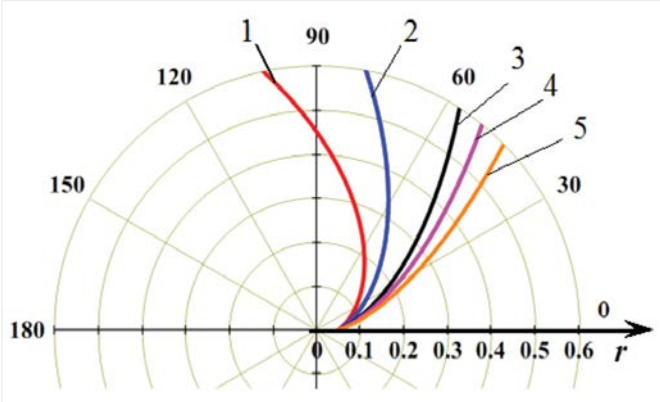


Figure 4. Trajectories of grains movement along the disc for grains with different aerodynamic coefficient, where: 1 – k_V = 1; 2 – k_V = 0.5; 3 – k_V =0.25; 4 – k_V = 0.125; 5 – k_V = 0.06

Figure 5 shows the dependence of the output velocity from the bladed disc depending on the angular velocity for grains of various sizes of k_V.

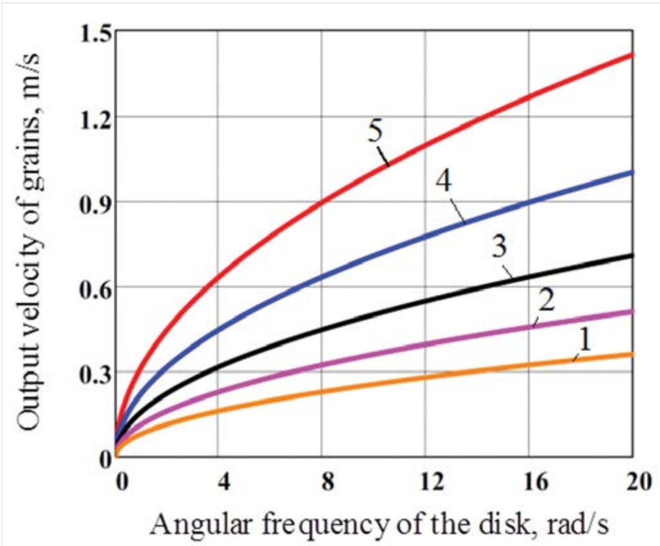


Figure 5. The output velocity of grains from the disc depending on the angular frequency of the disc and various values of grain size k_V, where 1 – k_V = 1; 2 – k_V = 0.5; 3 – k_V = 0.25; 4 – k_V = 0.125; 5 – k_V = 0.06

The rate of grain descent from the flat disc increases non-linearly as the angular speed of rotation of the disc increases (Figure 5). The increment in the value of the rate of grain output from a flat disc increases with a decrease in the resistance coefficient k_V, since with a lower resistance coefficient, an increase in the relative speed of grain movement along the surface of a flat disc is observed.

The process of the grain movement along the conical surface of a rotary spreader is modeled by the following equations:

$$\ddot{r} = r \cdot [\omega - \dot{\varphi}]^2 \cdot [\sin\beta]^2 - g \cdot \cos\beta - \frac{f \cdot \dot{r} \cdot N}{m \cdot \sqrt{(\dot{r})^2 + (r \cdot \dot{\varphi} \cdot \sin\beta)^2}} - -k_V \cdot \dot{r} \cdot \sqrt{(\dot{r})^2 + (r \cdot \dot{\varphi} \cdot \sin\beta)^2} \quad (13)$$

$$\ddot{\varphi} = 2 \cdot r^{-1} \cdot \dot{r} \cdot [\omega - \dot{\varphi}] - \frac{f \cdot N \cdot \dot{\varphi}}{m \cdot \sqrt{(\dot{r})^2 + (r \cdot \dot{\varphi} \cdot \sin\beta)^2}} - k_V \cdot \dot{\varphi} \cdot \sqrt{(\dot{r})^2 + (r \cdot \dot{\varphi} \cdot \sin\beta)^2} \quad (14)$$

$$N = m \cdot [g + r \cdot [\omega - \dot{\varphi}]^2 \cdot \cos\beta] \cdot \sin\beta, \quad (15)$$

where β is half the angle at the top of the cone.

