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Scientific foundations of the movement of components of grain material with an artificially formed distribution of air velocity

The article examines the study of the separation of grain materials in pneumatic channels with an artificially generated distribution of air velocity in the cross-section channel to determine the rational form and parameters of the material supply and options for grain material separation into fractions. The regularities of the weevil movement were theoretically investigated and established in the form of mathematical models of the dynamics of the movement of a solid particle in airflow, which differ from the known ones by taking into account the action of lateral forces, the concentration of the material, and the use of a power-law and an artificially formed exponential law of air distribution facilitated to increase the differences (splitting) trajectories of caryopses by 20 %. The solution of the system of nonlinear differential equations with initial conditions is performed in the Mathcad software environment in the form of trajectories of the grain in the air flow. It allows calculating their trajectories, which differ in windage coefficients and determine the rational values of the parameters of pneumo-gravity and pneumo-inertia separators. Using the obtained dependencies for the development of air separators contributes to determine the initial speed of entry and the direction of entry of the kernels into the airflow, as well as to determine the trajectories of material movement in the air channels with the bottom unloading of material.

Keywords: airflow, weevil, Zhukovsky and Magnus forces, trajectory, separation process, pneumatic separator.

Introduction

Solving the problem of dividing multicomponent grain material into separate fractions for a specific purpose (seeds, marketable grain, fodder) at the stage of primary grain processing will reduce the number and productivity of machines for secondary and special processing of conditioned grain. A promising direction for increasing the efficiency of post-harvest processing of grain in grain producers is the use of pneumatic separation machines at the first stage, the functioning of which does not depend on the initial moisture content of the grain. However, in production conditions, the separation efficiency of grain material ranges from 30 to 60 %, depending on the processing stage. The conducted research identified recommendations for the design, selection of parameters, and modes of operation of pneumatic separation channels. Nevertheless, further improvement of the quality of separation of the components of grain material (CPM) is complicated by not solving the issues of reducing the negative impact on the efficiency of separation of the irregularities of the air flow velocity fields along the width of the vertical and the height of the horizontal channels. The equalization of the velocity field with corrugated lamellar grids (at the inlet or outlet of the channel) ambiguously affects the separation efficiency and requires additional maintenance. Recently, pneumatic separators with dampers with adjustable opening angle have appeared (generators of a cascade of air jets). Establishing the optimal velocity profile for vertical and horizontal channels is the essence of the research to improve the separation efficiency of the CPM, which consists in the need to determine the influence of an artificially created velocity profile on the value of the divergence of trajectories and to determine the rational profile of the air flow velocity field in the channels.

The main conceptual provisions of the pneumatic separation of CPM into fractions during the primary processing of grain are reflected in [1]. Recent works [2–9] provide the implementation of ways to improve the efficiency of functioning and the quality of separation in air channels. To improve the separation of materials in a horizontal channel, authors of the work [2] propose to feed grain through a vertical air channel. In [3], the material is fed into the vertical channel through a multilevel cascade of guide chutes, which reduces the interaction between the grains at the entrance to the channel. Kyurchev and Kolodiy [4], for the first time, determined the separation of the CPM in the lower zone of the vertical pneumatic channel and proved the possibility of fractionation in the vertical channel with the lower gathering of the kernels. Kharchenko and Borshch [5] used a vertical pneumatic channel with a periodically varying cross-sectional area along the height to increase the efficiency. For the first time, scientists of works [6, 7] identified the efficiency of changing the flow rate along with the height of an inclined pneumatic duct and adjusting the average air velocity in the duct. However, in the mathematical description of the movement of the weevil, they used a model with a uniform flow. At the same time, Rogovskii et al. [8] used a model of the movement of a weevil in a vertical channel with a logarithmic distribution of air velocity and assumed a decrease in the divergence of trajectories due to the unevenness of the field of air velocities. Stepanenko et al. and Rogovskii et al. [9, 10] investigated the movement of caryopses in vertical and horizontal channels with a change in the air velocity toward its movement and determined an increase in the efficiency of separation of the CPM. Nevertheless, they did not consider the effect of additional, so-called lateral (transverse) forces caused by the unevenness of the air flow velocity field. The influence of the action of lateral forces in the vertical and horizontal pneumatic separation channels is reflected in works [11–13] and the negative influence (reduction of the divergence of trajectories) of the action of lateral forces of the Magnus and Zhukovsky type is shown. Concurrently, separate studies carried out by calculating the trajectories of movement with arbitrary forms of describing the field of velocities of air flows in the channels of pneumatic separators showed the possibility of improving the quality of separation with a certain configuration of the air velocity diagram. Stepanenko et al. [13] published some data from these studies.

We formulate a mathematical description of the CPM movement in pneumatic channels with an artificially generated air velocity distribution in the channel cross-section to improve the quality of separation (differences in trajectories) of the CPM.

Experimental

Since the design features of technical means for pneumatic separation are not considered, an analytical method for studying fractionation processes by constructing a mathematical description for calculating the trajectories of the CPM and their subsequent analysis has been chosen.

Results and Discussion

Studies on the processes of separation of grain in air channels [14, 15] found that the efficiency of separation of grain material largely depends on the uniformity of the air flow in the channel. The uniformity of the flow in the air channels is characterized by the field of the flow velocity, which can be described by semi-empirical dependences. The power law of distribution is most widely used in the form of the expression [16]:

$$\upsilon(x) = \upsilon_{\max} \cdot \left[\frac{x}{b}\right]^{\frac{1}{n}}, \tag{1}$$

where $\upsilon_{\max}$ — time-variable air velocity in the center of the channel; b — half the distance between the walls of the channel; x — distance from the point under consideration to the channel wall; n — coefficient depending on the Reynolds number Re [n=7–10 at Re=2,3($10^3 \ldots 10^5$)].

Or a more accurate logarithmic dependence of A. Altshul [17]:

$$\frac{\upsilon(x)}{\upsilon_{\max}} = \left[1 - 2\frac{\lg\left[\frac{b}{x}\right]}{\frac{0{,}975}{\sqrt{\lambda}} + 1{,}35}\right]; \tag{2}$$

where λ — channel resistance coefficient.

