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PROVING THE POSSIBILITY TO RATIONALIZE THE PROCESS OF SEED MATERIALS SEPARATION WITH A VIBRO-PNEUMATIC CENTRIFUGAL SEPARATOR USING A THEORETICAL MODEL

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The object of research is the seed material and working bodies of a vibro-pneumatic centrifugal separator; the subject is their interaction. The established surfaces, which are the results of the simulation of the process of separation of seed materials in the vibro-pneumatic centrifugal separator, have a curve to the plane whose parameters are the speed of the air flow and the frequency of oscillations of the working surface. It is noted that this nature of the dependence of the purity of the «heavy» fraction of seeds on parameters of the separation process makes it possible to determine the rational ranges of these parameters, at which the maximum value of this characteristic is reached. Experimental simulation of the separation process in the vibro-pneumatic centrifugal separator of wheat, sunflower, and soybean seed materials under production conditions showed a high convergence of the results with the results of the simulation of the process under the same initial conditions. It was established that the correlation coefficients between the points obtained experimentally and obtained by simulation for the given results are in the range from 0.89 to 0.95. At the same time, the differences are the purity values of the «heavy» seed fraction, and not in the nature of its change due to changes in the parameters of the separation process. The expediency of using modeling when determining the rational values of the parameters of the separation process in the vibro-pneumatic centrifugal separator is noted. This will help increase the energy and resource efficiency of the equipment due to the absence of the need for experimental setup. The rational ranges of air flow speed and vibration frequency of the rotor of the vibro-pneumatic centrifugal separator for the separation of seed materials have been determined: wheat – 1.2…1.5 m/s; 4500…5100 cycles per minute; sunflower – 1.3…1.5 m/s; 4500…5000 cycles per minute; soybeans – 1.3…1.6 m/s; 5000…5500 cycles per minute

Keywords: vibro-pneumatic centrifugal separator, density of seed material, multiphase medium, fluid, separation parameters

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1. Introduction

An increase in gross grain production depends on high-quality seed material. The quality of the seed material is due to the use of high-performance equipment, frugal with grain, which implements the grain production process, and effective and scientifically based technological lines with its use. All the above components are mandatory and mutually integrated and inextricably linked.

High yields cannot be obtained without the use of high-quality seed material with high germination energy and biological activity [1]. It has been proven [2] that a significant amount (sometimes up to 90 % depending on the culture and specificity of processing) of seeds does not meet the condition requirements. Seeds can be injured (micro and macro injuries), affected by pests, not cleaned, etc. These factors significantly reduce the purity of the seeds and, accordingly, the yield of the crop during cultivation. Injured and poorly cleaned seeds complicate the process of long-term preservation, as they increase the possibility of the self-heating effect, in which the entire batch of seeds can be lost. The use of injured seeds or seeds with reduced biological potential reduces the field germination of the crop by up to 45 %. Sprouts from such seed material are significantly slower in development, lagging behind in growth from the main population, as they have an understated development potential.

Incorrectly selected equipment for a certain technological line can also injure high-quality seed material. Working bodies of grain cleaning and transporting machines when interacting with grain injure both the shell and the germ of the grain. Failure to observe the technology of drying and subsequent cooling can significantly affect the biological quality of grain.

The technological line for the preparation of seed material includes a certain range of separating, calibrating, transporting, and drying machines and equipment. At the initial stage of cleaning, the grain heap is cleaned of easily separated impurities. Next is the calibration process, during which the grain is calibrated according to geometric parameters. To separate difficult-to-separate impurities, precision cleaning machines that separate material by seed density have shown high efficiency. Using the seed's natural density as a distinguishing feature, it is possible to effectively distinguish grain that is geometrically within normal limits, but has injuries, damage by pests and/or has internal defects.

Pneumatic separation tables and vibro-pneumatic centrifugal separators and vibro-pneumatic centrifuges showed high efficiency when separating seed material by seed density.

However, it is necessary to note the imperfection of existing machines that perform the process, the incorrectness of the developed technological processes, and the insufficient research into these processes. This is what makes the study on optimizing the kinematic and structural parameters of vibro-pneumatic centrifugal separators and bringing them to a clear relationship with the physical and mechanical properties of the material relevant.

2. Literature review and problem statement

There are a number of theoretical studies and engineering-technical scientific solutions that seek to solve the problem of obtaining seeds with high biological potential. Separating machines that separate material on a flat work surface (pneumo-separating tables, pneumatic pulse separators, etc.) are considered in a large number of works [3]. However, not enough attention has been paid to the processes of separation of seed material by cylindrical working surfaces of rotation.

