№ 1 (132) / 2026
Техніка, енергетика, транспорт АПК
ISSN: 2520-6168
Vol. 132, № 1 / 2026
Technology, energy, agriculture transport AIC
UDC 631.362.3
DOI: 10.37128/2520-6168-2026-1-13

STUDY OF GRAIN MATERIAL MOTION IN A VIBRO-CENTRIFUGAL SEPARATOR CONSIDERING KINEMATIC PARAMETERS

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The article investigates the influence of kinematic parameters on the velocity of grain material movement along the working surface of the rotor in a vibro-centrifugal separator. The relevance of the study is determined by the need to increase the efficiency of cleaning and sorting processes of grain mixtures through the use of centrifugal and vibration fields, which enhance the differences between particles in terms of specific mass and aerodynamic properties. The paper examines the mechanics of motion of an individual grain particle on the surface of a conical rotor performing simultaneous rotational and vibrational motion. The main forces acting on the particle during its movement are determined, including the centrifugal inertial force, the inertial force caused by vibrational motion, the gravitational force, the reaction force of the rotor surface, and the friction force between the particle and the working surface.

Based on the analysis of the conditions for continuous contact motion of a particle along the rotor surface, a differential equation describing its motion was obtained, and relationships for determining the displacement and velocity of grain particles depending on the vibration phase were derived. The conditions ensuring stable particle motion in the direction of expansion of the conical rotor with periodic stops were established. An analytical expression for determining the average velocity of grain material movement was obtained, taking into account the vibration amplitude and frequency, the angular velocity of rotor rotation, the cone angle of the working body, and the coefficient of friction between the material and the rotor surface.

The theoretical studies were supplemented by experimental investigations carried out on laboratory and pilot experimental installations, where the influence of rotor rotational speed, grain feed rate, and air flow parameters on the separation efficiency was analyzed. It was established that an increase in the vibration amplitude and frequency, as well as in the angular velocity of the rotor, leads to an increase in the average velocity of grain particle movement along the working surface. The obtained results can be used to substantiate the design and operating parameters of vibro-centrifugal separators and to develop high-performance grain cleaning machines.

Keywords: *grain material, vibro-centrifugal separator, kinematic parameters, particle motion, vibration, centrifugal force, grain separation, grain cleaning.*

Fig. 9. Tabl. 1. Ref. 19.

1. Problem formulation

Cleaning of cereal grains is one of the key stages of post-harvest processing, significantly affecting the quality of the final product, the energy efficiency of technological operations, and the minimization of grain losses. In the technological schemes of grain cleaning machines, various separation principles are employed, among which vibratory-centrifugal and pneumatic-centrifugal separators are distinguished by their ability to intensify the separation of grain mixtures based on the physicomechanical properties of the components.

Article received 12.01.2026. Article accepted 12.02.2026. Article published 17.04.2026.

However, existing designs of such separators often fail to provide the required separation quality due to insufficient theoretical justification of the kinematic parameters of grain movement along the working surface and the interaction of particles with working surfaces under the action of combined forces. In classical approaches, many studies focus on empirical determination of the relationships between performance and process parameters, whereas modern mathematical and mechanistic-mathematical models of grain motion in separators still require more comprehensive scientific development.

In particular, advanced mechanistic-mathematical models of pneumatic-centrifugal separators have demonstrated a critical dependence of separation efficiency on the rotational and vibrational characteristics of the working surface, as well as on the interaction of the grain mixture phases with the airflow, yet further development is needed to account for complex kinematic processes under real operational conditions [1]. Analysis of existing theoretical studies confirms that the trajectories of grain movement, particle velocities, and the effects of vibration parameters and working surface geometry remain insufficiently investigated in the context of their influence on separation quality [2]. Moreover, the mechanisms of interaction between grain particles with walls and force fields under combined vibrational and pneumatic effects are still inadequately studied, limiting the ability to accurately predict separation outcomes and optimally design machine working elements.

