**1. Boris KOTOV[1], 2. Seghii STEPANENKO[2], 3. Oleh TSURKAN[3,4], 4. Volodymyr HRYSHCHENKO[5],
5. Yurii PANTSYR[1], 6. Ihor GARASYMCHUK[1], 7. Anatolii SPIRIN[3,4], 8. Ihor KUPCHUK[3]**

Podillia State University (1), National Scientific Center «Institute of Agricultural Mechanization and Electrification» (2),
Vinnytsia National Agrarian University (3), Separated structural unit «Ladyzhyn Professional College of Vinnytsia National
Agrarian University» (4), National University of Life and Environmental Sciences of Ukraine (5)
ORCID: 1. 0000-0001-6369-3025; 2. 0000-0002-8331-4632; 3. 0000-0002-7218-0026; 4. 0000-0001-7789-3650;
5. 0000-0003-2969-1936; 6. 0000-0002-4304-4447; 7. 0000-0002-4642-6205; 8. 0000-0002-2973-6914

Fractioning of grain materials in the vertical ring air channel during electric field imposition

Abstract. The problem of obtaining high-quality (commercial) food grains and seeds of cereals and oilseeds can be solved by using fractional technology for post-harvest processing of grain. The shortcomings of existing machines can be eliminated if, when a particle moves in an ascending air flow, the orientation of its axes of inertia in the channel space is stabilized. One of the effective ways of directional orientation of elongated grains can be the imposition of a stable electric field on a two-phase flow (grain-air). The article theoretically summarizes and proposes a new solution to the scientific problem of increasing the efficiency of the process of separating grain material according to the complex of aerodynamic and electrophysical properties of individual components of the grain material.

*Streszczenie. Problem otrzymywania wysokiej jakości (handlowych) zbóż spożywczych oraz nasion zbóż i roślin oleistych można rozwiązać stosując technologię frakcyjną do pożniwnego przerobu ziarna. Wady istniejących maszyn można wyeliminować, jeśli podczas ruchu cząstki we wznoszącym się strumieniu powietrza ustabilizuje się orientacja jej osi bezwładności w przestrzeni kanału. Jednym ze skutecznych sposobów kierunkowej orientacji wydłużonych ziaren może być nałożenie stabilnego pola elektrycznego na przepływ dwufazowy (ziarno-powietrze). W artykule teoretycznie podsumowano i zaproponowano nowe rozwiązanie problemu naukowego zwiększenia wydajności procesu separacji materiału ziarnowego według kompleksu właściwości aerodynamicznych i elektrofizycznych poszczególnych składników materiału ziarnowego. (**Frakcjonowanie materiałów ziarnistych w pionowym pierścieniowym kanale powietrznym podczas nakładania pola elektrycznego**)*

Keywords: grain material, air channel, fractionation, electric field.
Słowa kluczowe: fakcjonowanie materiału ziarnistego, pole elektryczne

Introduction

The problem of obtaining high-quality (commercial) food grain and seeds of cereals and oilseeds can be successfully solved by using fractional technology of post-harvest processing of grain. The essence of the technology is the fastest, without intermediate storage, separation of grain coming from the field into seed, food and feed fractions. For such separation of grain heap at an early stage of post-combine processing it is possible and expedient to carry out air grain separating machines operating on fractional technology [1-3].

Analysis of literary sources and problem statement

The advantages of air separation are obvious: simplicity of designs; lack of moving parts; high reliability; the separation process depends little on the moisture content of the grain material [4-6]. However, the existing designs of pneumatic separating machines with vertical [7-9], horizontal [1-6] and inclined [8] air (aspiration) channels have insufficient technological efficiency, because their development and design did not take into account the following features: uneven air velocity in the section channels; interaction of particles with each other; rotation of particles in air vortices; unstable orientation of particles of oblong shape, which is random.

The listed factors at operating pneumatic separators with vertical channels lead to losses of qualitative grains, as a result of their hit in waste, and garbage impurity get to fraction of qualitative grain. The quality of separation does not exceed 50%, ie up to 50% of quality grain is released.

