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EXPERIMENTAL STUDY OF THE PROCESS OF GRAIN CLEANING IN A VIBRO-PNEUMATIC RESISTANT SEPARATOR WITH PASSIVE WEEDERS

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Abstract: *The article is devoted to increasing the efficiency of the process of vibro-pneumatic separation of grain and seeds by the intensification of the separation process under the additional influence on the grain layer of directive forces on particles. Through mechanical-mathematical and simulation models of particle movement in a grain layer and on a sieve surface, taking into account the separators of grain material, the layer dynamics of the mixture as well as the individual particle movement in the layer and their relationship with the constructive-kinematic and regime parameters of the vibro-pneumatic separation process have been identified.*

Key words: *grain mixture, vibro-pneumatic separator, grain separation, artificial braking, vibroseive surface.*

1. Introduction

Separation is one of the most important postharvest grain processing operations [6]. The analysis of existing separation methods [8] and technical means [9] that implement them, reveals that the available equipment according to its technological characteristics: productivity, efficiency, energy and material consumption and reliability does not confirm the modern requirements of grain production and its processing in farm conditions.

The possibilities of increasing the productivity and efficiency of the most widespread - flat-rate vibration separators are practically exhausted [13]. The gain in the throughput of machines occurs, as a rule, by increasing the surface of the lattices, which causes an excessive growth in the material and energy consumption of the working units [1].

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Despite the significant amount of theoretical and experimental research on grain separation processes [4], devoted to the problem of intensification of grain separation [10], the possibility of increasing the technical and technological efficiency of grain separators [7] has not been exhausted yet.

One of the drastic methods in the development of the productivity of vibrative machines [12], while maintaining or improving the quality of the process, can be an expansion of the specific load on the grid surface [18]. But for this purpose, it is necessary to solve the problem of the enhancement of the sifting system "grain layer - a sieve" [16].

The main aim of the study is to increase the specific productivity, reduce material and energy consumption of vibro-pneumatic separators (in a normalized quality of grain cleaning) by intensifying the loosening of the grain layer by increasing specific load.

2. Material and Method

Theoretical studies have been conducted by using the general provisions of the theory of vibration displacement, as well as the mechanics of solid and friable agents. The solution of the obtained equations was abided by analytically and by using computer technologies (environment MathCad-13, MatLab-6).

Experimental research was carried out on laboratory installations and experimental samples of grain separators using the theory of planning the experiments and the statistical processing of experimental data on a PC [2]. The determination of qualitative indices and production tests were undertaken according to the technique of grain cleaning machines probation [17].

The research program was provided to determine the identification parameters of the mathematical model and its appropriateness to verify the theoretical studies data to establish the quality of separation depending on the process parameters and working units in a wide range of factors [14].

To conduct the experiments, laboratory and experimental installations of flat-vibration separators have been established. In the physical simulation of processes [5], laws of similarity were taken into account, which include the geometric analogy of the structural variable as well as the similarity of the tides of air and grain material. To establish the influence of the velocity values of the relocation, the rate of immersion of the particle in the fluidized material, as well as to determine the effect of the specific loading of the sieve on the efficiency of the separation process, studies of the vibro-pneumatic grain separation on a flat grating with the change of the kinematic and aerodynamic parameters of the process were created [11]. The rate of submersion of a particle in a vibrational environment was determined by the length of the measured path, which passed the fraction for a fixed period of time [20]. The speed of the grain layer movement on an inclined lattice surface was determined by particle biding in vibrosieve, which have been visually identified at a constant length of working sieves [19].

The separation quality study was conducted using standard methods on artificially clogged barley grain (Figure 1). Significant factors changed at three levels within the following limits:

q_F – specific load on 1dc^2 sieve q_F = 40-60 kg/(dc^2·hour);

V_B – the speed of the injection air flow V_B = 0–1.5m/s;