Therefore, the development and refinement of theoretical models of grain motion in vibratory-centrifugal and pneumatic-centrifugal separators is a pressing task, taking into account the influence of kinematic parameters (vibration frequency and amplitude, angular velocities, geometric surface parameters, frictional forces, and aerodynamic forces) on separation efficiency. The improvement of such models will contribute to increased productivity and quality of grain cleaning machines through scientifically grounded selection of optimal design and operational parameters and their effect on the movement of particles in the grain medium.

2. Analysis of recent research and publications

In recent years, scientific literature has considered the intensification of grain cleaning processes using force fields generated by vibratory and pneumatic separators as an important scientific and practical problem. In particular, significant attention is paid to the development and improvement of mathematical-mechanical models of grain medium movement in separators to enhance separation quality, as well as to the determination of optimal kinematic parameters and aerodynamic characteristics of the working surfaces.

Studies by other authors have established that grains with higher specific weight are biologically more mature. Sowing with such seeds increases crop yield by 2–5 c/ha. Therefore, the development of new technological processes and machine designs, in which the separation of grain mixtures is carried out based on specific weight, is clearly justified. However, since the differences in specific weight of grains are relatively small (1.2–1.5 g/cm³ for wheat, 1.2–1.4 g/cm³ for barley and oats), it is necessary to place the grains in a centrifugal field to enhance these differences. This can be achieved using centrifuges.

One of the leading directions is the improvement of mechanical-mathematical models of pneumatic-vibratory centrifugal separation of grain material by density, which allows taking into account the interaction between the phases of the grain mixture and the airflow, as well as determining the rational operating parameters of the separator to improve separation efficiency [1, 19].

Research also covers theoretical models of grain mixture movement on working surfaces without sieves and with detailed hydrodynamic modeling of particle motion, allowing the prediction of particle trajectories and component distribution in separators with combined force action. This enables the determination of optimal design and operational parameters affecting separator productivity and separation quality [3, 15, 17, 18].

Some studies are aimed at analyzing kinematic parameters and optimizing the working elements of the separator, including mathematical modeling of grain mixture movement on vertical mesh surfaces of vibratory-centrifugal separators [4, 14, 16].

Numerous publications investigate the energy and design aspects of separators, including methods to improve drive efficiency and reduce operating costs through the use of new drive mechanisms, such as linear electric motors in the drive of vibratory-centrifugal separators [5, 12, 13].

Another direction involves optimizing aerodynamic elements of grain separation in pneumatic channels, taking into account the shape and geometry of the channels, which affects productivity and separation quality [6, 7, 8].

Additionally, important studies focus on particle motion parameters under combined vibratory-pneumatic action, where factors determining particle trajectories and their interaction with the force fields of working surfaces are analyzed [9, 10, 11].

The general conclusion of recent research indicates the need for further development of mathematical models that consider the actual kinematic, aerodynamic, and physico-mechanical parameters of grain mixtures, which will improve the accuracy of representing particle movement effects and the influence of external forces on the separation process.

3. The purpose of the article

The purpose of this article is to investigate the influence of kinematic and aerodynamic parameters on the movement of grain material in vibratory-centrifugal separators, and to develop improved mathematical-mechanical models for predicting particle trajectories and optimizing the separation process based on grain density. The study aims to identify rational operational and design parameters of the separator that enhance separation efficiency, quality, and productivity.

4. Results and discussion

Table 1 presents the results of the fraction analysis of seed mixtures obtained during the cleaning of winter wheat seeds (moisture 13 %) and buckwheat seeds (moisture 11 %) in the course of farm trials of the experimental seed-cleaning machine at the research farm "DPDG Olenivske." The analysis data indicate that the machine's pneumatic separating elements remove the majority of weed seeds while simultaneously sorting the main crop seeds by weight. The absolute weight of seeds removed together with light impurities was 1.7–3 times lower than that of the main fraction seeds. The specific loading of the ring-shaped separating channel reached 25 kg/s·m² with a channel area of 0.24 m².