The presence of an air velocity gradient in the channels causes the appearance of lateral forces [18] of the Zhukovsky type (lifting force $\overline{F}_Z$) and Magnus type (Magnus effect — $\overline{F}_M$). The action of these $\overline{F}_Z$ and $\overline{F}_M$ are directed normally to the vector of the relative flow velocity $\overline{u}$. In this case, the direction of the action of the force $\overline{F}_Z$ is directed towards an increase in the value of the air velocity in the channel section (i.e., towards the channel axis); the vector of force $\overline{F}_M$ in the direction of that side of the grain where the vector of the air flow velocity $\overline{V}_p(x)$ coincides with the direction of rotation of the grain (with the angular velocity $\overline{\omega}$ [19]).

Thus, the force $\overline{F}_Z$ deflects the weevil in the process of its movement to the central part of the channel, where the air velocity is the greatest. The direction of action of the lateral force $\overline{F}_M$ depends on the direction of rotation of the grain: If the grain starts to rotate clockwise when leaving the feeder, then it will deviate from the centerline to the (right) wall, if the direction of rotation is opposite, the grain will deviate from the wall (right) to the channel axis. In the absence of an air velocity gradient or grain rotation, the lateral forces do not act on it; $\overline{F}_M = \overline{F}_Z = 0$. Therefore, the uniformity of the air flow rate contributes to an increase in the separation efficiency of the CPM. As the center of pressure of the air flow does not coincide with the center of gravity, a moment of aerodynamic force acts on the caryopsis and it rotates in the flow during the movement. The caryopsis differs from the shape of the ball, therefore, when turning, it changes the area of the honey section, and the resistance force, because of which the components of the reaction of the air flow appear in the horizontal plane and the trajectory of its movement becomes a spatial curve [20].

With a uniform field of air flow velocities, a further increase in the quality of CPM separation is achieved by changing the air speed in the channels in the direction of its movement, which is highlighted in [8, 9].

Since the action and direction of lateral forces to a certain extent depend on the shape of the air velocity distribution curve and, accordingly, the modulus and vector of the velocity gradient, the magnitude and direction of the action of these forces can be directed to improve the quality of the SCM separation by artificially forming the required field of air velocities in the channels.

Let us consider the process of movement of the CPM in uneven air flows with predetermined shapes of the air velocity diagram in the plane of the Cartesian rectangular coordinate system HOU under generally accepted simplifying assumptions [10–13].

Using the model of the force interaction of the CPM with an uneven air flow, we write the differential equations of the grain motion in vector form:

$$m\frac{dV}{dt} = \overline{R} + \overline{G} + \overline{F}_M(\omega) + \overline{F}_Z, \tag{3}$$

$$I\frac{d\omega}{dt} = M, \tag{4}$$

where $\overline{G} = mg$ – gravity; $\overline{R} = -mk_V \overline{u}^2(t)$ – aerodynamic drag force; $\overline{F}_Z = \frac{4}{3}\pi\rho r^2 grad\, V(x)\overline{u}$ – Zhukovsky's strength; $\overline{F}_M(\omega) = \frac{16}{3}\pi\rho r^3 \omega \overline{u}$ – the strength of Magnus; $\overline{u} = \overline{V}_p(x) - \overline{V}$ – relative speed (flow velocity); I — moment of inertia; $m = \frac{\pi d_e^3}{6}\rho_g$ – the mass of the weevil; $d_e = 2r$ — equivalent grain diameter; ρ, ρ_g – the density of the air and the matter of the weevil, respectively; $\overline{V}$ — weevil speed; $\overline{V}_p(x)$ — air speed.

Projecting equation (3) on the XOU axis will have a system of differential equations of grain motion in coordinate form:

$$\begin{cases} m\dfrac{dV_x}{dt} = -R\sin\beta \pm \overline{F}_{Z(x)}\cos\beta \pm \overline{F}_{M(x)}\cos\beta \\ m\dfrac{dV_y}{dt} = mg - R\cos\beta \pm \overline{F}_{Z(y)}\sin\beta \pm \overline{F}_{M(y)}\sin\beta \end{cases} \tag{5}$$

where $V_x = \frac{dx}{dt}$; $V_y = \frac{dy}{dt}$; $\sin\beta = \frac{V_x \pm V_p(x)}{u}$; $\cos\beta = \frac{V_y \pm V_p(x)}{u}$; $u = \sqrt{(V_x \pm V_p(x))^2 + (V_y \pm V_p(x))^2}$;
u — the relative speed of the caryopsis in the stream (the speed of the flow around the caryopsis through the air);
β — the angle between the absolute velocity vector and the 0X axis.

The equations of system (5) are written in a general form in the presence of two air flows $V_p(x)$, each of which (horizontal or vertical) can be used separately.

Let us consider the process of movement of the CPM in the horizontal channel of the simplest "winnower" separator Figure 1.

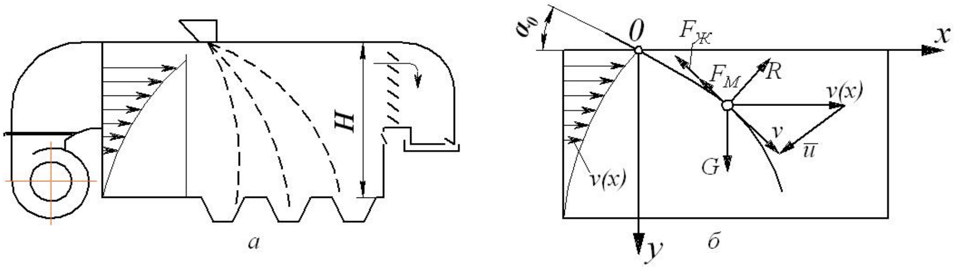


Figure 1. Scheme of the separator (a) and the force interaction of the weevil with an uneven air flow (b)

Without resorting to the details of the technical possibilities of forming a diagram of air velocities in a horizontal channel, we will accept the exponential dependence of the change in air velocity along the height of the channel:

$$V(y) = V_{\max} e^{-ky}, \tag{6}$$

It approximately characterizes the distribution of air velocity at the outlet of the centrifugal fan.