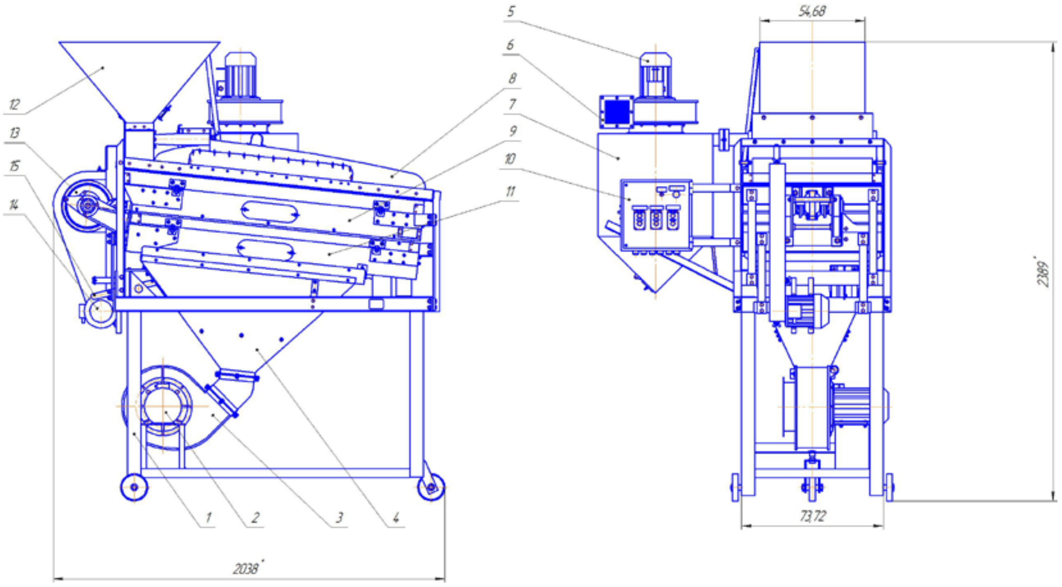
n_w – the density of the installed passive weeder on 1dm^2 sieve n_w = 0–15p./dm^2;

α – the angle of tilt of the working units to the horizon α = 0 –10°;

ω – the oscillation frequency of the sieve, ω = 30–80s^{-1};

S_w – diagonal step of arrangement of mechanical runners S_w = 10–120 mm.

When conducting factor experiments, Hartley's plan for B6 was implemented.



a.

b.

Fig. 1. *Design scheme (a) and general type (b) of vibro-pneumatic grain separator with intensive grain layer loosening: 1 – frame; 2 – discharge fan; 3 – direction of air flow; 4 – injection chamber; 5 – asynchronous motor; 6 – suction fan; 7 – sedimentary hopper; 8 – aspiration sleeve; 9, 11 – upper and lower vibrosieves; 10 – automatic control unit; 12 – hopper; 13 – vibration actuator; 14 – pulley; 15 – adjusting rod*

Analysis of the results of researches and constructions of the working units of grain separators made it possible to conclude that increasing the efficiency of separation, reducing the specific energy and material loads, and increasing the peak productivity can be achieved by raising the load on the sieve while simultaneously loosening the grain layer [15]. It is established that the intensity of separation increases with increasing porosity of the grain layer. However [3] the magnification degree of the grain layer loosening only due to the intensification of the kinematic regime causes a decrease in the separation efficiency of the grain mixture with gain in the specific load.

In order to enhance the porosity of the grain layer, raise the specific productivity and the quality of the lattice separation under rational kinematic regimes, which ensure the optimum screening of the sieve, it is promising to use passive weeders (Figure 1), made in the form of immersed in a grain layer, fixed relative to a sieve, braking rods (pins) with a different resistance coefficient relative to the sieve movement direction. Based on the analysis of the proposed construct of the vibro-pneumatic grain separator with intensive grain layer loosening (Figure 1).

3. Results and Discussion

3.1. Results of Simulation

To simplify the problems of theoretical studies, a cylindrical form of passive weeders is adopted, its surface has a different value of the friction coefficient in reference to the movement of the grain layer along the surface in the oscillatory motion of the sieves "forward" and "back" according to the $y = A \cdot \sin(\omega \cdot t)$ law.

The particle, which is in the vibro-pneumatic medium (Figure 2), is affected by the forces: gravity P in the gravity force field; resistant force; the ejecting force of Archimedes; force of resistance of air stream; force of inertia in portable motion; the ejection force caused by the interaction of the vibration-fluidized layer with the surface of the resistor, which prevents the movement of the grain layer.