Initial conditions are:

$$t = 0;\ \varphi = \varphi_{disc}; r = R_{disc};\ \dot{\varphi} = \dot{\varphi}_{disc};\ \dot{r} = \dot{R}_{disc};\ \theta = const;\ \omega = const \quad (16)$$

These equations connect the main design and kinematic parameters of a centrifugal cone spreader with the physical and mechanical properties of the grain material (f, k_V) which allows calculating the rational design parameters and operation mode.

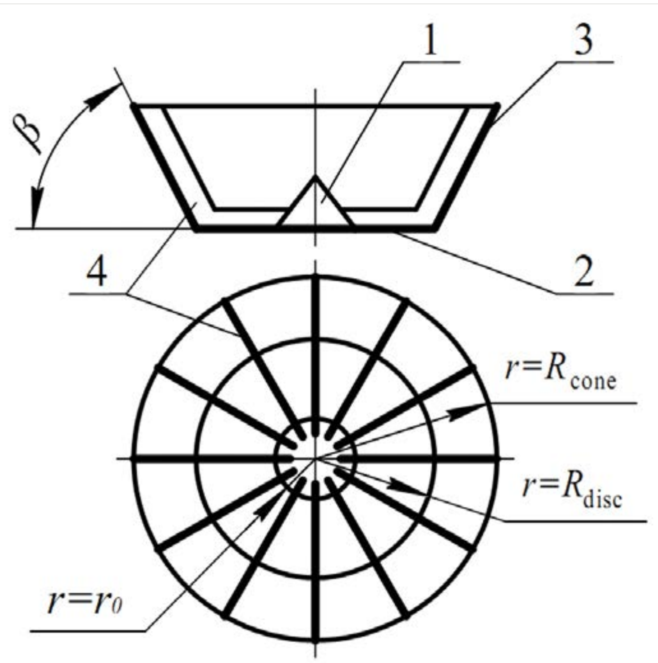


Figure 6. Scheme of a disc-conical spreader with blade partitions where 1 – leveler of grain flow; 2 – disc; 3 – cone; 4 – radial partitions

In the presence of bladed radially installed partitions on the conical surface (Figure 6), the grain movement along the conical surface of the rotary spreader is described by a simpler differential equation, which can be written as:

$$\ddot{r} + 2 \cdot \omega \cdot f \cdot \dot{r} + k_V \cdot \dot{r}^2 + f \cdot \omega^2 \cdot r \cdot [\sin\alpha + r \cdot k_V] + g \cdot [f \cdot \cos\alpha + \sin\alpha] + \omega^2 \cdot r \cdot \cos\alpha = 0 \quad (17)$$

With initial conditions:

$$t = 0; r = R_{disc}; \dot{r} = \dot{R}_{disc} \quad (18)$$

where R_{disc} is the radius of the disc; $\dot{R}_{disc}$ is the grain speed at $r = R_{disc}$.

Figure 7 shows the trajectory of the grain movement along a conical surface without blades and along a conical surface with blades.

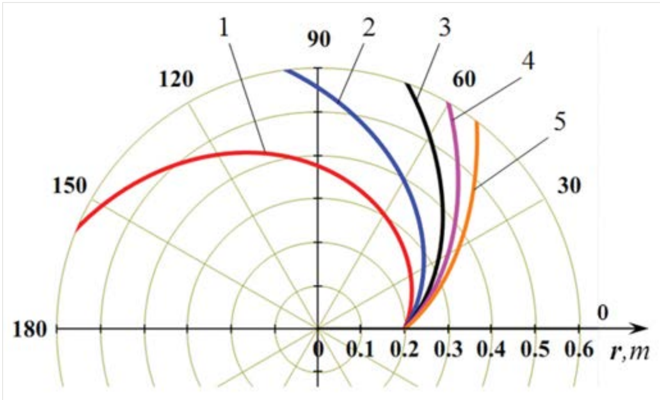


Figure 7. Trajectories of grain movement along the conical surface without blades at different values of k_V where 1 – k_V = 1; 2 – k_V = 0.5; 3 – k_V = 0.25; 4 – k_V = 0.125; 5 – k_V = 0.06