Known attempts to improve the quality of grain separation are accompanied by significant design improvements: the use of multi-level grain input into the channel [7]; the use of pneumatic weighing of the grain layer on the scaly surface of the pneumatic duct feeder [10, 11]. However, these improvements, although they allowed to increase the productivity and efficiency of separation to a small extent, do not solve the problem of grain fractionation in vertical channels, for this purpose, use horizontal [6] and inclined channels [8].

However, in [12-14] the possibility and efficiency of separation of grain material into fractions in vertical annular channels were revealed [4-7, 11]. In [7] the process of separation of grain material components in the lower part of the annular channel was investigated. But mathematical models do not consider the uneven flow rate. A similar shortcoming is in [12], in addition, incorrectly formulated differential equations are used. The pneumogravity process of separation of grain material components was studied more thoroughly in [15-17], and the aerodynamic scheme of the pneumoseparator was improved. But studies have adopted the shape of the grains in the form of a sphere, which even when rotating does not change the midline cross section and, accordingly, does not change the force of aerodynamic drag, which depends on the orientation of the elongated grains.

In the air channel with turbulent air flow under the influence of non-uniform air velocity and the action of vortices in the flow of non-zero grain, the latter begins to rotate relative to the oncoming flow, which leads to continuous (random) changes in the midline grain cross section. This changes the strength of the aerodynamic drag of the grain, and the trajectory of the particle is constantly changing, which leads to a decrease in the quality of separation of grain material by aerodynamic properties.

The shortcomings generalized above can be eliminated if the orientation of its axes of inertia in the space of the channel is stabilized during the motion of the particle in the ascending air flow. One of the effective ways of directional orientation of elongated grains can be the application of a constant electric field on a two-phase flow (grain-air). As is known from the analysis of the operation of electric separators [16,17] when the grain of oblong shape (ellipsoid of rotation) in the air-weighed layer in the electrostatic field under the action of overturning electric moments grain is oriented along the field lines. Thus, if cylindrical electrodes

are placed in the vertical annular channel (on the outer and inner surfaces of the pneumatic channel, the grains should be oriented along the radius, and kept in this position during movement. In addition, the charged particle is exposed to additional forces of an electric nature, which in different ways affect the trajectory of individual components of the grain material. The action of additional forces should increase the effect of grain separation by aerodynamic and electrical properties.

Purpose and tasks of research

Given the above, it is necessary to determine the conditions and methods for calculating the parameters of the process of separation of grain material. This can be achieved by mathematical modeling of the dynamics of grain motion in the inner channel under the action of aerodynamic electric and mass forces.

The purpose of research is to determine the trajectories of grains that differ in aerodynamic and electrical properties in the vertical non-uniform flow, and on their basis to quantify the quality of separation.

Materials and methods

The specificity of the problems under consideration determines the analytical calculation method of studying the process of grain material separation into fractions in the vertical pneumatic channel with the lower separation zone, since the process is affected by numerous factors that can not be implemented in actual or modeled experiments. At the first stage of research, it is desirable to identify a physical ability to intensify the process and estimate to what extent to do so.

The criterion for separation efficiency lies in deviation (dispersion) of grain material components' trajectories at the place of their unloading:

$$(1) \qquad \Delta x = x_2 - x_1,$$

where x_2- deviation of the heavy fraction; x_1- deviation of the medium fraction.

The limitation for trajectory analysis lies in maximum deviation x_{max}, the magnitude of which should never exceed the depth of the channel, the same for annular channel x_{max} (where R, r being the radii of the outer and inner cylindrical walls, of which the pneumatic channel consists). Under these conditions, the value of the efficiency criterion is determined by the following ratio:

$$(2) \qquad \varepsilon = \frac{\Delta x}{R - r}.$$

As the main feature of the separation (characterizing the grain), assumed is its hovering velocity v_v, the value of which is associated with sailing ration k_v by dependences:

$$(3) \qquad \frac{q}{v_v^2} = k_v = \frac{\xi(Re()_{am})}{2m},$$

where $\xi(Re())$ is the aerodynamic drag ratio; ρ_a- air density; S_m- grain's Midelev section; $m = V/\rho$- grain weight; V - grain volume; ρ - grain density; Re - Reynolds number.

To calculate the trajectories of grain material's components, one should formulate mathematical description (model) of individual grains' movement dynamics under the action of forces determined on the basis of existing physical ideas about the interaction between particles and airflow during stationary electric field imposition.

