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Research of the process of air separation of grain material in a vertical zigzag channel

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ABSTRACT

The aim of the research is to determine ways to improve the efficiency of grain materials pneumatic separation based on the study of the interaction mechanism of grains with the air flow in the channel elements, which are inclined sections of the air duct. The paper considers a modified separation method that separates the grain material according to the aerodynamic properties of the components in a vertical zigzag air channel in an aerodynamic and gravitational field. The studies were carried out by means of mathematical modeling followed by experimental confirmation of the modeling results. A computer mathematical model was created in the MathCad 13 application package to determine the parameters of the zigzag aspiration channel. This model describes the influx of parameters in the channel (width, height, cut of the zigzag ledge to the horizon, edge of the zigzag ledge) on the nature of the grain trajectory. As a result of the numerical simulation process using the mathematical package Mathematica, dependence was obtained to determine the trajectory of motion depending on the angular velocity. An increase in the pneumatic separation effect during the grain mixtures division due to the influence of the Magnus effect was established as a result of experimental studies. The design of a zigzag separator with an annular channel section has been improved based of the research carried out.

Keywords: air flow, grain material, grain, pneumatic channel, velocity field, mathematical model

INTRODUCTION

Removal of seeds of garbage plants, chaff, parts of stems and ears, and other impurities of organic and inorganic origin from grain increases the commodity value of grain, improves seed quality and storage stability. For seed grain, its cleaning and subsequent sorting by quality factor is the main operation that ensures the production of high-quality seeds for sowing. So the removal of garbage impurities from grain material is the main task of post-harvest processing of the crop and further processing into food products, seeds or forage.

The simplest most reliable and effective way to clean and sort grain is air separation–the separation of grain material components by air flows. The principle of air separation of grain material is based on the difference in the aerodynamic properties of its constituent components. The properties of different grains move in the air at different relative velocities which form the basis of air fractionation of grain.

The main indicator of the aerodynamic properties of the components of the grain mixture which determines the possibility of their separation in air flows is the terminal velocity, the value of which correlates quite closely with the size and density of the grains.

There are three main schemes for organizing air separation of grain material: in horizontal, vertical, and inclined air flow (channel) depending on the interaction of the directed air flow and the separated material (Shapiro and Galperin, 2005).

In world practice, the first technical means for cleaning and sorting of grain from garbage impurities by air flow were pneumatic separators with a horizontal channel. In them, garbage impurities as lighter ones were carried out by air outside the channel and clean grain fell into the bunker to the bottom of the channel under the influence of gravity (Olshanskii et al., 2016; Sheychenko et al., 2019).

In the further developments, improved separators with a horizontal air flow appeared, ensuring the separation of the grain material into fractions. Similarly, the separation of grain material into fractions is provided by pneumatic separators with an inclined channel (Kharchenko et al., 2021). In such separators, the force of gravity ensures the free entry of the grain material into the air flow, and the force of resistance to the air medium leads to its separation (Petit et al., 2020). A significant increased volume of the channel reduces the probability of grain collisions with each other and aggregation of them (Mykhailov et al., 2021). The presence of a jet generator (Zhou and Shen, 2022) makes it possible to control the division process.

The desire to increase the productivity and versatility of grain cleaning and separating machines determined the feasibility of combining vibrating-screen and pneumatic processes in one unit (Piven et al., 2018; Bulgakov et al., 2020).

It has become convenient to combine separate working bodies into one machine in accordance with grain processing technology with a vertical air channel of rectangular cross section. For this reason, vertical pneumatic separating channels are most widely used both as part of pneumatic-vibrating screen machines and as separate air aerodynamic separators (Stepanenko and Kotov, 2019).

In separators with a vertical air flow, the process of separating grain and impurities takes place in an air space of considerable height, which leads to a longer interaction time of the components with the air flow which significantly increases the separation efficiency and stability of the process (Kroulík et al., 2016).

The separation process in air flows is significantly influenced by the physical and mechanical properties of the grain material such as morphological composition, humidity, and degree of contamination which vary over a wide range (Bredykhin et al., 2021; Reguła et al., 2021).

When a grain material consisting of grains with different aerodynamic properties is introduced into a vertical ascending air flow, part of the grains and impurities is carried out by the flow from the channel. Other part falls against the direction of the air flow downwards and is discharged from the channel into the clean grain bin. That is, the material is divided into two fractions. An analysis of the trajectories of grain movement was performed in (Tishchenko et al., 2016) showed that the complete separation of the grain material in the channel is not achieved due to overlapping values of the signs of division. That is, when a grain and a particle of impurities have the same values of the terminal velocity.