These results demonstrate the effectiveness of the experimental seed-cleaning machine in achieving simultaneous impurity removal and density-based seed sorting. The observed separation efficiency indicates that the combination of vibratory and pneumatic forces ensures precise particle stratification within the working channels. Furthermore, the obtained data emphasize the importance of optimizing kinematic parameters, such as airflow velocity and vibration amplitude, to enhance the selectivity of the separation process.

In addition, the fraction analysis showed that the optimal combination of design and operational parameters of the separator allows improving both the productivity and quality of seed cleaning while reducing losses of the main crop during the removal of light impurities.

The sieves ensured efficient removal of both fine and coarse impurities from the seeds. In cases where certain impurities could not be completely separated using airflow and sieves - such as wild mustard seeds - additional cleaning was performed using a trieur unit and a pneumatic sorting table. Experimental studies demonstrated the high reliability of the seed-cleaning process of the machine (reliability coefficient 0.99) as well as its considerable technical and economic efficiency.

The centrifugal-pneumatic separator schematic developed at the Institute of Mechanization and Electrification of Agriculture can be applied in the design of high-performance seed-cleaning machines, as well as in the separating units of combines, threshers, and similar agricultural machinery.

To investigate conditions that ensure particle movement within the grain layer, initial experiments were conducted on the CE-3 laboratory centrifuge. These tests revealed that simple rotation of the grain layer alone did not result in particle redistribution. For the experiments, centrifuge cups were filled with grains (wheat or millet), and a few lead balls (diameter 2.5–4 mm) were placed near the rotation axis. The cups were covered with a cardboard lid. When the centrifuge rotated the cups, the lead balls - subjected to an acceleration of $\omega^2 r$ up to 550 m/s² over a rotation period of up to 300 s - remained in their initial positions, as the grain layer merely compacted under the motion.

These observations indicated that, in order for particles to move within the grain layers, a certain level of internal loosening or rarefaction must be created in the treated product. Such rarefaction occurs naturally when the grain layer moves along a rotating conical surface.

The experimental setup consisted of a conical centrifuge, a 1 kW DC motor driving the rotor, and a fan with a gearbox and its own motor. The motor power supply was connected to a system whose working elements were designed as truncated cones with the smaller base at the bottom. In the upper section of the cone, two rows of openings and rings were provided to separate the incoming grain mass into fractions and direct them outward. Grain fractions exiting the cone were collected in slots of the collectors and conveyed via chutes into receiving boxes.

Table 1

Results of the fraction analysis of seed mixtures obtained during the cleaning of seeds using the experimental seed-cleaning machine

Seed fractions and their characteristics	Machine productivity, kg/h during seed cleaning				
	Winter wheat				Buckwheat
	2640	4350	5390	22370	1880
Uncleaned seeds					
Purity, %	94,44	94,92	94,68	90,98	96,40
Absolute seed weight, g	33,26	33,58	33,42	3378	22,75
Number of weed seeds, pcs/kg	2820	1140	8480	6640	440
Cleaned seeds					
Purity, %	99,29	99,00	99,23	98,20	99,96
Yield, % of content in uncleaned seeds					
Absolute seed weight, g	88,58	90,06	90,33	97,84	8150
Number of weed seeds, pcs/kg	36,35	36,19	35,19	35,20	27,00
	0,0	0,0	25	70	0,0
Light impurities (non-seed fraction)					
Seed content, %, relative to the amount in the initial material	0,87	0,78	2,43	0,38	0,27
Absolute seed weight, g	12,10	12,10	13,90	27,20	-
Number of weed seeds, pcs/kg	27000	57100	11000	40800	1300
Light impurities (seed fraction)					
Seed content, %, relative to the amount in the initial material	3,77	2,66	3,27	0,54	12,10
Absolute seed weight, g	17,55	20,00	15,95	17,49	17,12
Number of weed seeds, pcs/kg	23080	19600	15400	43100	1040
Small impurities					
Seed content, %, relative to the amount in the initial material	6,44	6,25	3,76	1,11	8,90
Absolute seed weight, g	19,31	18,75	18,26	18,70	11,12
Number of weed seeds, pcs/kg	1520	1120	1580	8940	200
Large impurities					
Seed content, %, relative to the amount in the initial material	0,34	0,25	0,21	0,13	0,20
Absolute seed weight, g	37,8	37,3	36,0	37,9	14,41
Number of weed seeds, pcs/kg	380	60	424	260	320

Grain from the hoppers flowed by gravity through a stationary funnel and pipe onto the bottom. A air receiver, located below the cone and shaped like a rectangular box, supplied air from the fan through hoses. The air passed through 3 mm holes in the cone into the grain being processed. The holes were positioned behind ledges with a height of 3 mm.