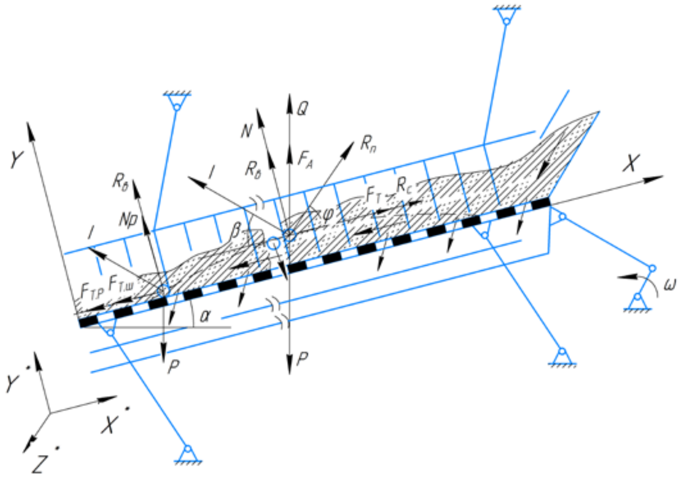


Fig. 2. *Calculation scheme of the force interaction of the particle with the grain layer in the process of separation in the case where the plane of oscillation of the sieve is located at an angle to the horizon*

In the vector form, the equation of motion of a particle in the grain layer is:

$$m \cdot \overline{a} = \overline{P} + \overline{R}_c + \overline{F}_A + \overline{P}_B + \overline{I} + \overline{Q} \tag{1}$$

where:

m is the mass of the particle [kg];

$\bar{\alpha}$ – acceleration [m/s^2].

As the particle moves in the plane, a mechanical-mathematical model is obtained in the form of a system of differential equations, which describes the motion of the particle in a free medium located on the oscillating lattice:

$$\begin{cases} m \cdot \ddot{x} = m \cdot (\Delta - 1) \cdot g \cdot \sin\alpha \pm m \cdot (\Delta - 1) \cdot A \cdot \omega^2 \cdot \sin(\omega \cdot t) \cdot \cos\beta - R_X(\varepsilon) \cdot \dfrac{\dot{x}}{\sqrt{\dot{x}^2 + \dot{y}^2}}; \\ m \cdot \ddot{y} = m \cdot (\Delta - 1) \cdot g \cdot \cos\alpha \pm m \cdot (\Delta - 1) \cdot A \cdot \omega^2 \cdot \sin(\omega \cdot t) \cdot \sin\beta - R_Y(\varepsilon) \cdot \dfrac{\dot{y}}{\sqrt{\dot{x}^2 + \dot{y}^2}} + \\ + f(Re) \cdot F_m \cdot \rho_n \cdot \dfrac{(\dot{y} \pm V_B)^2}{2} + \dfrac{4}{3} \cdot \pi \cdot r_ч{}^2 \cdot \rho_C(\varepsilon) \cdot g \cdot \dfrac{\sum n_i \cdot S_{wi}}{F_P} \cdot (H_w - y - r_w) \cdot \left[1 + 2 \cdot tg^2(\dfrac{\pi}{4} + \dfrac{\varphi}{2})\right] \cdot \sin\alpha; \end{cases} \tag{2}$$

$$\Delta = \frac{\rho_r}{\rho_C(\varepsilon)}; \quad \rho_C(\varepsilon) = \rho_r \cdot (1 - \varepsilon); \quad S_{wi} = \frac{\pi \cdot d_w^2}{4}; \quad Hw = \frac{q_F \cdot t}{\rho_C(\varepsilon)}; \tag{3}$$

$$R_{X,Y}(\varepsilon) = 3 \cdot \pi \cdot \rho_C(\varepsilon) \cdot \nu_{X,Y} \cdot d_r; \quad f(Re) = 13 \cdot \left(4{,}8 \cdot \varepsilon^{2{,}6} \cdot \frac{V_B}{\nu_Y} \cdot d_r\right)^{-0{,}5}; \tag{4}$$

where:

ρ_r is the particle density [kg/m^3];

$\rho_C(\varepsilon)$ – the dynamic density of the medium that is a function of porosity [kg/m^3];

ε – porosity of the grain layer;

α – angle of inclination of the plane to the horizon [deg.];

A – the amplitude of the sieve oscillations [m];

ω – oscillation frequency of the sieve [s^{-1}];

t – time [s];

β – angle between vibration direction and plane (vibration angle) [deg.];

$R_{X,Y}(\varepsilon)$ – the resistance of the medium, which is a function of porosity [N];

$\upsilon_{X,Y}$ – the coefficient of kinematic viscosity of the medium [m^2/s];

μ – coefficient of dynamic viscosity of the medium [(kg·m)/s];

d_r – equivalent grain diameter [m];

$f(Re)$ – coefficient of aerodynamic resistance;