Study [4] addresses the mechanization of post-harvest processing of grain. The issue of increasing the efficiency of the grain separation process based on a complex of physical and mechanical parameters is considered. However, the study is focused exclusively on the processes of sunflower separation. Work [5] simulates the process of grain heap separation. The capacity of the separation apparatus of the primary cleaning was thoroughly considered. Work [6] considers similar studies. The results obtained in these works are of practical importance and simulate the process of separating sunflower seeds but only take into account the influence of the kinematic and structural parameters of the corresponding grain cleaning machine. Paper [7] gives the results of mathematical modeling of the processes of separation of seed materials by seed density by pneumatic separation tables. Despite the fact that both pneumatic separation tables and vibro-pneumatic centrifugal separators use seed density as a sign of separation, the factors that bring the layer of seed material to a pseudo-liquefied state differ significantly. The authors of study [8] reported the results of research into the reduction of seed losses during post-harvest processing. The complex problem of preparation of seed material at the defining stages of the process has been studied. Potential losses in the production of rice, wheat, and corn seeds are given. However, the authors do not provide recommendations for reducing such losses. In work [9], the problem of separation of granular material under the influence of air flow is considered. Factors preventing the efficient separation of difficult-to-separate impurities were studied. Mathematical models for determining the trajectories of difficult-to-separate impurities have been obtained, and the relevance of preliminary stratification of materials with the development of relevant dependences has been given. The research takes into account the influence of the simultaneous supply of particles of the light fraction and the design parameters of the operation of the pneumatic separating machine. The work does not take into account the complex interaction of particles of the heavy and light fraction and the air flow. In [10], the process of separation of grain materials according to aerodynamic properties is considered. An improved design of the aspiration separator has been developed, in which the work process takes place using vibration processes. In the separator, the air flow of constant pressure acts on the seed material and causes self-oscillation in the separator pipe, which, in turn, causes centrifugal forces of inertia. Under this influence, material particles of different densities acquire different velocities and move along their own trajectories. The speed of particle movement was from 3.2 m/s to 8 m/s. At the same time, the particles are accelerated from 1.8 m/s^2 to 3.3 m/s^2, which can negatively affect the process of seed injury. It is known [11] that at particle movement speeds exceeding 6 m/s, it is possible to cause micro- and macro-trauma to grains. In work [12], the process of separating safflower seeds, which is a grain crop that is difficult to clean, was investigated. Since safflower is sown early, a large number of difficult-to-separate impurities gets into its heap during harvesting. The authors substantiated the perspective of placing additional mechanical process intensifiers on the working surface. Such intensifiers, however, on the one hand increase the productivity of the process, on the other increase the percentage of injured seeds. In work [13], the process of granular separation without the use of reagents under thermostatic conditions was investigated. Owing to this method, a reduction in the energy costs of the process is achieved. The method was tested on loose materials of granular composition. During the mathematical modeling of the process, the authors did not take into account the change in the physical and mechanical parameters of the raw material and the determining influence of such parameters on the process.

Our review of the literature on scientific and technical research and development to solve the problem of obtaining high-quality seed material by separating it by seed density shows the following. Most authors conducted research into the separation process on flat working surfaces, and insufficient attention was paid to separation on cylindrical surfaces. To a greater extent, researchers considered ways to intensify the process, without taking into account its thriftiness to the grain. During the mathematical modeling, the movement of a single particle was considered without its interaction with the layer.

Thus, it is necessary to optimize the structural and kinematic parameters of the vibro-pneumatic centrifugal separator when working with a specific grain crop.

3. The aim and objectives of the study

The purpose of this study is to prove the possibility of applying a physical-mathematical model, based on the calculation of the trajectories of the movement of raw material particles between the working bodies of the separator, to determine the rational parameters of the grain mass separation process. This will make it possible to increase the efficiency of seed separation from the grain mass in the vibro-pneumatic centrifugal separator.

To achieve the goal, the following tasks were set:

– to simulate the process of separating wheat, sunflower, and soybean seed materials depending on the main parameters of this process using a model based on the calculation of the trajectories of the movement of raw material particles between the working bodies of the separator;

– to conduct separation of seed materials of wheat, sunflower, and soybean under production conditions, compare them with the results of modeling, and determine the rational values of parameters of the separation process for different raw materials.

4. The study materials and methods

The object of research is the seed material, working parts of the vibro-pneumatic centrifugal separator. The subject of the study is the interaction of the working bodies of the vibro-pneumatic centrifugal separator with the physical and mechanical properties of the particles of the grain mass of the raw material, the influence of the physical and mechanical properties of seeds on the indicators of the efficiency of the technological process of separation.