The air velocity gradient will have the opposite sign compared to the power-law distribution (1), namely:

$$grad\, V(x) = -kV_{\max 1} e^{-ky}, \tag{7}$$

where $V_{\max 1}$ — air velocity in the area of the upper wall of the channel.

In this case, the forces $\overline{F}_M$ and $\overline{F}_Z$ with a conventionally specified direction of rotation, directed in the direction of counteraction to motor grains, which should increase the time of its stay in the separation chamber (channel).

Projection $\overline{F}_M$ and $\overline{F}_Z$ on the coordinate axis are determined by the following dependencies:

$$\overline{F}_{Z(x)} = -\frac{4}{3}\pi\rho r^3 kV_{\max 1} e^{-ky}\left[V_{\max 1} e^{-ky} - \frac{dx}{dt}\right], \tag{8}$$

$$\overline{F}_{M(x)} = -\frac{8}{3}\pi\rho r^3 \omega(t)\left[V_{\max 1} e^{-ky} - \frac{dx}{dt}\right], \tag{9}$$

$$\overline{F}_{Z(y)} = \frac{4}{3}\pi\rho r^3 kV_{\max 1} e^{-ky}\left[\frac{dy}{dt}\right], \tag{10}$$

$$\overline{F}_{M(y)} = -\frac{8}{3}\pi\rho r^3 \omega(t)\left[\frac{dy}{dt}\right], \tag{11}$$

Substituting the values of certain components into equation (5), we get:

$$\frac{d^2x(t)}{dt^2} = k_V\left[v(y) - \frac{dx(t)}{dt}\right]\sqrt{\left[v(y) - \frac{dx(t)}{dt}\right]^2 + \left[\frac{dy(t)}{dt}\right]^2} - \\ - \frac{\left[\overline{F}_{Z(x)} + \overline{F}_{M(x)}\right]}{m}\frac{\frac{dy(t)}{dt}}{\sqrt{\left[v(y) - \frac{dx(t)}{dt}\right]^2 + \left[\frac{dy(t)}{dt}\right]^2}} \tag{12}$$

$$\frac{d^2y(t)}{dt^2}=g-k_V\left[\frac{dy(t)}{dt}\right]\sqrt{\left[v(y)-\frac{dx(t)}{dt}\right]^2+\left[\frac{dy(t)}{dt}\right]^2}-$$
$$-\frac{\left[\overline{F}_{Z(x)}+\overline{F}_{M(x)}\right]}{m}\frac{\left[v(y)-\dfrac{dx(t)}{dt}\right]}{\sqrt{\left[v(y)-\dfrac{dx(t)}{dt}\right]^2+\left[\dfrac{dy(t)}{dt}\right]^2}} \tag{13}$$

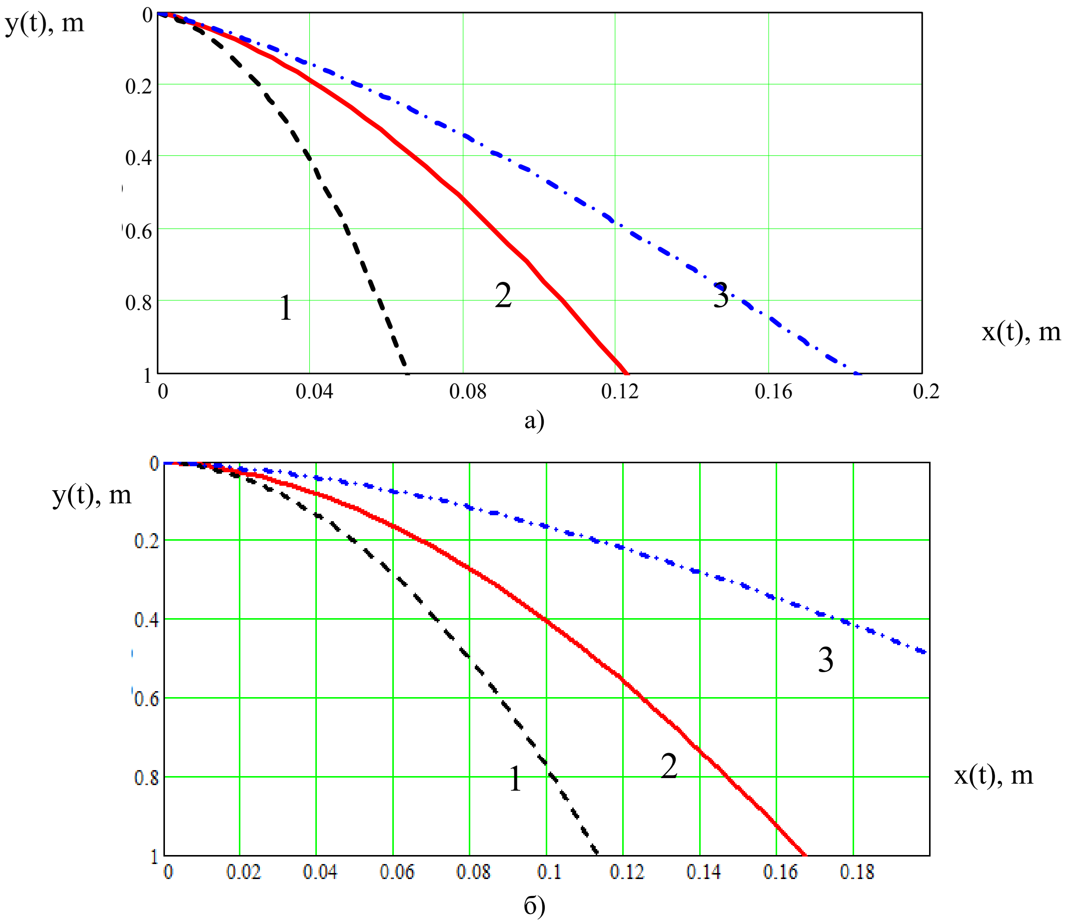
To close the system, we define the dependence $\omega(t)$:

$$I\frac{\omega(t)}{dt}=2{,}3\pi\rho r^3\frac{h-y}{h-r}\left[\left[V_{\max}e^{-ky}-\frac{dx(t)}{dt}\right]\right], \tag{14}$$

and write the initial conditions:

$$t=0;\ \ x=0;\ \ y=0;\ \ \frac{dx(t)}{dt}=V_0\cos\alpha_0;\ \ \frac{dy(t)}{dt}=V_0\sin\alpha_0;\ \ \omega=\omega_0. \tag{15}$$