The design of the setup allowed experiments to be conducted with cones having apex angles of α=70°20′;50°40′;37°20′;27°3′;13°12′. The rotation speed of the cones could be adjusted from 0 to 3000 rpm by varying the current in the motor excitation circuit and by repositioning the belt on the pulleys.

The experiments were carried out under the following conditions: Using smooth cones without an airflow at 600, 800, 1000, 1200, 1400 rpm, corresponding to a circumferential speed of the cone surface of 3.8–9.65; 5.2–13; 6.4–16; 7.7–19.3; 9–22.6 m/s for the cone with α=70°20′; Using stepped cones with airflow at 600, 800, 1200, 1600, 2000 rpm, corresponding to a circumferential speed of the cone surface of 2.75–6.8; 3.6–9.1; 5.6–13.65; 7.4–18.2; 9.3–22.8 m/s.

These experimental conditions allowed the study of particle movement under different cone geometries, rotation speeds, and airflow rates, providing valuable data on the combined effects of centrifugal and pneumatic forces on the stratification and separation of grain fractions.

The rotation speeds mentioned above ensured stable movement of the grain layer without causing particle breakage.

In experiments involving airflow through the processed material, measuring the exact air velocity was challenging. The static pressure values were adjusted by installing rings in the fan suction window. Average static pressures during the experiments were 15, 25, 35, 45, and 55 mm H_2O.

The grain feed rate was regulated by the hopper flap opening height within the range of 25–65 mm, corresponding to throughput of 0.9–5.4 t/h.

The material tested was a grain mixture of Krayevyd wheat, obtained from the research farm "DP Olenivske," where it had undergone preliminary cleaning.

To assess the results of the experiments, the following indicators of separation quality were used: the average bulk density of the grain mixture (γ, g/cm³), volumetric weight (weight of 1 L of the mixture, g), and the weight of 1000 grains of the main crop (g).

The average bulk density was determined using technical scales with an accuracy of 0.01 g and a volumeter (Lermontov device) fabricated by the author. The volumeter was calibrated using steel balls. Grain density was also determined using a liquid classifier with a class interval of 0.05 g/cm³.

Linear grain dimensions were measured with a linear classifier developed at the department of the institute. Volumetric weight was determined using a 1-L type A-AP-401 measuring cylinder with an accuracy of 0.5 g. The weight of 1000 grains was obtained by cross-dividing the sample and selecting 500 - 1000 grains, which were weighed on laboratory scales. Material moisture was periodically checked by drying samples of ground grain in a drying oven and reweighing them.

Rotation speed was measured with a tachometer. Air static pressure was measured with a U-tube water manometer, taking into account ambient barometric pressure and temperature.

Experimental results with different cones showed that the most stable grain movement occurred in steel and aluminum cones with apex angles of approximately α=70°20′ and 50°40′. Cones with smaller apex angles retained grain residues inside after the experiments, with the largest amount observed in the cone with an apex angle of α=13°12′.

In smooth cones, lighter grains tended to move closer to the axis of rotation. For example, oats separated from wheat, but within the wheat fraction itself, separation was not observed, as the weight of 1000 grains for both fractions was approximately the same (Fig. 1- Fig. 3).

In the presence of a small smooth surface on the cone - an acceleration platform - along with ledges and holes for air supply, the separation process proceeded according to the following scheme. After falling onto the bottom of the rotating cone, the grain was thrown onto its smooth section. Here, being captured by friction forces, it moved upward toward the ledges. During flight, the grain layer was exposed to air jets, which displaced the lighter particles toward the interior of the cone. The grain repeatedly fell from the ledges several times. At the end of the path, the processed material was divided into two parts: the heavier fraction remained on the outside, while the lighter fraction stayed inside.