The research was carried out on a vibro-pneumatic centrifugal separator [14] (Fig. 1). The working algorithm of the vibro-pneumatic centrifugal separator is as follows. The material received for processing is fed to a rotating disc spreader through the loading device. From the disc spreader, the material falls in a concentric layer onto the cylindrical working surface of the rotor of the vibro-pneumatic separator. Since the working surface rotates around the stationary axis of the vibro-pneumatic centrifugal separator, the seed material is pressed against the working surface under the action of centrifugal force. Then, under the influence of its natural weight and the force of inertia from the vibrations of the working surface, it begins to move from the top (loading) to the bottom (before unloading). A layer of seed material is blown by an air stream. Under the complex influence of the forces of inertia from the working surface of the separator and the air flow, the seed layer loosens and acquires the properties of a pseudo-fluid. At the same time, material particles with a higher density sink under the action of centrifugal force and are located in concentric layers near the working surface, while particles with a lower density move in the surface layer (float). The stratified material moves to unloading, where it is divided into appropriate trays by fractions.

The seed material received for processing was grain mass after secondary processing, i.e., after separation of fodder waste, light waste, coarse and fine impurities. Based on this, it was believed that biologically active seeds with the highest density fall into the «heavy» fraction moving along the working surface. Diseased and damaged grain with low density and low germination energy falls into the «light» fraction.

Fig. 1. General view of the experimental vibro-pneumatic centrifugal separator

Cereal crops with the following characteristics were used as an object of research:

1) winter wheat (variety «Kharkivska-99»): the weight of 1000 grains equals 38 g, nature – 0.750 kg/dm^3, particle density – 0.780 kg/dm^3, humidity – 13 %;

2) sunflower seeds (sunflower confectionary SPK): the mass of 1000 seeds equals 43 g, nature – 0.360 kg/dm^3, density – 0.440 kg/dm^3, humidity – 7 %);

3) soybean grain (Fortuna variety): the weight of 100 grains is 142 g, particle density is 0.800 kg/dm^3, moisture content is 11 %.

Preliminary studies of the separation process allow us to identify the parameters that have the main influence on the process. These parameters are seed density; frequency of oscillations of the working surface; amplitude of oscillations of the working surface; air flow speed at the entrance to the seed layer.

Determining the rational parameters of the seed separation process by seed density in the vibro-pneumatic centrifugal one included two stages. At the first stage, modeling of the grain mass separation process was carried out depending on the main parameters of this process. At the second stage, grain mass separation was carried out under production conditions depending on the same parameters.

5. Results of research into the influence of parameters of the separation process of a vibro-pneumatic centrifugal separator on seed quality

5. 1. Results of simulation of the grain mass separation process depending on the main parameters of the process

The parameters of the vibro-pneumatic centrifugal separator, which are considered in the study, are the frequency of oscillations of the working surface (rotor) and the speed of the air flow. Based on this, it was expedient to carry out a two-factor simulation of the seed mass separation process, where one factor is the frequency of rotor oscillations, and the second is the speed of the air flow. Modeling was carried out as follows.

In work [14], the task of describing the relative movement of the *i*-th circular layer of raw materials with a certain density, taking into account the frequency of oscillations of the working surfaces of the vibro-pneumatic centrifugal separator and the speed of the air flow, which gives the raw materials the properties of a fluidized medium, is set. One of the solutions to this problem is the value of the radius of the i-th circular layer of raw materials at the exit from the separator. That is, the coordinates of the location of particles with a certain density before their removal to the collection hopper are known.

Limit values of the density of the raw material for which the simulation was carried out were determined according to its type and varietal characteristics. The limit values of the density mean the density of the «light» (sick and damaged seeds) and «heavy» (biologically active seeds) fractions.

Next, it is assumed that particles with a certain density hit the corresponding coordinate subject to the law of normal distribution. At the same time, the coordinates of fractions with different densities represent a mathematical expectation in a normal distribution:

$$f(x)=\frac{1}{\sigma\sqrt{2\pi}}\exp\left(-\frac{(x-r_i)^2}{2\sigma^2}\right), \tag{1}$$

where $f_i(x)$ is the probability distribution function of coordinate x; σ^2 – variance of the coordinate; r_i is the radius of the i-th circular layer of raw materials at the exit from the separator (mathematical expectation).

The density of the raw material to be separated changes from its minimum value to its maximum value not discretely but continuously. At the same time, there is no information on the distribution of the number of raw material particles by density. Taking into account these factors complicates the task and makes it impossible to solve it accurately. Based on this, the task was simplified: the distribution functions were calculated for the averaged density values of the so-called «light» and «heavy» fractions of the seed material; the variance of the coordinate was assumed to be equal to one. It should be noted that the separation of raw materials in this design of the vibro-pneumatic centrifugal separator is carried out into two fractions, which makes this simplification permissible.

For clarity, Fig. 2 shows the distribution functions of the probability of finding «light» and «heavy» fractions of raw materials before their removal to collection hoppers after separation under the same parameters of the separation process (air flow speed υ and rotor oscillation frequency ν).