The trajectories of movement of grains on a conical surface (Figure 7) have a similar character to the movement of grains on the surface of a flat disc (Figure 4). The only difference is that when moving along a conical surface, the trajectories are more twisted compared to the trajectories of movement along the surface of a flat disc. This is explained by lower values of the relative speed on a conical surface compared to a flat one, because on a conical surface, the force of gravity is added to the braking force in addition to the resistance of the air medium and friction.

Based on the theoretical investigation of the movement of grain material components in the air channel and on rotary spreaders, the rational parameters of the channel and on spreaders were determined. The width of the pneumatic channel was B = 0.18 m, the angle of inclination of the generatrix to the horizon was 45 degrees. The radius of the spreader cone at the place where the material came off was R_{cone} = 0.36 m, the radius of the disc part was R_{disc} = 0.2 m, the opening angle of the cone was 90 degrees, r_0 = 0.05 m. Based on these data, an improved pneumatic centrifugal separator (Figure 8) was manufactured with the new design of the spreading disc shown in Figure 9.

Figure 8. General view of the improved pneumatic centrifugal separator

According to the results of the conducted experimental studies, the dependence of the influence of the parameters of the experimental spreader on the quality indicators of pneumatic centrifugal separation was established.

Figure 9. General view of the experimental spreading disc

After analyzing the adequacy and significance of the coefficients, the following regression equations were obtained:

$$E = 46.97 + 5.91 \cdot v - 0.002 \cdot n \cdot q \quad (19)$$

$$Y_v = 6.5 - 0.12 \cdot q - 0{,}84 \cdot v + 0.02 \cdot n + 0.0004 \cdot n^2 - 0.01 \cdot n \cdot v - 0.01 \cdot q \cdot v \quad (20)$$

where

- E – separation efficiency indicator;
- Y_v – indicator of the accuracy of separation, mm;
- n – frequency of rotation of the spreading disc, rpm;
- v – velocity of the ascending air stream, m/s;
- q – supply of grain material, t/h.

Graphical dependencies of the efficiency of separation are shown in Figure 10.

Analysis of the graphs presented in Figure 10 shows that when the speed of the ascending airflow is increased to 9 m/s, the efficiency of separation increases significantly and is about 90–98%. An increase in the supply of the grain mixture to the spreading disc worsens the efficiency of separation. The graph in (Figure 10) shows that at a low feed rate of about 5 tons per hour, the rotation frequency of the spreading disc almost does not affect the separation efficiency. With a large supply of grain mixture and a decrease in the speed of the spreading disc from 160 rpm to 100 rpm, the efficiency of separation increases by 7%. Analysis of the surface plot makes it possible to conclude that by increasing the speed of the rising airflow to 9 m/s and reducing the supply of the grain mixture to the spreading disc, the separation efficiency increases.