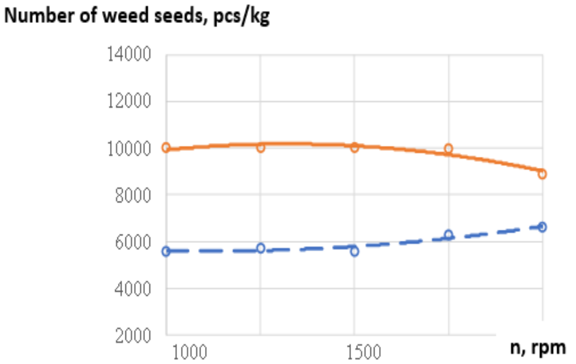

Fig.1. Changes in the number of weed seeds on the rotor speed of the separator

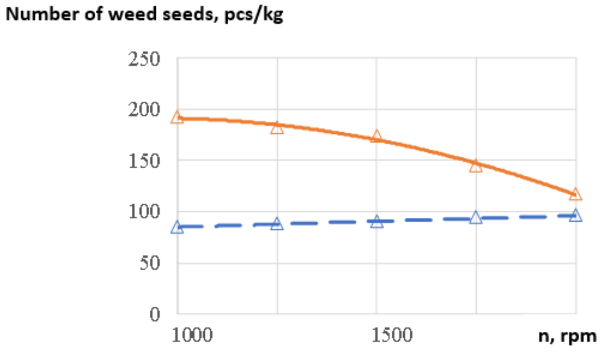

Fig.2. Changes in the oat content in the grain mixture on the rotor speed of the separator

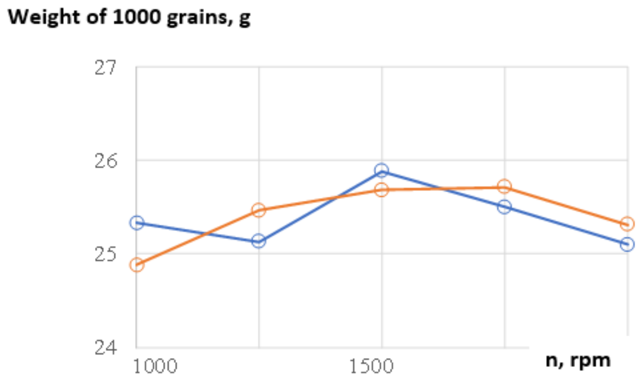

Fig.3. Changes in the weight of 1000 wheat grains depending on the rotor speed of the separator

The use of ledges and the effect of airflow contributed to more efficient separation of the mixture.

Let us consider how the selected quality indicators changed: the bulk density of the grain mixture, volumetric weight, and weight of 1000 grains, depending on the centrifuge rotation speed (*n*), static pressure in the air receiver (P_{ST}), hopper flap opening height (h_b, mm, controlling the grain feed Q), and the number of passes (N), i.e., the number of repeated passes of the heavy fraction.

The average bulk density of the heavy fraction decreased with increasing rotation speed because, at higher speeds, the lighter particles did not have sufficient time to separate due to the rapid movement of the material along the cone surface (Fig. 4- Fig. 6).

The average bulk density and the weight of 1000 grains of the light fraction changed only slightly, while the volumetric weight had a minimum at low rotation speeds; as the rotation speed increased, it quickly approached the value of the first (heavy) fraction.