The example is given for the case of a constant frequency of rotor oscillations and for two values of air flow speed (υ=1 m/s – solid line; υ=1.5 m/s – dashed line). The x coordinate on the plot is normalized to the maximum value of the distance x_{max} between the working bodies of the vibro-pneumatic centrifugal separator, which are coaxial hollow cylinders. The wall coordinate of the inner working surface (hollow cylinder with a smaller radius) is 0, and the coordinate of the outer working surface (cylinder with a larger radius) is x_{max}. At the same time, it was assumed that the separation between the collecting hoppers is at a distance of $0.5 \cdot x_{max}$ from each of the working surfaces.

Based on the fact that the separation between the collection hoppers has a coordinate of $0.5 \cdot x_{max}$, it should obviously be assumed that the share of the «heavy» fraction, the particles of which will have a coordinate of less than $0.5 \cdot x_{max}$, will fall into the hopper intended for the «light» fraction of seed material. The same conclusion can be drawn for part of the «light» fraction, the particles of which will have a coordinate greater than $0.5 \cdot x_{max}$. The result will be a decrease in the quality of the obtained seeds.

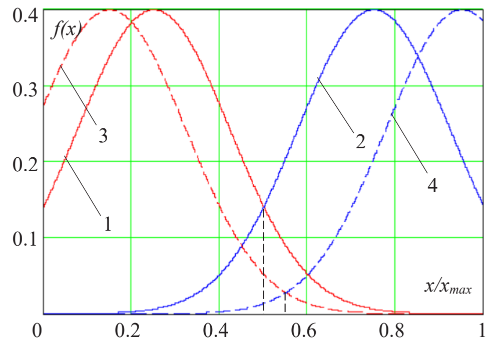

Fig. 2. Probability distribution functions of coordinates of «light» and «heavy» fractions of seed material at different air flow speeds during separation in a vibro-pneumatic centrifugal separator: 1 – «light» fraction, υ=1 m/s, ν=4000 cycles per minute; 2 – «heavy» fraction, υ=1 m/s, ν=4000 cycles per minute; 3 – «light» fraction, υ=1.5 m/s, ν=4000 cycles per minute; 4 – «heavy» fraction, υ=1.5 m/s, ν=4000 cycles per minute

One can find the number of particles of «light» and «heavy» fractions of seed material that fall into the hoppers designated, respectively, for the «light» (i=1) and «heavy» (i=2) fractions as follows:

$$S_1 = N_1 \cdot \int_{-\infty}^{0.5 \cdot x_{max}} f_1(x)\mathrm{d}x + N_2 \cdot \int_{-\infty}^{0.5 \cdot x_{max}} f_2(x)\mathrm{d}x, \tag{2}$$

$$S_2 = N_1 \cdot \int_{0.5 \cdot x_{max}}^{+\infty} f_1(x)\mathrm{d}x + N_2 \cdot \int_{0.5 \cdot x_{max}}^{+\infty} f_2(x)\mathrm{d}x, \tag{3}$$

where S_1 and S_2 are the number of particles in the bunkers designated, respectively, for «light» (i=1) and «heavy» (i=2) fractions; $f_1(x)$ and $f_1(x)$ are probability distribution functions for particles of the «light» (i=1) and «heavy» (i=2) fractions; N_1 and N_2 are the number of particles of the «light» (i=1) and «heavy» (i=2) fractions in the raw material, i.e., the seed material received for processing.

Since the final product of separation in the vibro-pneumatic centrifugal separator considered in the paper is the seed, the purity of the «heavy» fraction should be considered a criterion for the efficiency of the separation process. Purity of the «heavy» fraction means the ratio of the number of particles of the «heavy» fraction in the corresponding hopper (i=2) to the total number of particles in it:

$$Purity = \frac{N_2 \cdot \int_{0.5 \cdot x_{max}}^{+\infty} f_2(x)\mathrm{d}x}{N_1 \cdot \int_{0.5 \cdot x_{max}}^{+\infty} f_1(x)\mathrm{d}x + N_2 \cdot \int_{0.5 \cdot x_{max}}^{+\infty} f_2(x)\mathrm{d}x}. \tag{4}$$

Considering that there is no density distribution of particles in the original seed material between the «light» and «heavy» fractions, it is assumed that $N_1=N_2$. Taking this into account, for (4) we can obtain:

$$Purity = \frac{N \cdot \int_{0.5 \cdot x_{max}}^{+\infty} f_2(x)\mathrm{d}x}{N \cdot \int_{0.5 \cdot x_{max}}^{+\infty} f_1(x)\mathrm{d}x + N_2 \cdot \int_{0.5 \cdot x_{max}}^{+\infty} f_2(x)\mathrm{d}x} \cdot 100\,\% =$$

$$= \frac{\int_{0.5 \cdot x_{max}}^{+\infty} f_2(x)\mathrm{d}x}{\int_{0.5 \cdot x_{max}}^{+\infty} f_1(x)\mathrm{d}x + \int_{0.5 \cdot x_{max}}^{+\infty} f_2(x)\mathrm{d}x} \cdot 100\,\%. \tag{5}$$

From Fig. 2, it can be seen that the purity of the «heavy» fraction will be determined by the parameters of the separation process: the area of the distribution functions within $[0.5 \cdot x_{max}, +\infty)$ will be different for different values of the air flow rate and the rotor oscillation frequency.