The solution of the system of equations (12)–(14) under the initial conditions (15) was calculated in the Mathcad computer environment in the form of the trajectory of the grain with different values of the hovering speed and, accordingly, the mass (Figure 2).



a)

б)

1–3, respectively $k_V=0{,}139;\ \ 0{,}184;\ \ 0{,}392;$

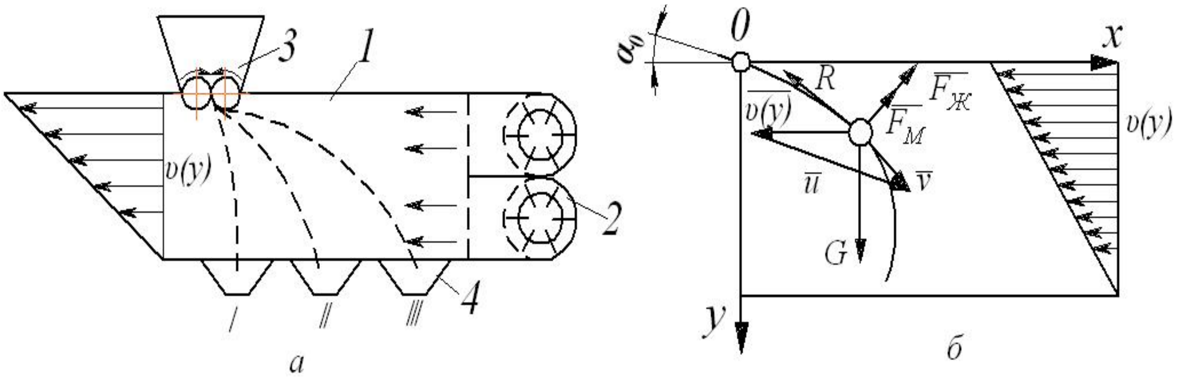
Figure 2. Trajectory of movement of caryopses in a horizontal channel with uniform (a) and exponential distribution of air velocity along the height of the channel (b)

Comparing the resulting dependencies $y(x)$, it can be noted that changing the air velocity diagram in the channel contributes to increase in the divergence of the trajectories and, accordingly, in the efficiency of separating the grain material into fractions.

A promising direction for improving the quality of the separation of grain material into fractions in a horizontal flow is the use of inertial forces when the grain moves against the direction of the air flow. In this case, the speed of air flow around the caryopsis increases when entering the channel and the resistance force.

An increase in the air velocity in the zone of grain entry into the channel by changing the air velocity diagram increases both the resistance forces R and strengths $\overline{F}_M$, $\overline{F}_Z$, which will act as "lifting".

Figure 3 presents the diagram of the pneumo-inertial separator and the force interaction of the weevil with the air flow.



1 — pneumatic channel, 2 — fans, 3 — feed rollers, 4 — collectors of fractions.

Figure 3. Scheme of a pneumo-inertial separator (a) and the force interaction of a weevil with an air flow (b)

Let us assume a linear distribution of the air flow rate along the channel height:

$$v(y) = V_{\max} - by(t) \tag{16}$$

The system of differential equations for the movement of a grain in a horizontal uneven flow with a countercurrent feed of material in coordinate form will look like:

$$\begin{cases} m\dfrac{d^2x(t)}{dt^2} = -R\dfrac{\left[v(y)+\dfrac{dx(t)}{dt}\right]}{u} + F_{Z(x)}\dfrac{\left[\dfrac{dy(t)}{dt}\right]}{u} + F_{M(x)}\dfrac{\left[\dfrac{dy(t)}{dt}\right]}{u} \\ m\dfrac{d^2y(t)}{dt^2} = mg - R\dfrac{\left[\dfrac{dy(t)}{dt}\right]}{u} - F_{Z(y)}\dfrac{\left[-v(y)+\dfrac{dx(t)}{dt}\right]}{u} - F_{M(y)}\dfrac{\left[-v(y)+\dfrac{dx(t)}{dt}\right]}{u} \end{cases} \tag{17}$$

Where $u = \sqrt{\left[v(y)+\dfrac{dx(t)}{dt}\right]^2 + \left[\dfrac{dx(t)}{dt}\right]^2}$, $R = k_V m u^2$.

Force projections $F_{Z(x,y)}$ and $F_{M(x,y)}$ on the axis of the rectangular coordinate system XOY can be written as:

$$\overline{F}_{Z(x)} = -\frac{4}{3}\pi\rho r^3 b\left[V_{\max} - by - \frac{dx}{dt}\right], \tag{18}$$

$$\overline{F}_{M(x)} = \frac{8}{3}\pi\rho r^3 \omega\left[V_{\max} - by - \frac{dx}{dt}\right], \tag{19}$$

$$\overline{F}_{Z(y)} = -\frac{4}{3}\pi\rho r^3 b\left[\frac{dy}{dt}\right], \tag{20}$$

$$\overline{F}_{M(y)} = \frac{8}{3}\pi\rho r^3 \omega\left[\frac{dy}{dt}\right], \tag{21}$$

Substituting the value of the acting forces in equation (17), we finally get:

$$\begin{gathered}\frac{d^2x(t)}{dt^2} = \frac{-k_V\left[v(y)+\dfrac{dx(t)}{dt}\right]}{\sqrt{\left[v(y)+\dfrac{dx(t)}{dt}\right]^2+\left[\dfrac{dy(t)}{dt}\right]^2}} + \\ +\frac{\rho}{\rho_g}\left[V_{\max}-by-\frac{dx(t)}{dt}\right](b+2\omega)\frac{\dfrac{dy(t)}{dt}}{\sqrt{\left[v(y)+\dfrac{dx(t)}{dt}\right]^2+\left[\dfrac{dy(t)}{dt}\right]^2}}\end{gathered} \tag{22}$$

$$\begin{gathered}\frac{d^2y(t)}{dt^2} = g - \frac{k_V\left[\dfrac{dy(t)}{dt}\right]}{\sqrt{\left[v(y)+\dfrac{dx(t)}{dt}\right]^2+\left[\dfrac{dy(t)}{dt}\right]^2}} - \\ -\frac{\rho}{\rho_g}\left[\frac{dy(t)}{dt}\right](b+2\omega)\frac{\left[v(y)+\dfrac{dx(t)}{dt}\right]}{\sqrt{\left[v(y)+\dfrac{dx(t)}{dt}\right]^2+\left[\dfrac{dy(t)}{dt}\right]^2}}\end{gathered} \tag{23}$$

To close system (22) — (23), it is necessary to have the dependence $\omega = \omega(t)$. In the presence of the initial rotation speed of the weevil ω_0 (which is provided by the rollers of the feeding device (Figure 3a), rotating at different speeds.