Research results

Formulation of the mathematical model for material movement process is implemented on the basis of compiled computational pattern (Fig. 1) of force interaction in the field of aerodynamic and electric forces, under the following assumptions: the grains are presented in the form of ellipsoids with defined size, density and mass; air flow is stationary and leveled; the aerodynamic drag force is proportional to the flow velocity square; the air flow velocity is distributed in the cross section according to power law [13]:

$$(4) \qquad v(x) = v \left(\frac{x}{B}\right)^{0.1}_{max},$$

(where B – half the depth of the channel axis; v_{max} – air velocity on the axis) and is considered as a rectifiable uniform flow.
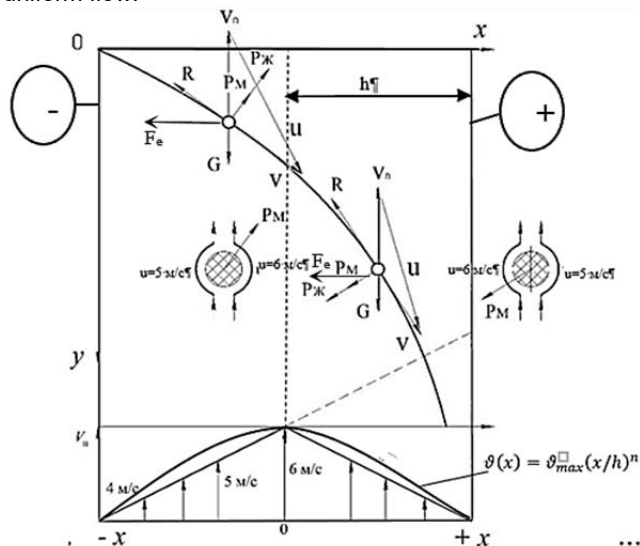

Fig. 1. Pattern of forces acting on particles in the pneumatic channel with imposed electric field

From the pattern of forces acting on (isolated) particle in the vertical air flow, we can determine their value and direction gravity:

$$(5) \qquad \overline{G} = m\overline{g},$$

where g - free fall acceleration; m - the grain weight is directed vertically down and applied in the center of masses;

the force of aerodynamic resistance to air directed opposite to the relative speed vector:

$$(6) \qquad \overline{R} = mk_v\bar{u}^2,$$

where $\bar{u} = \bar{v}_a(x) - v$ is the grain's relative velocity; $\bar{v}_a(x)$- air flow rate; v - the grain's absolute velocity applied to the point of grain symmetry (velocity vector on the line tangent to the trajectory curve);

electric field strength:

$$(7) \qquad \overline{F}_e = Q\overline{E},$$

where Q - the grain's electric charge; E - electric field strength.

With the grain being oriented with the long axis along the electrostatic field, its electric charge is determined using the formula:

$$(8) \qquad Q = \frac{E_0 \varepsilon_0 b^2}{4[1 + (\varepsilon_r - 1)\Phi_1]},$$

for grains shaped as compressed ellipsoid oriented of the long axis along the electrostatic field, the electric charge is determined using the formula:

$$(9) \qquad Q = \frac{E_0 \varepsilon_0 ab}{4[1 + (\varepsilon_r - 1)\Phi_1]},$$

where $\Phi_1 = \frac{k^2}{\sqrt{(1-k^2)^3}} \left(arth\sqrt{1 - k^2} - \sqrt{1 - k^2}\right)$ is the axial depolarization ratio; $k = \frac{a}{b}$ the sphericity ratio; b - the length of the ellipsoid's major axis; a - the length of the small axis; E_0- the free space electric field's strength; ε_r- the grain's relative dielectric constant; ε_0- the electric constant ($\varepsilon_0 = 8.85 \cdot 10^{-12}$F/m).

The grain shaped as ellipsoid, which is fed with an arbitrary orientation into the electric field, begins rotating so that its long axis would be directed along the field lines, i.e. to orient the long axis perpendicular to the electrodes that form the field. The process of the grain's turning in the electric field is carried out under the action of torque on the field's M_e side.