The value of the purity of the «heavy» fraction was determined for the values of the air flow speed and the rotor oscillation frequency from the following ranges: air flow speed – 1...2 m/s; frequency of oscillations of the working surface (rotor) – 4000...6000 cycles per minute. The discreteness of the air flow speed change during simulation was chosen as a multiple of 0.1 m/s. The frequency of rotor oscillations varied with discreteness – 250 cycles per minute.

Calculation of the purity of the «heavy» fraction was carried out with alternate changes of the selected parameters of the separation process. That is, at a constant value of the rotor oscillation frequency, the speed of the air flow was changed with the appropriate discreteness, while for each value of the speed, the purity of the «heavy» fraction was calculated. Next, the frequency of oscillations was increased by the amount of the discreteness of its change, and the purity was calculated at different speeds of the air flow.

The values of the purity of the «heavy» fraction obtained by modeling at different air flow rates and the values of the purity of the «heavy» fraction at different frequencies of rotor oscillations were approximated by polynomial functions of the form:

$$F(Purity) = \sum_{j=0}^{n} a_j \cdot Purity^j, \quad (6)$$

where a_j are approximation coefficients; n is the power of the polynomial.

Thus, approximation functions were obtained that describe the change in the purity of the «heavy» fraction for changes in the air flow rate at different values of the rotor oscillation frequency, and approximation functions that describe the change in the purity of the «heavy» fraction for changes in the rotor oscillation frequency at different values of the air flow speed.

For clarity, the results of the simulation of the seed material separation process in the vibro-pneumatic centrifugal separator are shown in the form of surfaces. At the same time, simplification is made due to the use of a quadratic model, where the arguments are the speed of the air flow (υ) and the frequency of the rotor oscillations (ν) (Figs. 3–5).

The quadratic regression equations took the following form:

$$Purity(\upsilon,\nu)=94.556+3.333\cdot\upsilon+2.333\cdot\nu-15.333\cdot\upsilon^2-6.333\cdot\nu^2-1.5\cdot\upsilon\cdot\nu, \quad (7)$$

$$Purity(\upsilon,\nu)=97.556+13.167\cdot\upsilon+0.583\cdot\nu-25.333\cdot\upsilon^2-2.083\cdot\nu^2-0.5\cdot\upsilon\cdot\nu, \quad (8)$$

$$Purity(\upsilon,\nu)=95.889+3.667\cdot\upsilon+1.167\cdot\nu-17.333\cdot\upsilon^2-9.833\cdot\nu^2+0.5\cdot\upsilon\cdot\nu. \quad (9)$$

The raw materials used in the study were seed materials of wheat, sunflower, and soybean. The shape and size of the main fraction of these types of raw materials and the average density of the raw materials are given in Table 1.

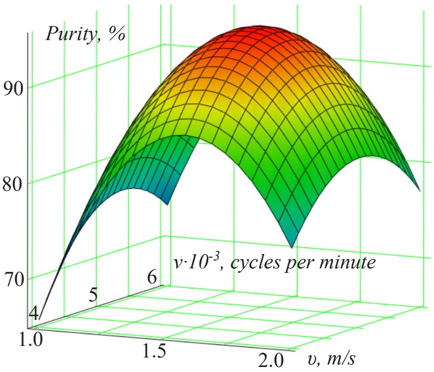

Fig. 3. Results of simulation of changes in the purity of the «heavy» fraction of wheat grain depending on the frequency of oscillations of the working surface and the speed of the air flow at the entrance to the seed layer

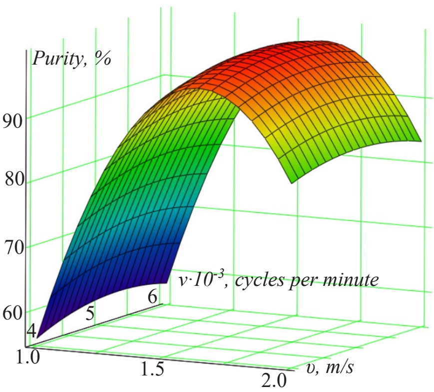

Fig. 4. Results of simulation of changes in the purity of the «heavy» fraction of sunflower seeds depending on the frequency of oscillations of the working surface and the speed of the air flow at the entrance to the seed layer