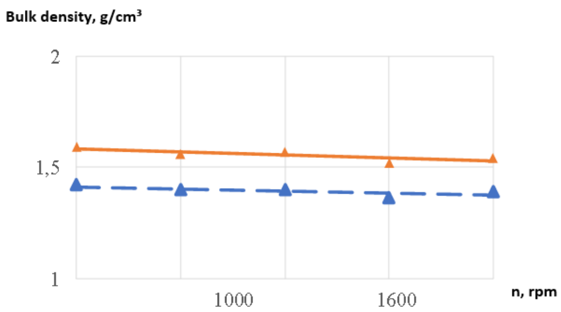

Fig. 4. Changes in the average bulk density depending on the rotor speed

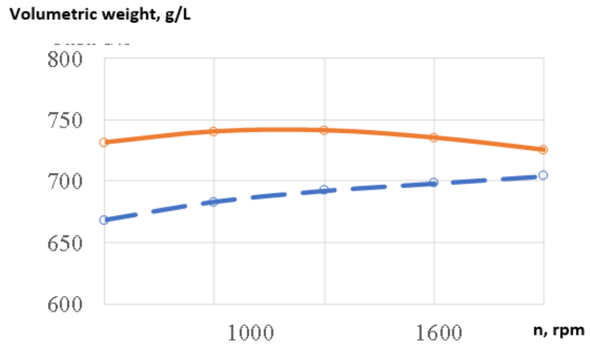

Fig. 5. Changes in volumetric weight depending on the rotor speed

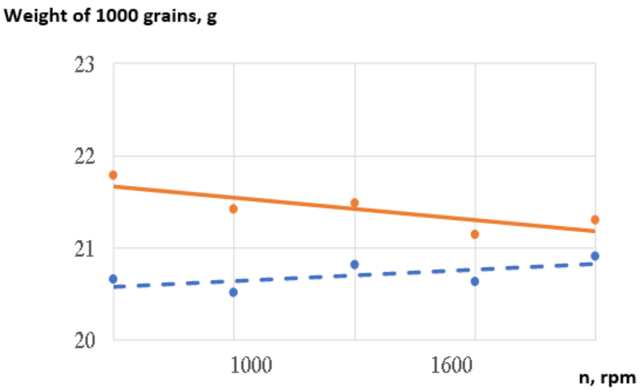

Fig. 6. Changes in the weight of 1000 grains depending on the rotor speed

At a certain rotor speed, a clearly visible optimum of volumetric weight was observed for the main fraction.

With an increase in grain feed, the separation efficiency improved at higher rotor speeds, while at low speeds no significant difference was noted. The average bulk density of the main fraction remained almost unchanged; at the same time, the bulk density of the light fraction increased due to the inflow of heavier grains.

Simultaneously, the volumetric weight and the weight of 1000 grains increased in both fractions, with a slightly faster increase in the light fraction.

Increasing the static air pressure under the cone contributed to better separation of the grain mixture, especially at low cone rotation speeds.

Since the residence time of the mixture in the rotating cone was short (up to 1.2 s), experiments with repeated passes were conducted to determine how the selected indicators changed with extended separation time. In a first approximation, these repeated passes characterized changes in the quality of the heavy fraction as the separation time increased. During the repeated-pass experiments, only the heavy fraction was used, and each light fraction obtained in subsequent trials was excluded from further analysis (Fig. 7- Fig. 9).

Depending on the number of passes, the average bulk density of the main fraction increased slightly, while that of the light fraction increased significantly. The volumetric weight of the light fraction increased faster than that of the heavy fraction, while the weight of 1000 grains increased similarly in both fractions.

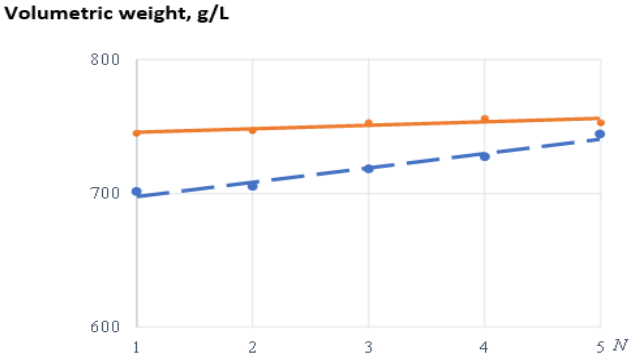

Fig. 7. Changes in grain volumetric weight depending on the number of passes (N) through the separator