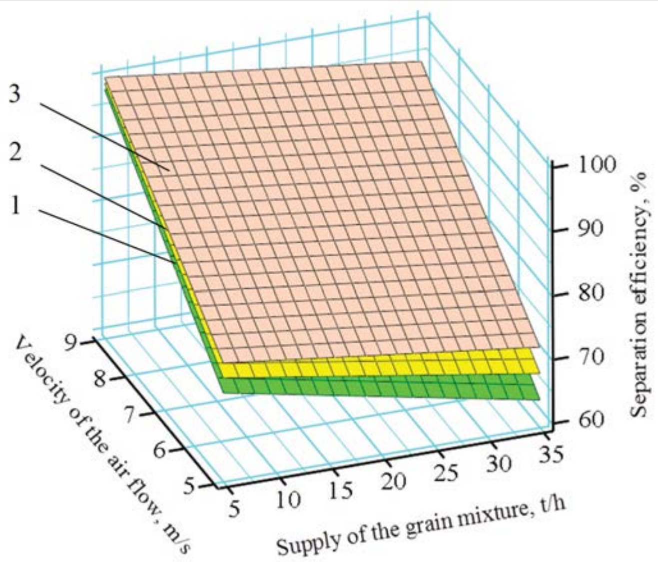


Figure 10. Surface plots of the efficiency of separation from the supply of the grain mixture and the velocity of the air flow at different values of the step of setting k of sectors on the spreading disc, where 1 – n = 100 rpm; 2 – n = 130 rpm; 3 – n = 160 rpm

Thus, at the speed of the rising airflow of 9 m/s, the supply of grain material to the spreading disc is 5 t/h and the rotation frequency is 100 rpm the separation efficiency is the highest and is about 99%.

Figure 11 shows the graphical dependence of the accuracy of pneumatic centrifugal separation, characterized by the content of full-fledged grain in waste, on the rotational speed of the spreading disc ω, the speed of the ascending airflow v, and the supply of grain material q. The graphical dependencies are based on equation (20).

Analysis of the graphs presented in Figure 11 shows that with an increase in the supply of the grain mixture to the spreading disc, the content of full-fledged grain in waste decreases. The content of full-fledged grain in waste also decreases with a decrease in the speed of the air flow. The content of full-fledged grain in waste decreases when the frequency of rotation of the spreading disc increases.

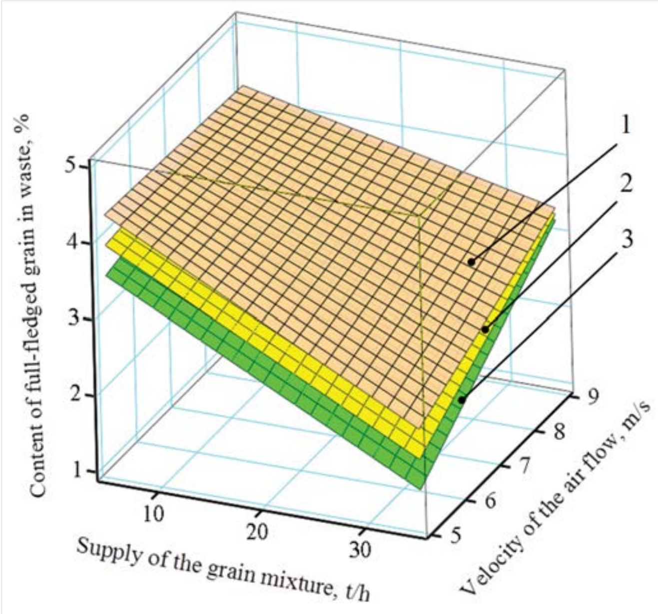


Figure 11. Surface plot of the content of full-fledged grain in waste from the supply of the grain mixture to the spreading disc and the speed of the air flow at different values of the rotation frequency of the spreading disc, where 1 – n = 100 rpm; 2 – n = 130 rpm; 3 – n =160 rpm

CONCLUSIONS

The regularities of grain movement are theoretically determined and an improved mathematical model of the dynamics of solid grain movement in the air stream, which differs from the known ones in that it takes into account the non-uniformity of the velocity field, the action of lateral forces, and the concentration of material, which allowed to increase the splitting of grain movement trajectories by 10–15%.

The solution of the system of nonlinear differential equations with initial conditions performed in the MathCad software environment in the form of grain movement trajectories in an inclined air flow allowed for calculating their movement trajectories differing by the sailing factor and to determine the rational values of the design parameters of the separator.

As a result of experimental studies of the process of fractionation of grain materials in the aspiration chamber, it was found that the rational parameters of the operation of the aspiration chamber are within the following limits: air flow velocity υ = 7.2 – 7.4 m/s; grain supply q = 17–25 t/h; divider speed n = 100–130 rpm. With this, the efficiency of fractionation of grain materials increases to 76-78% and the accuracy of separation to 98.0–98.8%.

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