V_B – filtration rate of air flow [m/s];

F_m – the area of the midsection of the particle [m^2];

ρ_n – the density of the air flow [kg/m^3];

r_w – the radius of the particle [m];

H_w – height of the grain layer [m];

$\sum n_i \cdot S_{w.i}$ – the total cross-sectional area of the pin loosers [m^2];

$n_{w.i}$ – the density of the installed passive weeder per 1 dm^2 of the sieve [p/dm^2];

$S_{w.i}$ – cross-sectional area of the pin binder [m^2];

F_p – working area of the sieve [m^2];

φ – angle of internal friction;

d_w – the diameter of the pin binder [m];

q_F – unit load [kg/(dm^2·h)].

To analyze the particle motion by system (2), a simulation model (Simulink package of MatLab environment) was created as a functional block (Figure 3).

The solution of system (2) with the help of the obtained model allows to determine the coordinates of the motion of the particle and according to the structure of the trajectory of motion (Figure 4).

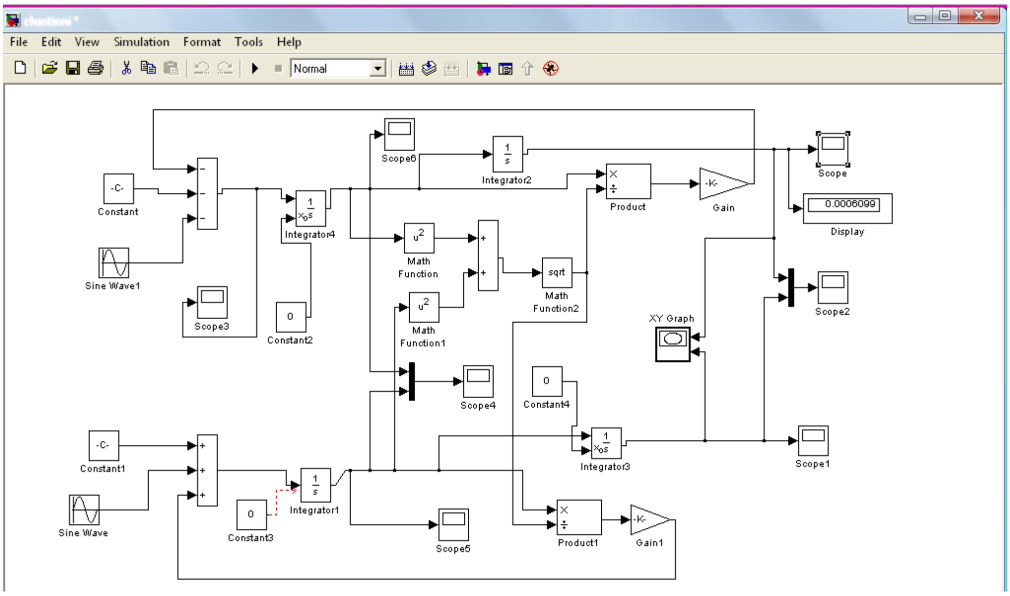
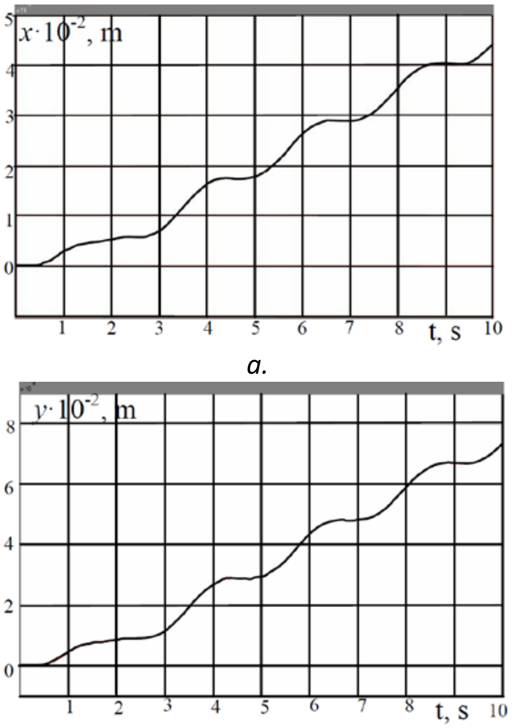


Fig. 3. *A simulation model of particle motion in a vibro-pneumatic grain layer*



a.

b.