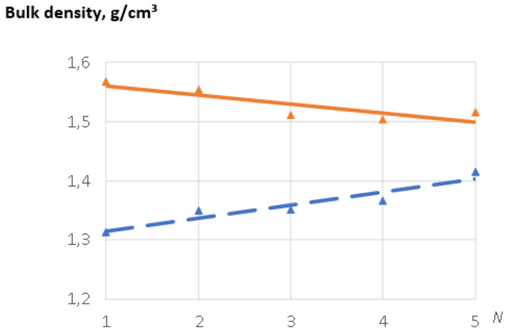

Fig. 8. Changes in average bulk density depending on the number of passes (N) through the separator

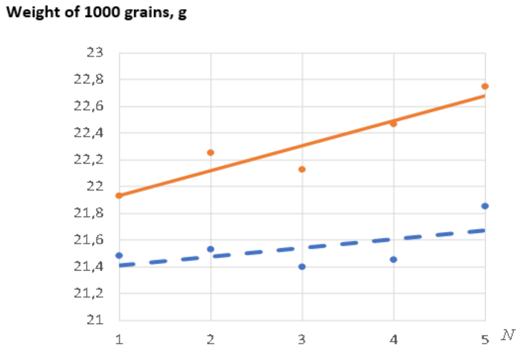

Fig. 9. Change in the bulk weight and absolute weight of 1000 grains depending on the number of passes (N) through the separator

The conducted theoretical and experimental investigations confirmed the significant influence of kinematic and aerodynamic parameters on the movement and separation of grain material in a vibro-centrifugal separator. The analysis of particle motion on the rotating conical surface showed that the combined action of centrifugal, gravitational, frictional, and vibrational inertial forces determines the trajectories and velocities of grain particles and directly affects the efficiency of fraction separation.

Experimental studies demonstrated that the introduction of stepped elements on the conical rotor together with directed airflow considerably intensifies the stratification of grain material according to its physicomechanical properties. Under such conditions, lighter particles are displaced toward the inner part of the cone under the action of air jets, while heavier grains move toward the outer zone under the influence of centrifugal forces. This mechanism ensures effective separation of grain mixtures into fractions differing in bulk density and grain weight.

The obtained results indicate that the quality indicators of separation – bulk density, volumetric weight of the mixture, and the weight of 1000 grains – significantly depend on the rotor rotation speed, grain feed rate, static air pressure, and the number of repeated passes of the material through the separator. An optimal range of rotor rotational speeds was identified, within which the separation process becomes most stable and provides the highest quality of fraction differentiation.

The experiments also confirmed that increasing the static pressure of the supplied air improves the selectivity of separation, especially at relatively low rotational speeds of the rotor. At the same time, repeated passes of the heavy fraction through the separator lead to a gradual improvement of the qualitative indicators of the separated material, which confirms the possibility of intensifying the cleaning process by increasing the duration of separation.

The obtained theoretical dependences and experimental results create a scientific basis for further improvement of the design and operating modes of vibro-centrifugal grain separators and can be used in the development of high-performance grain cleaning and sorting machines.

5. Conclusion

The conducted theoretical and experimental studies made it possible to determine the main regularities of grain material movement on the working surface of a vibro-centrifugal separator rotor. It was established that the motion of individual particles is determined by the combined action of centrifugal force, inertial forces caused by vibrational motion, gravitational force, friction forces, and the reaction of the working surface. The interaction of these forces forms the trajectories of grain particles and determines the efficiency of their separation according to physicomechanical properties.

It was experimentally confirmed that the grain mixture in a centrifuge does not separate when only rotational motion is applied. Under such conditions, the grain layer is compacted and rotates together with the working body, which prevents the redistribution of particles within the layer and does not ensure effective fraction separation.

In a centrifuge with a smooth conical surface, a certain degree of stratification of the grain mixture can occur due to the influence of centrifugal forces. In particular, partial separation of oats from wheat was observed. However, separation within the wheat fraction itself was practically absent because the grains had similar physical characteristics, including the weight of 1000 grains and specific density.