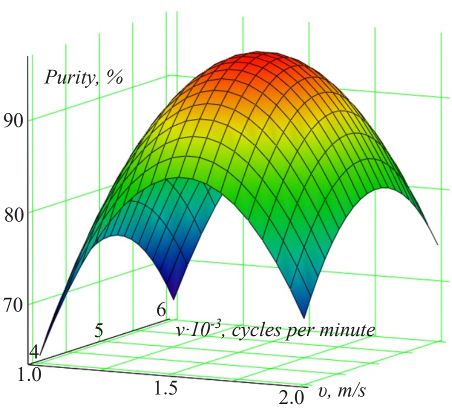

Fig. 5. Results of modeling the change in the purity of the «heavy» fraction of soybean seeds depending on the frequency of oscillations of the working surface and the speed of the air flow at the entrance to the seed layer

Table 1

The shape, size, and average density of the «heavy» fraction of the raw material

Raw material	Grain shape	Average characteristic sizes $a \times b \times c$, mm	Mean density, kg/m^3
Wheat	elliptical	3×3×8	780
Sunflower	triangular	11×5×3	440
Soy	round	6×6×6	800

The shape, size, and average density of the «heavy» fraction of the raw material are among the initial data for calculating the trajectory of the movement of raw material particles in the process of separating seed material by a vibro-pneumatic centrifugal separator.

5. 2. Results of the grain mass separation process depending on the main parameters of the process, obtained under production conditions

Raw materials used for research under production conditions were also seed materials of wheat, sunflower, and soybean. Separation of seed material was carried out under production conditions on a vibro-pneumatic centrifugal separator, which is shown in Fig. 1.

The ranges of initial data that were used during the experimental simulation of the process of separation of seed material by a vibro-pneumatic centrifugal separator are given in Table 2. Experimental modeling means the result of seed separation obtained under production conditions.

Table 2

Ranges of the output data on the parameters of a vibro-pneumatic centrifugal separator

Parameter	Range
Specific load, kg/m^3	2.5...3.0
Frequency of oscillation of the work surface, s^{-1} (cycles per minute)	67 (4000)...100 (6000)
The speed of airflow at the inlet to the layer, m/s	1...2
Electric motor power, kW	0.8
Fan power, m^3/min	280

Separation under production conditions was carried out as follows. The seed material obtained after secondary processing of the grain mass of the corresponding crop was subjected to separation in a vibro-pneumatic centrifugal separator. At the same time, the raw material after processing was divided into two bunkers: a bunker with seeds and a bunker with diseased and broken grain. Next, the batch from the hopper with seeds was disassembled manually and the number of particles of the «light» (N_1) fraction (diseased and broken grain) and the number of particles of the «heavy» (N_2) fraction in the total number of particles ($N=N_1+N_2$) were determined. The purity of the «heavy» fraction was calculated according to (10):

$$Purity_{\text{exp.}} = \frac{N_2}{N_1+N_2}. \qquad (10)$$

At the same time, the speed of the air flow varied in the range from 1 to 2 m/s with the discreteness of the change as a multiple of 0.25 m/s. The frequency of the rotor oscillations varied in the range from 4000 to 6000 revolutions per minute with a discreteness of change of 500 revolutions per minute.

Experimental points obtained in this way were fitted with polynomial functions of form (6) for clarity.

Fig. 6–11 simultaneously show the results of the separation of seed materials in a vibro-pneumatic centrifugal separator depending on the main parameters of the process, obtained by modeling (solid lines) and the results obtained under production conditions (dashed lines).

The simultaneous presentation of the results of the separation of seed materials of wheat, sunflower, and soybean, obtained by simulation and under production conditions, was carried out in order to compare the results obtained by different methods. At the same time, there is an opportunity to visually prove the adequacy of the applied mechano-mathematical model and to determine the rational values of the parameters of the separation process for various raw materials.

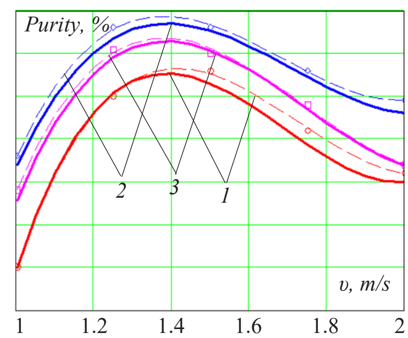

Fig. 6. Purity of the «heavy» fraction of wheat seeds, obtained by modeling the separation process (solid lines) and the separation of seed material under production conditions (dashed lines), depending on the speed of the air flow, m/s: 1 – 1; 2 – 1.5; 3 – 2