Fig. 4. *Graphical interpretation of the particle motion in the vibro-pneumatic grain layer relative to the x (a) and y (b) axes*

The analysis of the particle motion on the simulation model made it possible to establish that, when moving a particle with a higher density than the average particles, the velocity of movement in the vertical direction does not exceed 6 mm/s, therefore, using the hypothesis of the nature of the motion of the particle according to the Stokes law, the differential system Equations (2) can be simplified by replacing the force of resistance R_c by the force of viscous friction.

In order to further obtain closed solutions, the force of interaction of the particle with the vibration medium is assumed to be proportional to the velocity of its movement in the layer. Within these assumptions, the coordinates of the trajectory of the particle satisfy the system of unrelated linear differential equations, which can be written as:

$$\begin{cases} m \cdot \ddot{x} = m \cdot (\Delta - 1) \cdot g \cdot \sin\alpha \pm m \cdot (\Delta - 1) \times \\ \times A \cdot \omega^2 \cdot \sin(\omega \cdot t) \cdot \cos\beta - R_X(\varepsilon) \cdot \dot{x}; \\ m \cdot \ddot{y} = m \cdot (\Delta - 1) \cdot g \cdot \cos\alpha \pm m \cdot (\Delta - 1) \times \\ \times A \cdot \omega^2 \cdot \sin(\omega \cdot t) \cdot \sin\beta - R_Y(\varepsilon) \cdot \dot{y} + \\ + f(Re) \cdot F_m \cdot \rho_n \cdot \frac{V_B^2}{2} + \frac{4}{3} \cdot \pi \cdot r_w{}^2 \times \\ \times \rho_C(\varepsilon) \cdot g \cdot \frac{\sum n_i \cdot S_{wi}}{F_P} \cdot (H_w - y - r_w) \times \\ \times \left[1 + 2 \cdot tg^2 (\frac{\pi}{4} + \frac{\varphi}{2}) \right] \cdot \sin\alpha; \end{cases} \tag{5}$$

All members of the right-hand side of equation (5) are a function of the porosity of the vibro-pneumatic liquefied layer, the value of which depends on the kinematic, technological, and structural parameters of the working units. Analytical dependence was obtained by analysis of theoretical references and experimental data:

$$\varepsilon = 0{,}45 \cdot V_B^{1{,}4} \cdot \omega^{0{,}98} \cdot d_w^{-2{,}47} \cdot n_w^{0{,}47}, \tag{6}$$

where:

V_B – the velocity of the air flow supplied under the sieve [m/s];

d_w – the diameter of the pin binder [m];

n_w – the density of the pin loosers per 1 dm^2 of the sieve [p/dm^2].

Dependence (6) is valid for:

V_B = 0–1.4 m/s;

ω = 50–70 s^{-1};

d_w = 0–12mm;

n_w = 0–25p./dm^2;

A = 5mm.

By solving the equations of system (5), the final expressions were obtained to determine the coordinates of particle.

The dependences of the relative displacement of the particle on time are shown in Figures 5 to 9.

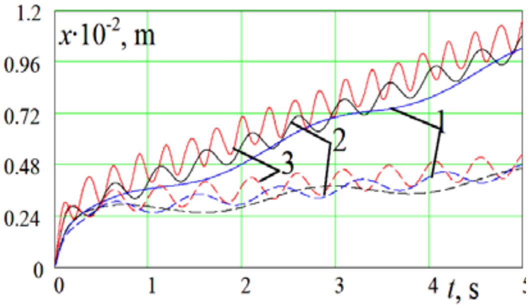


Fig. 5. *Graph of the particle displacement along the x axis from the time of seed separation t at different values of the kinematic mode:*
1 – ω = 50 s^{-1}; 2 – ω = 60 s^{-1}; 3 – ω = 70 s^{-1};
—— with baking powder;
- - - without baking powder

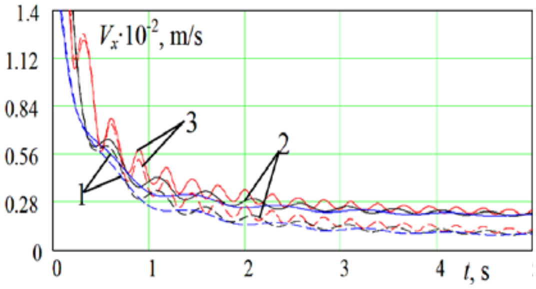


Fig. 6. *The speed of the particles inside the layer on the x-axis of the separation time t at different values of the kinematic mode:*
1 – ω = 50 s^{-1}; 2 – ω = 60 s^{-1}; 3 – ω = 70 s^{-1};
—— with baking powder;
- - - without baking powder

As a result, the intersection of the *Z*-graphs and the separation efficiency *E* gives the optimum point, which has the highest efficiency and the highest degree of separation. The highest separation efficiency *E* = 71.8% and the highest separation clarity *Z* = 98.3% can be achieved simultaneously at air flow velocity υ = 7m/s.