The change in the angular velocity of rotation of the caryopsis can be determined from the equation [13]:

$$\frac{d\omega(t)}{dt} = 15\frac{\mu}{\rho r^2}\omega(t) \tag{24}$$

where μ — coefficient of dynamic viscosity of air.

On condition $t=0;\ \omega=\omega_0;$ the change in the speed of rotation in time is determined by the dependence:

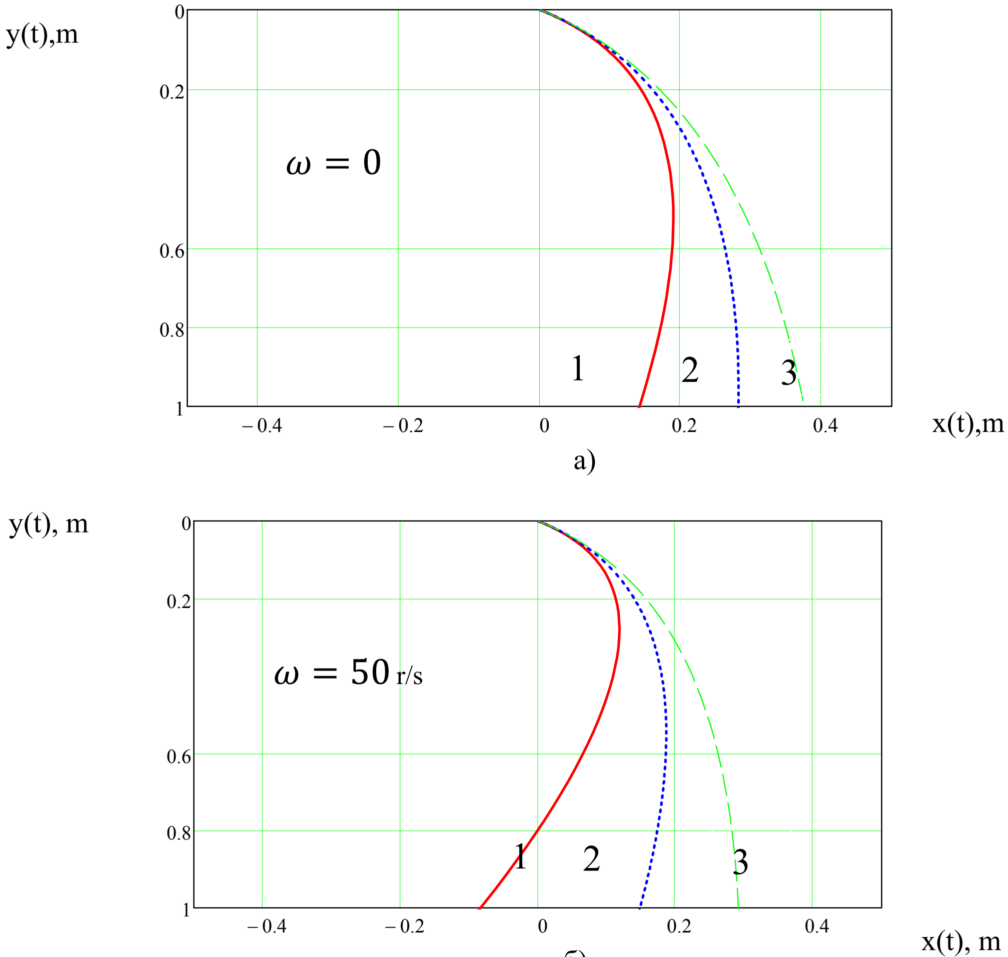
$$\omega(t) = \omega_0 e^{-15\frac{\mu t}{\rho r^2}} \tag{25}$$

To solve the system of equations, the initial conditions are formulated:

$$t=0;\ x=0;\ y=0;\ \frac{dx(t)}{dt}=V_0\cos\alpha_0;\ \frac{dy(t)}{dt}=V_0\sin\alpha_0;\ \omega=\omega_0. \tag{26}$$

V_0 — the rate of introduction of grain material into the pneumatic separation channel.

The system of equations (22)–(24) with the initial conditions (26) was solved in the Mathcad computer environment. The results are presented in the form of the trajectory of movement of individual components of the grain material in Figure 4.



a)

б)

1–3, respectively $k_V = 0{,}139;\ \ 0{,}184;\ \ 0{,}392;$

Figure 4. Trajectories of caryopses with different values of windage coefficients

The main disadvantages of vertical pneumatic separation channels of traditional rectangular cross-section, besides significant volumetric unevenness of the air flow rate, stagnant corner zones, are the imperfection of the system for feeding grain into the channel (curved pitched boards, multilevel input), which do not provide: uniform grain distribution, channel; stratification and separation of the grain stream, which in turn, leads to the jet introduction of the grain material into the air stream.

Multiple collisions of grains incorporate the involvement of small fractions in the traces of movement of larger components. As a result, some of the main fractions are carried away, while some of the trash impurities end up in the east of the commercial fractions.

Using cylindrical pneumatic channels with an annular cross-section can significantly improve separating the CPM into fractions. The use of “volumetric” feeders (conical or in the form of surfaces of revolution with a curvilinear generatrix) provides uniform along the perimeter of the channel, the introduction of grain (almost a monolayer) into the air flow, and also eliminates stagnant zones in the channel.

At the same time, it should be noted that the unevenness of the air flow velocity field in the annular channel negatively affects the separation efficiency of the grain material.