The torque value is determined using the formula [18]:

$$(10) \qquad M_e = \frac{E_0^2}{8\pi} V_q \Phi_2 \sin 2\gamma = \mu \sin 2_{max},$$

where $\Phi_2 = \frac{\Phi_1' - \Phi_1}{((\varepsilon_z - 1)^{-1} + \Phi_1)((\varepsilon_z - 1)^{-1} + \Phi_1')}$; $\Phi_1' = \frac{k^2}{2(1-k^2)}\left(\frac{1}{k^2} - \frac{arth\sqrt{1-k^2}}{\sqrt{1-k^2}}\right)$; V_q- the grain volume; γ - the angle between the movement direction and the ellipsoid's long axis.

In the course of grain orientation under the action of electric field (moment M_e), the rotation is counteracted by the air resistance moment. The magnitude of this moment is determined for the following reasons. If the force of resistance to environment ΔF generated by rotating body with its length element Δl, which is distant from the gravity center by l distance, then elementary moment ΔM due to this force will equal to:

$$(11) \qquad \Delta M_c = l\Delta F$$

The resistance force acting on the length element in linear (Stokes) approximation [16, 19] can be written as:

$$(12) \qquad dF = kudl$$

where k is a generalized resistance ratio; u - a linear velocity of element dl, which (for rotational motion) is determined by apparent expression:

$$(13) \qquad u = l\dot\phi = \frac{d\phi}{dt},$$

where $\frac{d\phi}{dt}$ is the rate of change in the inclination of the grain's long axis angle.

The moment of air resistance to grain rotation is defined using the equation [18, 20]:

$$(14) \qquad dM_c = k\dot\phi l^2 dl,$$

after integration:

$$(15) \qquad M_c = k\dot\phi \frac{l^2}{3} \quad \text{and} \quad \dot\phi = \dot\gamma.$$

Due to the fact that the pressure center of the air flow (Fig. 1) acting on the grain does not coincide with the center of masses, the resistance generates the torque relative to the center of masses [21], which is directed so as to orient the grain with a larger axis across the air flow $\overline{V}_a$. The magnitude of the torque is determined using the formula [22] :

$$(16) \qquad M_a = ku^2 l_c \sin\gamma,$$

where $u = v_a - v$ is the grain's relative velocity (flow rate); v_a- the air flow rate; v - the grain movement speed; l_c- the distance between the geometric center and the center of masses.

Having determined all the forces and torques acting on the grain, one can write the differential equations that determine the motion of the grain's center of masses in the ascending air flow in the following vector form (translational motion equation):

$$(17) \qquad m\frac{d\overline{v}}{dt} = \overline{G} + \overline{F_e} + \overline{R},$$

and the equation of the grain's rotational motion, which describes the rotational motion dynamics:

$$(18) \qquad J\frac{d\gamma}{dt} = M_c(\gamma) + M_a(\dot\gamma) + M(\gamma),$$

where $J = m(a^2 + b^2)0.25$.

By substituting the values of moments (15) and (16) we obtain:

$$(19) \qquad m(a^2 + b^2)0.25\frac{d^2\gamma}{dt^2} - k\frac{l^3}{3}\frac{d\gamma}{dt} + k\big(v_a(x) -$$

$$v(t)\big)^2 \sin\gamma = 0.$$

The integration of equation (19) allows determining the time of the grain's reorientation in the air channel after its convergence into the air stream, but for this purpose one should determine $v(t)$- the change in the grain speed.

The dynamics of the grain material components' motion within the electropneumatic gravity classifier's vertical air flow is shown in Fig. 2 and Fig. 3.

Figure 2 shows the structural and technological diagram of the said classifier. Figure 3 shows the diagram of electrical communications (electrodes' connection to a high voltage unit). The block diagram is shown in paper [15, 16].
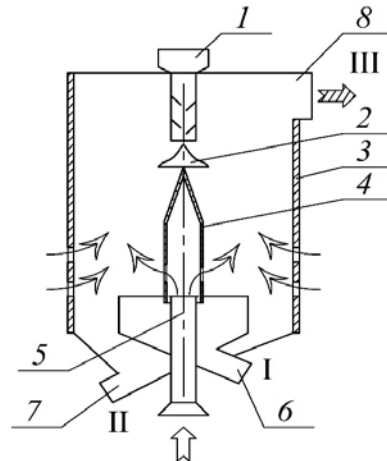