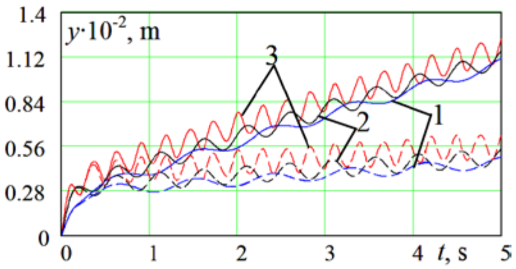


Fig. 7. *The plot of the displacement of the particle along the y-axis from the time of seed separation t at different values of the kinematic mode:*
1 – ω= 50 s^{-1}; 2 – ω = 60 s^{-1}; 3 – ω = 70 s^{-1};
—— with weeder; - - - without weeder

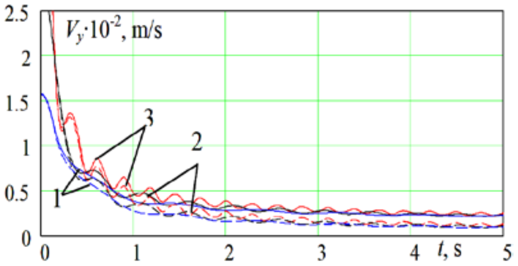


Fig. 8. *The speed of the particles inside the layer on the y-axis of the separation time t at different values of the kinematic mode:*
1 – ω = 50 s^{-1}; 2 – ω = 60 s^{-1}; 3 – ω = 60 s^{-1};
—— with weeder; - - - without weeder

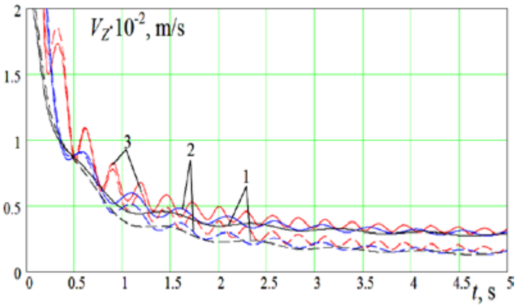


Fig. 9. *The dependence of the nature of the absolute speed of the particle within the layer on the separation time t at different values of the kinematic mode:*
1 – ω = 50 s^{-1}; 2 – ω = 60 s^{-1}; 3 – ω = 70 s^{-1};
(A = 5 mm; VB = 1 m/s; α = 6º;)
—— with weeder; - - - without weeder

3.2. Results of Experimental Research

According to the results of experimental studies, regression equations of the particle immersion velocity, the particle velocity of the particle on the sieve and the efficiency of the separation process from the specific load, the airflow rate, the weeder, the slope angle to the horizon and the angular velocity of the sieve were obtained. The rate of immersion of the particle in the grain layer is determined from the regression equation:

$$\begin{aligned}V_{\mathrm{w}} &= -51{,}66+1{,}04\cdot x_1+15{,}04\cdot x_2+1{,}40\cdot x_3+\\&+2{,}22\cdot x_4+937{,}80\cdot x_6-0{,}01\cdot x_1^2-0{,}02\cdot x_1\times\\&\times x_3-4{,}50\cdot x_2^2-1{,}03\cdot x_2\cdot x_4-0{,}01\cdot x_3^2+\\&+0{,}01\cdot x_3\cdot x_4+0{,}08\cdot x_5^2-162{,}96\cdot x_4\cdot x_6\end{aligned}\tag{7}$$