Without resorting to the details of the technical implementation of the change in the air flow velocity diagram in the annular channel, let us consider the movement of weevils in an air flow with an artificially formed air velocity irregularity. Diagrams of the pneumatic separation channel and the force interaction of the weevil with the air flow are shown in Figures 5a and 5b, respectively.

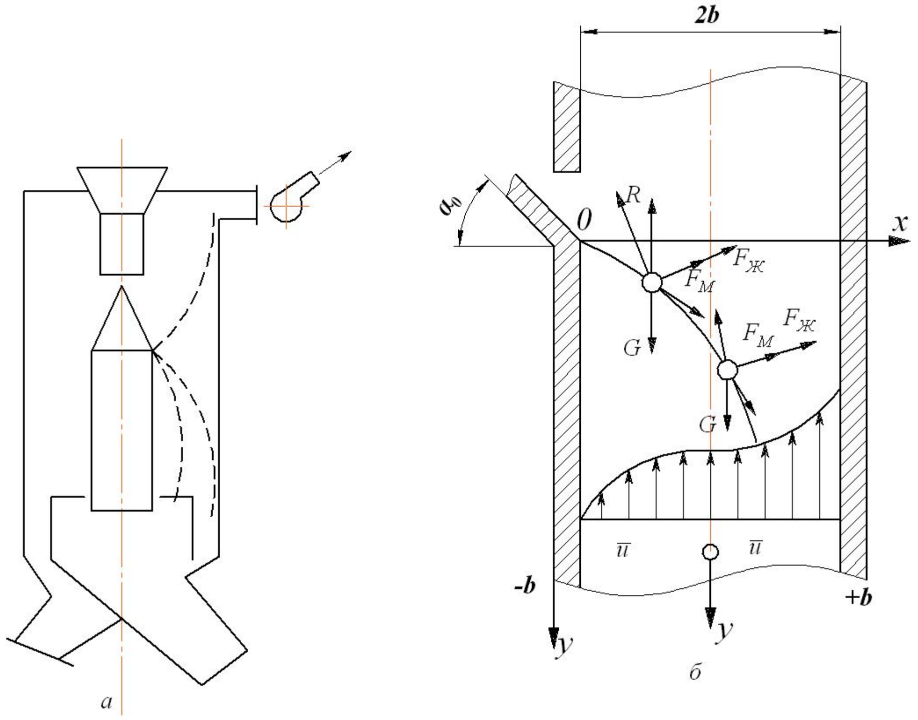


Figure 5. Scheme of a pneumo-gravity separator (a) and the force interaction of a weevil with an air flow (b)

The OS axis conventionally divides the air volume of the channel into two parts (along the axis), in which the average air flow rate is the same.

In the first part, the distribution of air velocity is described by a power law:

$$\upsilon(x) = \upsilon_{\max} \cdot \left[\frac{x}{b}\right]^{\frac{1}{10}} \tag{27}$$

and in the second part, the air velocity distribution is described by the exponential law:

$$\upsilon(x) = \upsilon_{\max} \cdot e^{k_V y} \tag{28}$$

On a weevil in an air channel except for gravity $\overline{G} = mg$, and aerodynamic resistance $R = k_V m u^2(t) = k_V m\left[V_p(x) - v(x)\right]^2$, lateral (deflecting) forces act $F_{Z(x,y)}$ and $F_{M(x,y)}$.

The equation for the dynamics of the movement of a weevil in a vertical irregular flow in the coordinate form will be as follows:

$$\begin{cases} \dfrac{d^2x(t)}{dt^2} = -k_V\left[V_p(x) - v(x)\right]^2 \cos\alpha + \dfrac{F_{Z(x)} + F_{M(x)}}{m} \sin\alpha \\ \dfrac{d^2y(t)}{dt^2} = g\sin\alpha + k_V\left[V_p(x) - v(x)\right]^2 \sin\alpha + \dfrac{F_{Z(y)} + F_{M(y)}}{m} \cos\alpha \end{cases} \tag{29}$$

From the analysis of the interaction of the forces acting on the grain and the equations of motion (29), it follows that the lateral forces $F_{Z(x,y)}$ and $F_{M(x,y)}$ deflect grains of different mass and windage in one direction throughout the entire time of movement in the channel. Moreover, one can see from the equations that less mass lateral forces have a greater effect on caryopses with a smaller mass and a less effect on caryopses of a larger mass, which contributes to the divergence of the trajectories of movement of caryopses of different fractions.

The projections of the forces acting on the weevil are determined by analogy with the previous study in the following form:

- Within the channel (- b…0):

$$\overline{F}_{Z(x)1} = \frac{4}{3}\pi\rho r^3 \frac{[V_{\max 1}]}{10 b^{0,1} x^{0,9}} \left[\frac{dx(t)}{dt}\right], \tag{30}$$

$$\overline{F}_{M(x)1} = \frac{8}{3}\pi\rho r^3 \omega(t) \left[\frac{dx(t)}{dt}\right],$$

$$\overline{F}_{Z(y)1} = \frac{4}{3}\pi\rho r^3 \frac{[V_{\max 1}]}{10 b^{0,1} x^{0,9}} \left[[V_{\max 1}]\left[\frac{x}{b}\right]^{0,1} - \frac{dy(t)}{dt}\right], \tag{31}$$

$$\overline{F}_{M(y)1} = \frac{8}{3}\pi\rho r^3 \omega(t) \left[[V_{\max 1}]\left[\frac{x}{b}\right]^{0,1} - \frac{dy(t)}{dt}\right],$$

- Within the channel (0…+b):

$$\overline{F}_{Z(x)2} = \frac{4}{3}\pi\rho r^3 k_V V_{\max 1} e^{k_V x} \left[\frac{dx}{dt}\right],$$

$$\overline{F}_{M(x)2} = \frac{8}{3}\pi\rho r^3 \omega(t) \left[\frac{dx}{dt}\right],$$

$$\overline{F}_{Z(y)2} = \frac{4}{3}\pi\rho r^3 k_V V_{\max 1} e^{k_V y} \left[V_{\max 1} e^{k_V y} - \frac{dy(t)}{dt}\right], \tag{32}$$

$$\overline{F}_{M(y)2} = \frac{8}{3}\pi\rho r^3 \omega(t) \left[V_{\max 1} e^{k_V y} - \frac{dy(t)}{dt}\right],$$