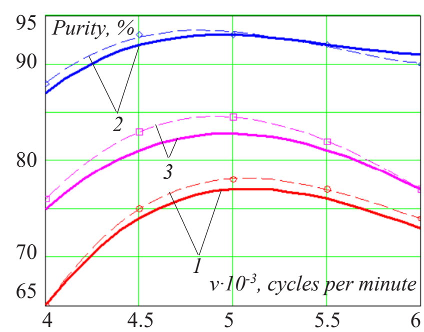

Fig. 7. Purity of the «heavy» fraction of wheat seeds, obtained by modeling the separation process (solid lines) and the separation of seed material under production conditions (dashed lines), depending on the frequency of rotor oscillations, cycles per minute: 1 – 4000; 2 – 5000; 3 – 6000

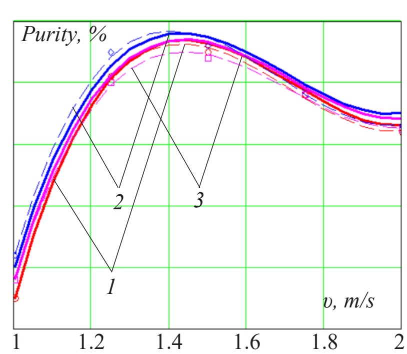

Fig. 8. Purity of the «heavy» fraction of sunflower seeds, obtained by modeling the separation process (solid lines) and the separation of seed material under production conditions (dashed lines), depending on the speed of the air flow, m/s: 1 – 1; 2 – 1.5; 3 – 2

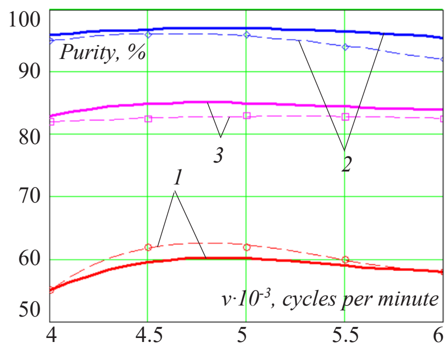

Fig. 9. Purity of the «heavy» fraction of sunflower seeds, obtained by modeling the separation process (solid lines) and the separation of seed material under production conditions (dashed lines), depending on the frequency of rotor oscillations, cycles per minute: 1 – 4000; 2 – 5000; 3 – 6000

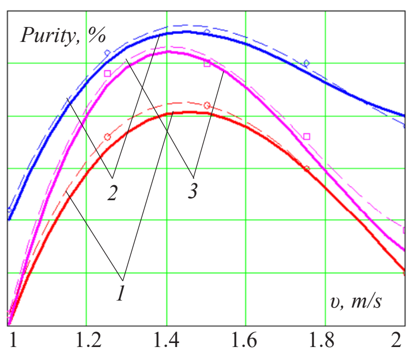

Fig. 10. Purity of the «heavy» fraction of soybean seeds, obtained by modeling the separation process (solid lines) and the separation of seed material under production conditions (dashed lines), depending on the speed of the air flow, m/s: 1 – 1; 2 – 1.5; 3 – 2

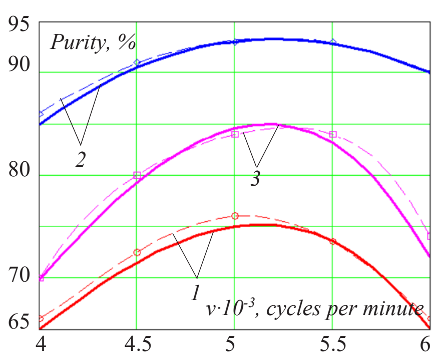

Fig. 11. Purity of the «heavy» fraction of soybean seeds, obtained by modeling the separation process (solid lines) and the separation of seed material under production conditions (dashed lines), depending on the frequency of rotor oscillations, cycles per minute: 1 – 4000; 2 – 5000; 3 – 6000

6. Discussion of results of the simulation of the seed material separation process in a vibro-pneumatic centrifugal separator

Surfaces from Fig. 3–5, which are the results of modeling the process of separating seed materials in a vibro-pneumatic centrifugal separator, have a bend to the Oυ×Oν plane. Here, the speed of the air flow (υ) and the frequency of the rotor oscillations (ν) are parameters that change the purity of the «heavy» fraction obtained from the seeds. This indicates that there are ranges of air flow speed and rotor oscillation frequency during the separation of seed materials, at which the maximum purity of the «heavy» fraction of these mixtures is achieved. Obviously, these ranges should be considered reasonable.