The speed of the particles in the grain layer is determined from the regression equation:

$$\begin{aligned}V_{pr} &= -511{,}40+11{,}25\cdot x_1+57{,}7\cdot x_2+\\&+18{,}5\cdot x_3+21{,}4\cdot x_4+9721{,}80\cdot x_5-\\&-0{,}10\cdot x_1^2+0{,}55\cdot x_1\cdot x_2-0{,}24\cdot x_1\cdot x_3+\\&+0{,}10\cdot x_1\cdot x_4+96{,}30\cdot x_1\cdot x_5-\\&-29{,}30\cdot x_2^2-1{,}23\cdot x_2\cdot x_3-\\&-7{,}05\cdot x_2\cdot x_4+2758\cdot x_2\cdot x_5-0{,}17\cdot x_3^2-\\&-183{,}44\cdot x_3\cdot x_6-11{,}71\cdot x_4\cdot x_6-466{,}18\cdot x_6^2\end{aligned}\tag{8}$$

The efficiency of separation of the grain mixture is determined by the regression equation:

$$
\begin{aligned}
E = {} & 216,54 - 1,68 \cdot x_1 - 106,60 \cdot x_2 - \\
& - 7,72 \cdot x_3 - 12,14 \cdot x_4 - 3939,46 \cdot x_5 + \\
& + 0,50 \cdot x_1 \cdot x_2 - 0,17 \cdot x_1 \cdot x_4 + \\
& + 35,10 \cdot x_1 \cdot x_5 + 28,3 \cdot x_2^2 + 3,10 \cdot x_2 \cdot x_3 + \\
& + 0,31 \cdot x_2 \cdot x_4 + 0,02 \cdot x_3^2 + 0,12 \cdot x_3 \cdot x_4 + \\
& + 345,70 \cdot x_3 \cdot x_5 - 0,09 \cdot x_4^2 + \\
& + 95,70 \cdot x_4 \cdot x_6 - 856,43 \cdot x_6^2,
\end{aligned}
\tag{9}
$$

where:

$x_1 = V_B$, m/s – the speed of the injection air flow;

$x_2 = \alpha$, deg. – angle of inclining working bodies to the horizon;

$x_3 = \omega$ s^{-1} – oscillation frequency of the sieve;

$x_4 = S_w$, dm – diagonal step of arrangement of the mechanical weeder;

$x_5 = n_w$, p./dm^2 – located number weeder 1 dm^2 sieve;

$x_6 = q_F$, kg/(dm^2·h) – specific load on 1 dm^2 of sieve.

Equations (7-9) adequately describe (at P = 0.95) the required dependencies under the conditions of changing factors within V_B = 0.8–1.2 m/s; α = 2–10°; ω = 30–80s^{-1}; S_w = 60–100mm; n_w = 8–15p./dm^2; q_F = 40–60kg/(dm^2·h). The adequacy of mathematical models was verified by using the analysis of variance using Fisher's criterion at a confidence level of 0.95. According to the results of experimental studies, the time of separation of grain materials from the parameters of the process of intensification of the grain layer, from the kinematic and mode parameters of the vibro-pneumatic separator, the parameters of the vibrating medium binder are determined.

A graphical interpretation of the obtained dependencies is shown in Figures 10 to 13.

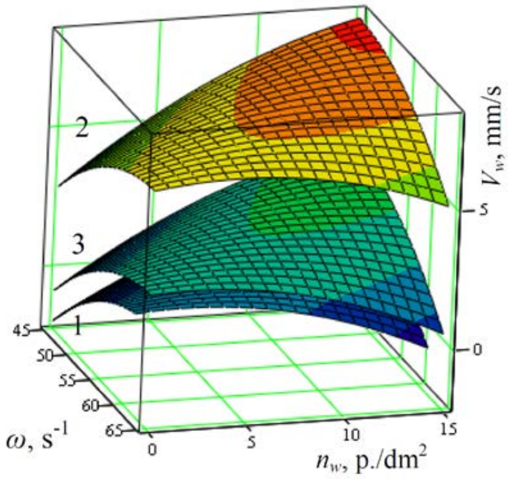


Fig. 10. *The speed of the particles of V_w share of pins density n_w and oscillation frequency sieves ω with different values of angle to the horizontal working plane αº: 1 – 2º; 2 – 6º; 3 – 10º; at V_B = 1 m/s; q_F = 60 kg/(dm^2·h)*

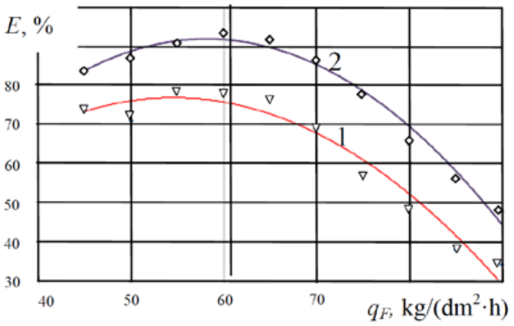


Fig. 11. *Dependence of separation efficiency E on the specific load q_F: 1 – without weeder; 2 – with weeder*