Initial conditions:

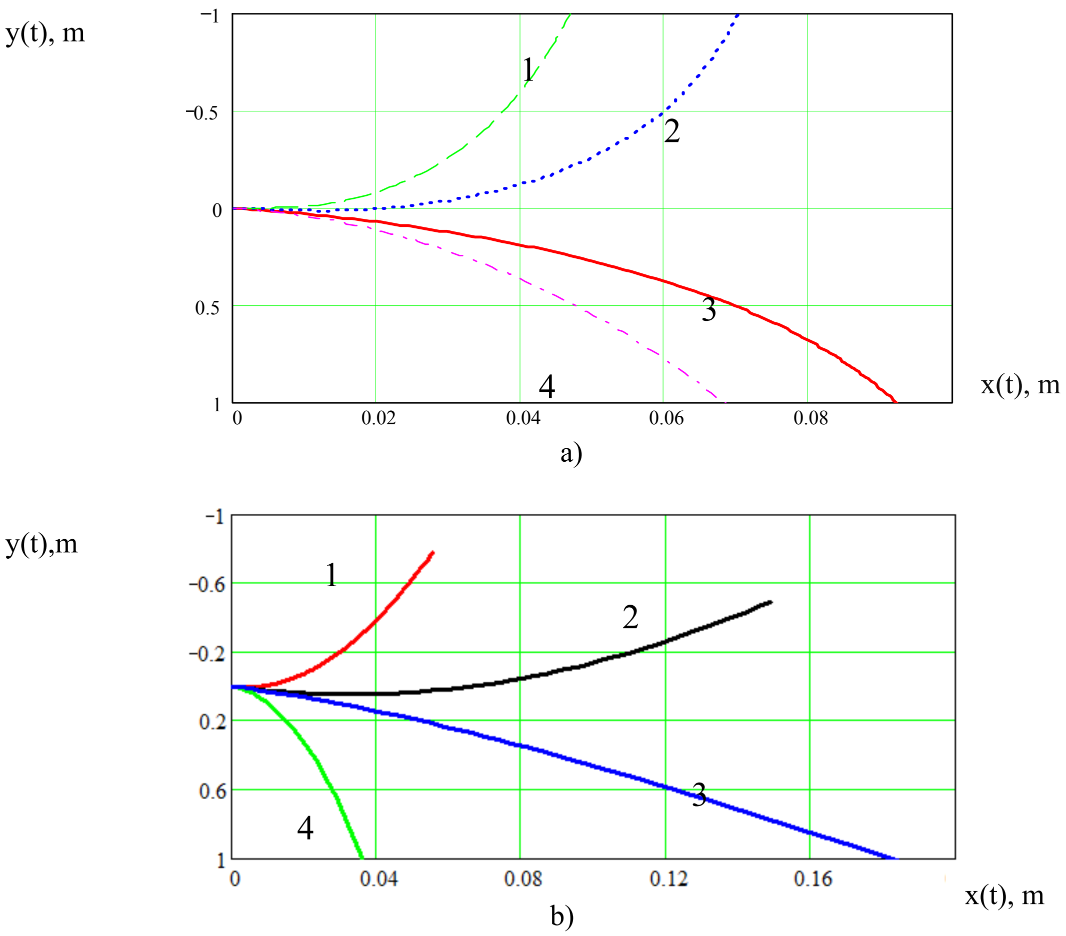
$$t = 0;\;\; x = -b;\;\; y = 0;\;\; \frac{dx(t)}{dt} = v_0 \cos\alpha_0;\;\; \frac{dy(t)}{dt} = v_0 \sin\alpha_0; \tag{33}$$

Limiting conditions:

$$\text{at } \le 0;\;\; F_{Z(x,y)}; F_{M(x,y)} = F_{Z(x,y)1}; F_{M(x,y)1} \tag{34}$$

at $\ge 0;\;\; F_{Z(x,y)}; F_{M(x,y)} = F_{Z(x,y)2}; F_{M(x,y)2}$

The solution of equations (28)–(29), taking into account (30)–(31) under the initial conditions (32) and limiting conditions (33), was obtained in the Mathcad computer environment by means of the trajectories of the caryopses in a uniform air flow (Fig. 6a) and with an artificially formed velocity field (Fig. 6b).



a)

b)

1–4, respectively $k_V = 0{,}4$; 0, 27; 0,159; 0,08

Figure 6. Trajectories of caryopsis movement in a uniform air flow
(a) and with an artificially formed velocity field (b)

As can be determined from the obtained graphical dependencies, the value of the divergence of the trajectories can be significantly increased using a rational configuration of the velocity diagram in the channel cross-section.

A further increase in the efficiency of separating caryopses according to aerodynamic properties can be achieved by distributing the air flow velocity along the channel height, namely by increasing the air velocity in the direction of its movement. For example, when the air speed (average by volumetric flow rate) changes according to a linear law:

$$V_{\max} = a - by$$

where $a = 12$, $b = 1{,}8$.

The shape of the trajectories and the magnitude of their difference change significantly, i.e., separation efficiency of CPM.

Figure 6 shows the trajectories of movement of grains of four fractions of grain material at various parameters of the air velocity diagram in the vertical section of the channel, indicating the real possibility of separating grain material into fractions in a pneumo-gravity separator.

Let us also consider the process of separating grain material into fractions in an inclined pneumatic separating channel described in [10, 12, 19–22]. Technologically, with vertical loading, the inclined channel operates in a counter-current mode and it can be considered as a pneumo-inertial separator (Figure 7), in which the inclined channel is located at an angle α to the horizon with plane-parallel walls. The air velocity along the channel height is distributed exponentially and is determined by relationship (6).

Using the model of a quasi-horizontal channel [11, 13], when the movement of the weevil is considered in a rotated α rectangular coordinate system XOУ.

