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 successfully 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.

Introduction

The problem of obtaining high-quality (commercial) food grains 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 design; 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 incoming 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-weighted 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:

\[ \Delta x = x_2 - x_1 \]

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 inner and outer cylindrical walls, of which the pneumatic channel consists). Under these conditions, the value of the efficiency criterion is determined by the following ratio:

\[ \varepsilon = \frac{\Delta x}{R - r} \]

As the main feature of the separation (characterizing the grain), assumed is its hovering velocity \( v_p \), the value of which is associated with sifting ratio \( k_p \) by dependences:

\[ k_p = \frac{(Re)_{\text{lim}}}{2m} \]

where \( (Re)_{\text{lim}} \) is the aerodynamic drag ratio; \( \rho_a \) - air density; \( S_m \) - grain’s Midelev section; \( m = V / \rho \) - grain weight; \( V \) - grain volume; \( \rho \) - 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]:

\[ v(x) = v \left( \frac{x}{B} \right)^{0.1} \]

(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](image)

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

\[ F = m \vec{g} \]

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: \( F_a = m \vec{u} \); the force of electrostatic field:

\[ F_e = Q \vec{E} \]

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:

\[ Q = \frac{E \epsilon_0 a^2}{4 \pi (1 + (\epsilon_r - 1) \phi_1)} \]

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

\[ Q = \frac{E \epsilon_0 a b^2}{4 \pi (1 + (\epsilon_r - 1) \phi_2)} \]

where \( \phi_1 = \frac{k^2}{(1 + k^2)} \) \((\arctan 1 - k^2 - \sqrt{1 - k^2}) \) is the axial depolarization ratio; \( k \) - 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; \( \epsilon_r \) - the grain’s relative dielectric constant; \( \epsilon_0 \) - the electric constant \((\epsilon_0 = 8.85 \cdot 10^{-12} \text{F/m})\).
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):

$$ M_e = \frac{2}{\pi} \phi_0^2 \phi_0 \sin 2 \gamma = \mu \sin 2 \max, $$

where $\phi_0 = \frac{\sqrt{\left((x_e-1) + (y_e-1) + (z_e-1)\right)^2}}{\sqrt{1 - x^2 - y^2 - z^2}}$; $\phi_0^2 = \frac{k^2}{2(1-k^2)} \left(\frac{1}{\kappa^2} - \frac{1}{\kappa^2} \right)$; $V_g$ - the grain volume; $\gamma$ - 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 $\Delta F$ generated by rotating body with its length element $dl$, which is distant from the gravity center by $l$ distance, then elementary moment $\Delta M$ due to this force will equal to:

$$ \Delta M_e = \Delta F $$

(11)

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

$$ dF = kudl $$

(12)

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

$$ u = \phi \frac{d\phi}{dt}, $$

(13)

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]:

$$ dM_e = k\phi \frac{d\phi}{dt} \tau dl, $$

(14)

after integration:

$$ M_e = k\phi \frac{d\phi}{dt} \tau l, $$

(15)

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 $V_0$. The magnitude of the torque is determined using the formula [22]:

$$ M_a = k u^2 l_c \sin \gamma, $$

(16)

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):

$$ m \frac{dv}{dt} = \vec{F}_e + \vec{F}_a + \vec{R}, $$

(17)

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

$$ J \frac{d\phi}{dt} = M_c(y) + M_a(y) + M(\gamma), $$

(18)

where $f = m(a^2 + b^2)0.25$.2.5.

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

$$ m(a^2 + b^2)0.25 \frac{d\phi}{dt}^2 - k_1 \frac{d\phi}{dt}^2 - k_3 \frac{d\phi}{dt} - k(v_a(x) = -v(t))^2 \sin \gamma = 0. $$

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].
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 outlet 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 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 $E$, 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 fall into the collector from which they are 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 fractions are 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 fractions are divided into three different fractions’ grains, the change in flow velocity in height is determined by the following linear functions:

$$v_a(y)_1 = a_1 - b_1 y,$$

for the channel’s lower part:

$$v_a(y)_2 = a_2 + b_2 y,$$

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

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

$$R_x = m k_p S_x \left( \frac{dx(t)}{dt} \right)^2 + \left( \frac{dy(t)}{dt} + v_0(y) \right)^2,$$

$$R_y = m k_p S_y \left( \frac{dy(t)}{dt} \right)^2 + \left( \frac{dx(t)}{dt} + v_0(y) \right)^2.$$

Grain’s transparent frontal area:

$$S_x = \pi a \sqrt{a^2 \sin^2 \phi} = \pi a^2 \sin \phi;$$

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

where $\phi$ is the grain’s dielectric constant (moisture-dependent) and grain density ($\varepsilon_g = 10...80$).

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:

$$v_g^a(y) = \frac{v_g}{\varepsilon},$$

where $v_g$ - air velocity in the empty channel; $\varepsilon$ - 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:

$$t = x = y = 0; \quad \frac{dx(t)}{dt} = v_0 \cos a_Y; \quad \frac{dy(t)}{dt} = 0 \sin a_Y;$$

where $v_0$ - the rate of the grain’s entry into air flow; $a_Y$ - 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.
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) $v_1 = 1$ m/s, (mass) $m = 42 \cdot 10^{-3}$ g; second fraction: $v_2 = 9$ m/s, $m = 38 \cdot 10^{-3}$ g; third fraction: $v_3 = 5.5$ m/s, $m = 35 \cdot 10^{-3}$ 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 %.

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