A similar result was obtained during the separation of the same seed materials in a vibro-pneumatic centrifugal separator under production conditions, that is, experimentally (Fig. 6–11). Dependences of the purity of the «heavy» fraction of the seed obtained as a result of processing have a bend relative to the axes on which the velocity of the air flow (dashed lines in Fig. 6, 8, 10) and the frequency of rotor oscillations (dashed lines plotted in Fig. 7, 9, 11).

It should be noted that the dependences of the purity of the «heavy» fraction of the studied cultures, obtained by modeling (solid lines), and the dependences obtained under production conditions (dashed lines), for the same values of the parameters of the separation process, have close values. Determination of the correlation coefficients between the points obtained experimentally and obtained by simulation for the given results show that the values of these coefficients are in the range from 0.89 to 0.95. The results shown in Fig. 9 have the lowest correlation coefficient. However, the differences are in the values of purity of the «heavy» seed fraction, and not in the nature of its change due to changes in the parameters of the separation process. This may be due to the assumptions made during the simulation.

This result allows us to state that the developed mechano-mathematical model of wheat, sunflower, and soybean seed separation by a vibro-pneumatic centrifugal separator can be used to find rational values of the parameters of this process. It refers to the theoretical variation of such parameters of the separation process as the speed of the air flow and the frequency of oscillations of the rotor of the vibro-pneumatic centrifugal separator.

According to the given results (Fig. 6–11), the ranges of rational values of air flow speed and vibration frequency of the vibro-pneumatic centrifugal separator rotor were determined. In these ranges, during the separation of the seed material, the maximum purity of the «heavy» fraction of the seed, which is the final product of the process, is achieved.

The ranges of these parameters of the vibro-pneumatic centrifugal separator for the studied raw materials are as follows:

– wheat grain: air flow speed 1.2...1.5 m/s; rotor oscillation frequency – 4500...5100 cycles per minute;

– sunflower seeds: air flow speed 1.3...1.5 m/s; rotor oscillation frequency – 4500...5000 cycles per minute;

– soybean: air flow speed 1.3...1.6 m/s; rotor oscillation frequency – 5000...5500 cycles per minute.

Thus, the final data of the variation using the mechanical-mathematical model are the ranges of rational values of the speed of the air flow and the frequency of oscillations of the rotor of the separator. With these rational values, the maximum purity of the «heavy» fraction of the final products (seeds) is achieved. The obvious advantages of this method are the absence of mandatory experimental studies to determine the rational values of the specified parameters of the separation process. Compared, for example, with the results of works [9, 10], this significantly simplifies the setting of the vibro-pneumatic centrifugal separator, and also contributes to its energy and resource efficiency due to the absence of the need for experimental setting.

The disadvantage of the study is that both during the simulation of the separation process and during its implementation under production conditions, variations were carried out with a limited number of determining parameters. That is, the research was carried out at different frequencies of oscillations of the working surface and the speed of the air flow at the entrance to the seed layer. At the same time, such parameters as, for example, the amplitude of vibrations of the working surface or the frequency of rotation of the disk spreader were not taken into account.

A limitation of the study is that the raw materials for theoretical and experimental modeling were only seed materials of wheat, sunflower, and soybean, which does not cover a wide range of agricultural raw materials that can be processed. The extension of the research results, namely, the determination of the rational parameters of the separation process in the vibro-pneumatic centrifugal separator for other seed materials is a prospect for further research.

7. Conclusions

1. The established surfaces, which are the results of the simulation of the process of separation of seed materials in the vibro-pneumatic centrifugal separator, have a curve to the plane, the parameters of which are the speed of the air flow and the frequency of oscillations of the working surface. It is noted that this nature of the dependence of the purity of the «heavy» fraction of seeds on the parameters of the separation process makes it possible to determine the rational ranges of these parameters, at which the maximum value of this characteristic is reached.

2. Experimental simulation of the separation process in the vibro-pneumatic centrifugal separator of wheat, sunflower, and soybean seed materials under production conditions showed a high convergence of the results with the results of the simulation of the process under the same initial conditions. It was established that the correlation coefficients between the points obtained experimentally and obtained by simulation for the given results are in the range from 0.89 to 0.95. At the same time, the differences are in the purity values of the «heavy» seed fraction, and not in the nature of its change due to changes in the parameters of the separation process. The expediency of using modeling when determining the rational values of the parameters of the separation process in the vibro-pneumatic centrifugal separator is noted. This will help increase the energy and resource efficiency of the equipment due to the absence of the need for experimental setup. The rational ranges of air flow speed and vibration frequency of the rotor of the vibro-pneumatic centrifugal separator for the separation of seed materials have been determined: wheat – 1.2...1.5 m/s; 4500...5100 cycles per minute; sunflower – 1.3...1.5 m/s; 4500...5000 cycles per minute; soybeans – 1.3...1.6 m/s; 5000...5500 cycles per minute.

Conflicts 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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