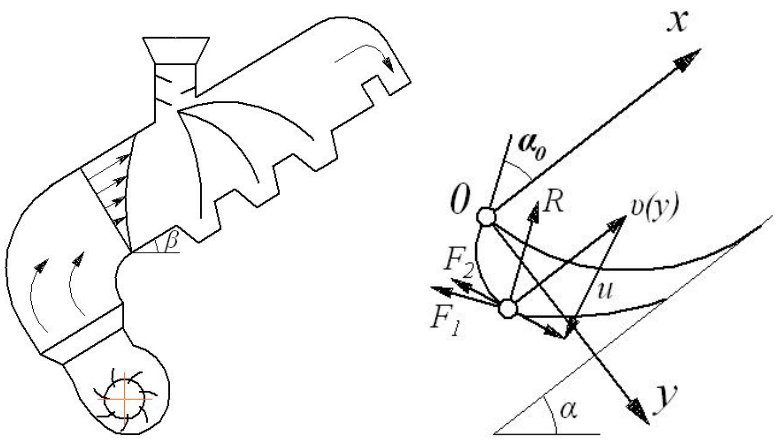


Figure 7. Diagram of an inclined pneumatic separation channel (a) and calculated scheme of action of forces (b)

In this case, we use the system of differential equations (5) in the following form:

$$\begin{cases} m\dfrac{dV_x}{dt} = R\sin\alpha - \left[F_{Z(x)} + F_{M(x)}\right]\cos\alpha - mg\sin\alpha \\ m\dfrac{dV_y}{dt} = mg\cos\alpha - R\cos\alpha - \left[F_{Z(y)} + F_{M(y)}\right]\sin\alpha \end{cases} \tag{35}$$

where $\sin\alpha = \dfrac{\frac{dy}{dt}}{u}$; $\cos\alpha = \dfrac{\frac{dy}{dt} + \frac{dx}{dt}}{u}$; $u = \sqrt{\left[\dfrac{dy}{dt} + \dfrac{dx}{dt}\right]^2 + \left[\dfrac{dy}{dt}\right]^2}$;

Lateral forces are determined from Eqs. (8) — (11) by replacing in (10) and (11) the sign in front of the derivative $\dfrac{dx}{dt}$ to the opposite.

Conclusions

1. The regularities of the movement of the caryopsis were theoretically investigated and established in the form of mathematical models of the dynamics of the movement of a solid caryopsis in air flow, which differs from the known ones by considering the action of lateral forces, the concentration of the material. The use of a power-law and artificially formed exponential law of air distribution made it possible to increase the discrepancy (splitting) trajectories of caryopses by 20 %.

2. The system of nonlinear differential equations with initial conditions was solved in the Mathcad software environment in the form of trajectories of the weevil in the air flow, which allows calculating their trajectories that differ in windage coefficients and determine the rational values of pneumo-gravitational and pneumo-inertial parameters.

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С.П. Степаненко, Б.И. Котов, А.В. Спирин, В.Ю. Кучерук

Ауа жылдамдығының жасанды түрде қалыптасқан таралуымен астық материалы компоненттерінің қозғалысының ғылыми негіздері

Мақалада материалды жеткізудің ұтымды формасы мен параметрлерін және астық материалын фракцияларға бөлудің нұсқаларын анықтау үшін арнаның көлденең қимасында ауа жылдамдығын жасанды түрде бөлу арқылы пневматикалық арналардағы астық материалдарының бөлінуін зерттеу қарастырылған. Бізтұмсықтың қозғалыс заңдылықтары теориялық тұрғыдан зерттеліп, қатты бөлшектердің ауа ағынындағы қозғалысының динамикасының математикалық үлгілері түрінде анықталды, олар бүйірлік күштердің әрекетін, материалдың концентрациясын есепке алатындығымен ерекшеленетіні белгілі, сондай–ақ, қуат заңын және ауаның таралуының жасанды түрде қалыптасқан экспоненциалды заңын пайдалану дәннің траекториясының айырмашылығын (бөлінуін) 20% арттыруға мүмкіндік береді. Бастапқы жағдайлары бар сызықты емес дифференциалдық теңдеулер жүйесін шешу Mathcad бағдарламалық ортасында ауа ағынындағы астық траекториялары түрінде жүзеге асырылады, олардың желкенділік коэффициенттерімен ерекшеленетін траекторияларын есептеуге және пневматикалық гравитация және пневматикалық инерциялық сепараторлар параметрлерінің ұтымды мәндерін анықтауға мүмкіндік жасайды. Ауа сепараторларын жасау үшін алынған тәуелділіктерді қолдана отырып, бастапқы кіріс жылдамдығын және ядролардың ауа ағынына кіру бағытын есептеуге, сонымен қатар, материалды төмен босатумен ауа арналарындағы материалдың траекториясын анықтауға болады.

Кілт сөздер: ауа ағыны, біздұмсық, Жуковский және Магнус күштері, траектория, бөлу процесі, пневматикалық сепаратор.

С.П. Степаненко, Б.И. Котов, А.В. Спирин, В.Ю. Кучерук

Научные основы движения компонентов зернового материала с искусственно сформированным распределением скорости воздуха

В статье рассмотрено исследование разделения зерновых материалов в пневматических каналах с искусственно созданным распределением скорости воздуха в поперечном сечении канала, для определения рациональной формы и параметров подачи материала и вариантов разделения зернового материала на фракции. Закономерности движения долгоносика были теоретически исследованы и установлены в виде математических моделей динамики движения твердой частицы в воздушном потоке, которые отличаются от известных тем, что учитывают действие боковых сил, концентрацию материала, а использование степенного закона и искусственно сформированного экспоненциального закона распределения воздуха позволило увеличить различия (расщепление) траекторий зерновок на 20 %. Решение системы нелинейных дифференциальных уравнений с начальными условиями выполняется в программной среде MathCad в виде траекторий зерна в воздушном потоке, позволяет рассчитать их траектории, различающиеся коэффициентами парусности, и определить рациональные значения параметров пневмогравитационного и пневмоинерционного сепараторов. Используя полученные зависимости для разработки воздушных сепараторов, можно рассчитать начальную скорость входа и направление входа ядер в воздушный поток, а также определить траекторию движения материала в воздушных каналах с нижней разгрузкой материала.

Ключевые слова: воздушный поток, долгоносик, силы Жуковского и Магнуса, траектория, процесс разделения, пневматический сепаратор.

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