Fig. 2. Structural-and-process diagram of electropneumatic gravity classifier: 1 - loading hopper; 2 - grain flow distributor; 3 - cylindrical grounded housing; 4 - insulator; 5 - air intake pipe; 6 - heavy fraction collector- unloader; 7 - medium fraction collector -loader; 8 - light fraction's exit to the sedimentation chamber with a fan; 9 - crowning electrode.
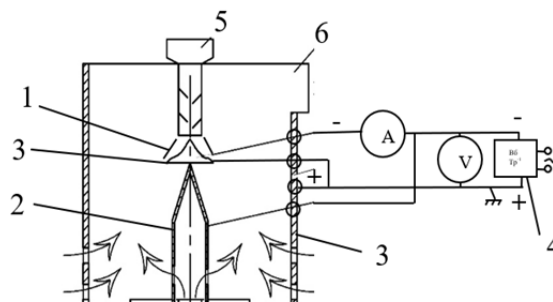

Fig. 3. Electrical switching diagram: 1 - crowning electrode; 2 - polarizing electrodes; 3 - grounded electrodes; 4 - power supply unit; 5 - loading hopper; 6 - light fraction's exit to the sedimentation chamber.

Electropneumatic gravity classifier contains the grain material hopper loader into the channel, from which the grain material through the pipe with braking elements is fed by a loose flux to the distribution cone, on which a grounded electrode is fixed, over which the crowning electrode in the form of a conical wire mesh 0.2 mm in diameter is placed. The grounded electrode is separated from the polarizing electrode by the insulator, which is located on the outer surface of the inner hollow conical insert located axially in a cylindrical housing. (Negative) voltage from the high-voltage unit is applied to the electrode through the insulator. The internal cavity insert is connected to the ambient air and to the pneumatic duct through the windows. There are slits on the pneumatic duct's outer walls for ambient air suction. From the slits, air flow moves in the boundary layer of the inner surface, washing the grounded housing electrode; at the same time, light particles' sticking to the surface is

leveled. The cylindrical part of the unloader's collector is used as the separator of the fractions being separated. To clean the light fraction from debris (light fine particles) at the air flow outlet from the pneumatic channel, an inertial sedimentary chamber is installed.

The process of the electric pneumatic-gravitational classifier's functioning (operation) can be described (defined) as follows. The exhaust fan generates a certain discharge in the channel's volume, thus generating an out-let air flow. Presence of distributed windows and cracks in the structural elements of the diagram of air velocities in the channel's cross section can be adjusted so as to eliminate the negative impact of the channel's stagnant zones.

Passing along the feed pipe, grain material enters the channel from the hopper, whereupon its flow is inhibited and fed to the distribution cone in a loose form. Passing between negative and grounded positive crowning electrodes, the particles receive negative electric charge Q and, entering the space between the cylindrical part of polarizing and grounding electrodes, are oriented as a long axis in the direction of electric field vector $\vec{E}$, i.e. in the radial direction. Particles of grain material components that have greater weight (or density) deviate from the channel's axis by a smaller distance and fall into the collector, from which they are unloaded; lighter ones (medium fraction) are deflected by a greater distance and while falling down removed from the channel through the nozzle. Light-fraction particles have the largest deviation, being carried by the flow to the channel's upper part, and from there – to the sedimentation chamber where they are deposited and discharged through the pipe to the outside. In such a manner grain material components are divided into three fractions. In terms of commercial purpose, these can be seed (I), food (II) and forage (III) fractions. The issue of how effective is the use of electric field to improve separation efficiency is determined in the materials of this article based on mathematical model formulation and research. The dynamics of grain material components' plane movement in the vertical ascending air flow at distributed velocity and imposed electric field is determined by designing equation (17) on the axis of rectangular HOU coordinates:

(20) $\qquad m\dfrac{dv_x}{dt} = -R_x \sin\beta - F_e,$

(21) $\qquad m\dfrac{dv_y}{dt} = mg - R_y \cos\beta,$

where R_x, R_y- projections of resistance forces on OX and OU axis;

$$\sin\beta = \dfrac{dx(t)/dt}{u(x,y)}; \cos\beta = \dfrac{dy(t)/dt}{u(x,y)};$$

where $u(x,y)$ is the grain's relative velocity (streaming velocity), the value of which is determined using the formula:

(22) $\qquad u(x,y) = \sqrt{\left(\dfrac{dx(t)}{dt}\right)^2 + \left(\dfrac{dy(t)}{dt} + v_a(x)\right)^2}.$

As is known from [13, 18], air velocity is unevenly distributed in the cross section of vertical channels (according to the exponential or logarithmic law). In the near-wall zones of the channel, the velocity is zero. Flow unevenness determines the action of uncontrolled lateral forces. In proposed aerodynamic diagram of the device, one can align the diagram of air velocities in the cross section of the channel. Fig. 4 illustrates the field of air velocities in the channel being studied. Change in the velocity in the channel's lower part and reduction of its value in the channel's upper part causes deformation of the particles' trajectory in the direction of straightening, which increases divergence in trajectories of grain material's light and heavy components. When calculating the trajectories of different fractions' grains, the change in flow velocity in height is determined by the following linear functions:
for the channel's lower part:

(23) $\qquad v_a(y)_1 = a_1 - b_1 y,$

for the channel's upper part:

(24) $\qquad v_a(y)_2 = a_2 + b_2 y,$

where a_1, b_1, a_2, b_2- approximation ratios.

Air velocity in the channel's cross section is uniform $\dfrac{dv_a}{dx} = 0$. Let's define projections of acting forces:

(25) $\qquad R_x = mk_0 S_x \left(\dfrac{dx(t)}{dt}\right)\sqrt{\left(\dfrac{dx(t)}{dt}\right)^2 + \left(\dfrac{dy(t)}{dt} + v_a(y)_{1,2}\right)^2};$

(26) $\qquad R_y =$

$mk_0 S_y \left(\dfrac{dy(t)}{dt} + a(y)_{1,2}\right)\sqrt{\left(\dfrac{dx(t)}{dt}\right)^2 + \left(\dfrac{dy(t)}{dt} + v_a(y)_{1,2}\right)^2}.$

Grain's transparent frontal area:

(27) $\qquad S_x = \pi a\sqrt{a^2 \sin^2\phi} = \pi a^2 \sin\phi;$

(28) $\qquad S_y = \pi a\sqrt{b^2 \cos^2\phi} = \pi ab \cos\phi;$

(29) $\qquad F_{ex} = QE = \dfrac{S_y \varepsilon_r}{4\pi(1+(\varepsilon_r-1))\Phi_1} E(y),$

$$F_{ey} = 0,, E(y) = E3_{max}$$

where ε_r is the grain's dielectric constant (moisture-dependent) and grain density ($\varepsilon_r = 10 \ldots 80$).

We should keep in mind that the channel hosts a countercurrent movement between grain flow and air flow so that the channel's certain section is occupied by grain, and effective air velocity in the intergranular space will be increased as compared to the empty channel. The value of grain's actual velocity can be determined from the apparent ratio:

(30) $\qquad v_a^*(y) = \dfrac{v_f}{\varepsilon},$

where v_f- air velocity in the empty channel; ε - two-phase flow differential.

Hence, obtained equations (20), (21) with relations (22) - (30) constitute a mathematical model of the dynamics of the grain's planar motion in a vertical channel with imposed electrostatic field.

For numerical solution of differential (nonlinear) equations, let us set the initial conditions:

(31) $\qquad t = x = y = 0; \dfrac{dx(t)}{dt} = v_0 \cos\alpha_0; \dfrac{dy(t)}{dt} = v_0 \sin\alpha_0;$

where v_0- the rate of the grain's entry into air flow; α_0- the angle of the grain's entry into the air flow.