The analysis of the obtained dependences allows us to note the following features of the process: the highest immersion rate occurs at the frequency of oscillations of the sieve between 52-57s^{-1} at all values of specific loads; increasing the velocity of the air stream reduces the immersion rate of the particle at the value of the optimal frequency of oscillations of the sieve; the immersion speed decreases as the load on the sieve increases; maximum immersion speed is achieved with a specific density of pins between 9-11p./dm^2; changing the angle of the sieve increases the particle immersion rate almost twice from the reached value of 3.99mm/s at optimum ω and N and practically does not affect the speed of movement of the grain layer.

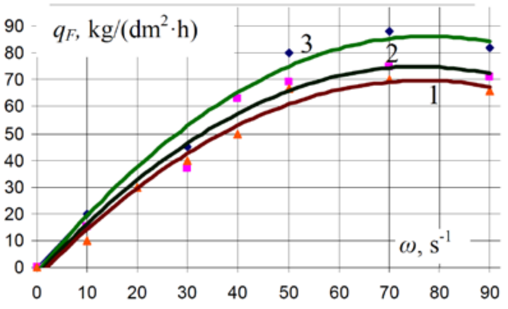


Fig. 12. *The efficiency of separation E from the frequency of the sieve oscillations ω at different values of the specific load q_F.: 1 – 40 kg/(dm^2·h); 2 – 50 kg/(dm^2·h); 3 – 60 kg/(dm^2·h) at m_w = 8 p/dm^2; V_B = 1 m/s; ω = 55 s^{-1}*

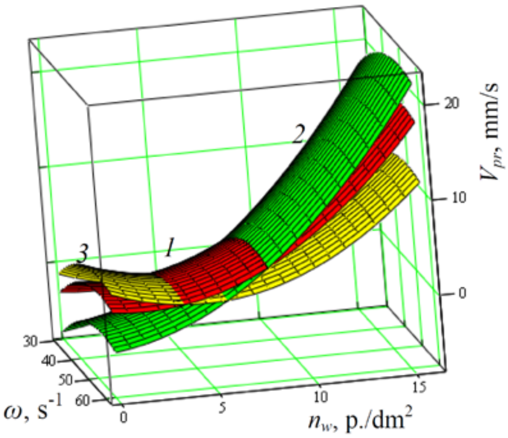


Fig. 13. *The speed of the particle density of V_{pr} share of pins density n_w and oscillation frequency sieves ω at different values of air velocity V_B: 1 – V_{B1} = 0,5 m/s; 2 – V_{B2} = 1 m/s; 3 – V_{B3} = 1,5 m/s; at α = 6°; q_F = 60 kg/(dm^2·h)*

When the load is increased to 40-60kg/(dm^2·h), the separation efficiency changes within 5%. Thus, in the presence of loosening elements maximum efficiency is achieved at lower values of the vibration frequency, which can be explained by the intensification of the loosening of the grain layer by increasing its porosity and sieving the sieve itself, while displacing the grain of the ladder fraction from the openings of the sieve.

4. Conclusions

1. The intensification of the loosening of the grain layer by immersed weeders, which creates different resistance to the movement of the grain during oscillatory movements of the sieve with simultaneous supply of air to the layer, allows the increase of the effective sifting while increasing the specific load on the sieve to 40-60kg/(dm^2·h).
2. Theoretical and experimental studies have proved the feasibility of reducing the effective vibration of the grain layer while reducing the speed of movement of the grain along the sieve when using a passive weeder, which allows the intensification of the kinematic mode by increasing the oscillation frequency to 52-57s^{-1}. The speed of immersion of the particle increases to 6mm/s, and the speed of movement of the grain can be reduced to 60mm/s.
3. Analytical dependences of the grain movement velocity on kinematic modes, specific loading, air velocity, size and density of the weeder were determined whereby the effective viscosity was determined and the state of the grain layer (porosity,

medium density, displacement resistance) was identified. It is established that the highest intensity of loosening is achieved with the following parameters: the frequency of oscillations of the sieve ω = 52-57s^{-1}; oscillation amplitude A = 5mm; the speed of air supplied by a sieve V_{pr} = 1.2-1.5m/s; the density of placement of the weeder n_w = 9-11p./dm^2.

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