Effective separation of the grain mixture in the centrifuge occurs when stepped elements are present on the working surface of the cone and when air passes through the moving grain layer. In this case, the grain repeatedly moves along the cone surface and falls from the ledges, while the air jets act on the moving particles. Under the influence of aerodynamic forces, lighter particles are displaced toward the inner zone of the cone, whereas heavier grains move toward the outer zone under the action of centrifugal forces. This combined mechanism significantly increases the efficiency of fraction separation.

The experimental results showed that the quality indicators of separation, such as the average bulk density of the grain mixture, volumetric weight, and the weight of 1000 grains, depend on the kinematic and aerodynamic parameters of the separator. In particular, rotor rotational speed, grain feed rate, static air pressure under the cone, and the number of repeated passes of the material through the separator significantly affect the separation efficiency.

An optimal range of rotor rotational speeds was identified in which the separation process is the most stable and provides the best differentiation of grain fractions. At excessively high rotational speeds, the material moves too quickly along the cone surface, and light particles do not have sufficient time to separate from the main fraction, which reduces the effectiveness of the separation process.

It was also established that increasing the static pressure of the air supplied under the cone contributes to improved separation of the grain mixture, especially at relatively low rotor speeds. Repeated passes of the heavy fraction through the separator lead to gradual improvement in the qualitative characteristics of the material, which confirms the possibility of intensifying the cleaning process by increasing the effective separation time.

The obtained theoretical relationships and experimental results can be used to substantiate the rational design and operating parameters of vibro-centrifugal grain separators and may serve as a basis for the development of high-performance grain cleaning and sorting machines.

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ДОСЛІДЖЕННЯ РУХУ ЗЕРНОВОГО МАТЕРІАЛУ У ВІБРОВІДЦЕНТРОВОМУ СЕПАРАТОРІ З УРАХУВАННЯМ КІНЕМАТИЧНИХ ПАРАМЕТРІВ

У статті досліджено вплив кінематичних параметрів на швидкість переміщення зернового матеріалу по робочій поверхні ротора у вібровідцентровому сепараторі. Актуальність дослідження зумовлена необхідністю підвищення ефективності процесів очищення та сортування зернових сумішей шляхом використання відцентрових і вібраційних полів, які посилюють відмінності між частинками за питомою масою та аеродинамічними властивостями. У роботі розглянуто механіку руху окремої зернівки по поверхні конічного ротора, що здійснює одночасний обертальний і вібраційний рух. Визначено основні сили, що діють на частинку під час її переміщення, зокрема відцентрову інерційну силу, інерційну силу, зумовлену вібраційним рухом, силу тяжіння, реакцію поверхні ротора та силу тертя між частинкою і робочою поверхнею.

На основі аналізу умов безперервного контактного руху частинки по поверхні ротора отримано диференціальне рівняння, що описує її рух, та виведено залежності для визначення переміщення і швидкості зернових частинок залежно від фази вібрації. Встановлено умови, що забезпечують стійкий рух частинок у напрямку розширення конічного ротора з періодичними зупинками. Отримано аналітичний вираз для визначення середньої швидкості переміщення зернового матеріалу з урахуванням амплітуди та частоти вібрації, кутової швидкості обертання ротора, кута конуса робочого органа та коефіцієнта тертя між матеріалом і поверхнею ротора.

Теоретичні дослідження були доповнені експериментальними випробуваннями, проведеними на лабораторних і дослідно-експериментальних установках, де проаналізовано вплив частоти обертання ротора, подачі зерна та параметрів повітряного потоку на ефективність сепарації. Встановлено, що збільшення амплітуди та частоти вібрації, а також кутової швидкості обертання ротора призводить до зростання середньої швидкості переміщення зернових частинок по робочій поверхні. Отримані результати можуть бути використані для обґрунтування конструктивних і режимних параметрів вібровідцентрових сепараторів та розроблення високопродуктивних машин для очищення зерна.

Ключові слова: *зерновий матеріал, вібровідцентровий сепаратор, кінематичні параметри, рух частинок, вібрація, відцентрова сила, сепарація зерна, очищення зерна.*

Рис. 9. Табл. 1. Літ. 19.

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