Solution of formulated system of equations with initial conditions (30) in MathCAD computer environment is obtained in the form of grain material components' trajectories, which differ by separation coefficient k. Fig. 4 shows grains' trajectories in the air flow of electropneumatic gravity classifier of grain material.
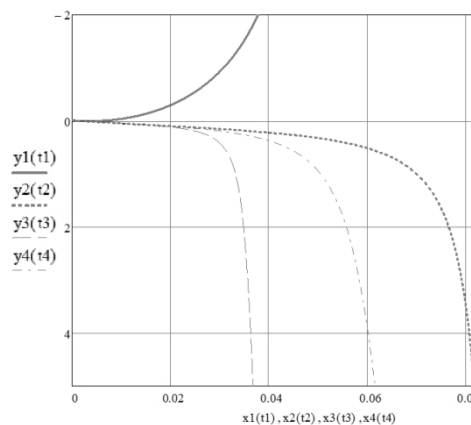

Fig. 4. Grain trajectories in the air flow of electropneumatic gravity classifier of grain material

Conclusions

1. Theoretically, a new solution to the scientific problem of increasing the efficiency of the process of separation of grain material by a set of aerodynamic and electrophysical properties of individual components of grain material is generalized and proposed.

2. Based on the analysis of the total action on the grain material components of gravitational, aerodynamic and electric forces, a mathematical model is formulated in the form of differential equations of dynamics of individual grains in air flow with variable speed, and aggregate algebraic equations that determine the interaction of grains with air flow.

3. On the basis of numerical solution, a system of equations is formulated to determine the trajectories of individual components of grain material (wheat), which have the following parameters: the first fraction: (velocity) $v_v = 1$ m/s; (mass) $m = 42 \cdot 10^{-3}$ g; second fraction: $v_v = 9$ m/s; $m = 38 \cdot 10^{-3}$ g; third fraction: $v_v = 5,5$ m/ s; $m = 35 \cdot 10\text{-}3$ g. With the average value of the electric field strength $E = 2...3$ kV/cm, the magnitude of the difference in trajectories at the place of unloading increased from 0,035 m to 0,044 m. Air speed (maximum value decreased from 12 to 9 m/s, respectively air consumption decreased by 25 %.

Authors: KOTOV Boris – D. Eng. Sc., Professor, Faculty of Engineering and Technology, Podillia State University (32316, 12, Shevchenko Str., Kamianets-Podilskyi, Khmelnytskyi region, Ukraine), e-mail: eetsapk@pdatu.edu.ua; STEPANENKO Serhii – D. Eng. Sc., Senior Researcher, National Scientific Center «Institute of Agricultural Mechanization and Electrification» (08631, 11,Vokzalna St, Glevakha, Fastiv district, Kiyv region, Ukraine), e-mail: stepanenko_s@ukr.net; TSURKAN Oleh – Dr. Eng. Sc., Associate Professor, Faculty of Engineering and Technology, Vinnytsia National Agrarian University, director of Separated structural unit «Ladyzhyn Professional College of Vinnytsia National Agrarian University» (24321, 5 P. Kravchyka str., Ladyzhyn, Vinnytsia region, Ukraine), e-mail: tsurkan_ov76@ukr.net; HRYSHCHENKO Volodymyr – PhD in Engineering, Senior Lecturer, Education and research institute of Energetics, Automatics and Energy saving, National University of Life and Environmental Sciences of Ukraine (03041, 12, Heroyiv Oborony str., Kyiv, Ukraine), e-mail: vlgr@nubip.edu.ua; PANTSYR Yurii – PhD in Engineering, Associate Professor, Dean of the Faculty of Engineering and Technology, Podillia State University (32316, 12, Shevchenko Str., Kamianets-Podilskyi, Khmelnytskyi region, Ukraine), e-mail: panziryuriy@gmail.com; GARASYMCHUK Ihor – PhD in Engineering, Associate Professor, Head of the Department of Electrical Engineering, Electromechanics and Electrotechnology, Educational and Scientific Institute Of Energy, Podillia State University (32316, 12, Shevchenko Str., Kamianets-Podilskyi, Khmelnytskyi region, Ukraine), e-mail: igorgarasymchuk@gmail.com; SPIRIN Anatolii – PhD in Engineering, Associate Professor, Faculty of Engineering and Technology, Vinnytsia National Agrarian University (21008, 3 Sonyachna str., Vinnytsia, Ukraine), e-mail: spirinanatoly16@gmail.com); KUPCHUK Ihor – PhD in Engineering, Associate Professor, Deputy Dean for Scientific Research, Faculty of Engineering and Technology, Vinnytsia National Agrarian University (21008, 3 Sonyachna str., Vinnytsia, Ukraine), e-mail: kupchuk.igor@i.ua.

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