The reason for the unsatisfactory operation of vertical channels of rectangular cross section is the dense introduction of grain material into the air flow. The grain density leads to intensive interaction of the grain material components with each other. This interaction leads to the loss of high-quality grains due to their entry into the waste through the upper part of the channel, as well as the ingress of low-quality grain and impurities into the cleaned grain.

Known attempts to improve the quality of separation are accompanied by structural complications. To improve efficiency, it was proposed to introduce grain into the channel in multilevel layered flows (Nesterenko et al., 2017) to evenly distribute the material in the longitudinal section of the channel. Another way to increase efficiency is to use pneumatic separation of the grain mixture when introducing a vertical channel into the air stream (Zhou and Shen, 2022).

It is proposed to change the cross-sectional area of the channel in the direction of air movement (Kolodiy and Kyurchev, 2015), as well as to throw the material into the air channel using a rotating vane feeder (Burkov et al., 2022).

Despite a certain improvement in the quality of separation, the accuracy of grain separation remains insufficient, and the grain material is re-cleaned to obtain clean grain, since the probability of marketable grain in the waste increases with an increase in the specific load.

A new principle in separation technology was implemented by cascade separation of the grain mixture in one technical tool. The first such separators were zigzag type devices–vertical channels of a zigzag profile in the longitudinal section of the channel. Such a separator consists of parts of an inclined channel connected in series with each other. Each element of the channel receives 1/n part of the source material. Due to the decrease in the concentration of material in each stage of the channel, the fission efficiency increases (Lukas et al., 2020).

The time of grain material contact with the air flow increases with the passage of its, which makes it possible to achieve greater level of grain cleaning and reduce the dimensions of the entire grain cleaning unit (Banjac et al., 2017; Li et al., 2020; Kaas et al., 2022). Despite the practical use of zigzag type separators in various industries, there is virtually no information on theoretical or experimental studies in publications in addition to describing the qualitative nature of the flow of the process of moving fractions in these devices.

The most widespread are studies aimed at determining and substantiating the parameters of air separating systems (Burkov et al., 2022; Aliiev et al., 2019; Kharchenko et al., 2021; Kolodiy and Kyurchev 2015) where the physical properties are disclosed, and a mathematical description of the flow is formulated the process of grain movement in air flows.

The work (Shevchenko and Aliiev, 2022) defines physical and mathematical approaches to describing the interaction of grains with air currents. In the paper (Adamchuk et al., 2021) the conditional efficiency of the additional effect of the radial flow on the separation of grains was determined.

The mechanism of the pneumatic-separation process in channels of complex shape including zigzag has not been studied enough. It doesn't take into account the action of side forces of the Magnus type and the non-uniformity of the velocity field, etc.

The authors propose to use a vertical zigzag channel in this paper to improve the efficiency of grain cleaning. The aim of the research is to determine ways to improve the efficiency of grain materials pneumatic separation based on the study of the interaction mechanism of grains with the air flow in the channel elements, which are inclined sections of the air duct.

MATERIALS AND METHODS

This paper considers a modified separation method that separates the grain material according to the aerodynamic properties of the components in a vertical zigzag air channel in an aerodynamic and gravitational field.

Separating channel (Figure 1) consists schematically of a cascade of series-connected inclined pneumatic channels having parallel walls and a rectangular transverse section. The separator is designed to clean grain from garbage impurities at the preliminary and final stages of pneumatic vibrating screen separation as well as the subsequent fractionation of seeds.

When designing air separators, an empirical approach often leads to false results and significant time and resource costs to eliminate them. Therefore, it is advisable to use the methods of mathematical modeling in the first study and subsequent experimental verification of the results obtained.

The theoretical substantiation of the conditions for the process of separating the components of grain material in a pneumatic channel of complex shape presents significant difficulties which lead to further complication

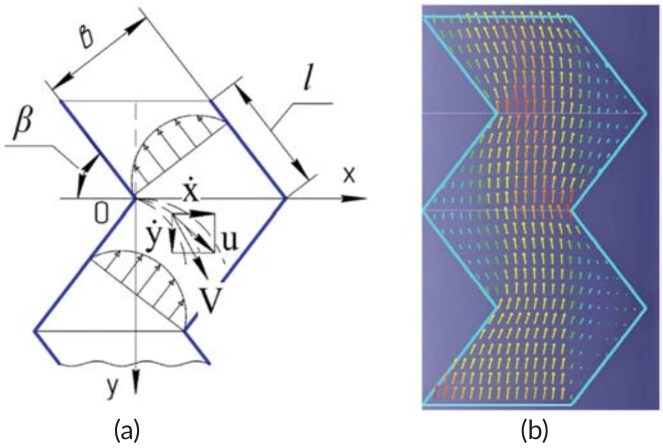

Figure 1. Scheme of a cascade of series-connected inclined pneumatic channels *(a)* and the air velocity field in the pneumatic channel of a zigzag type separator *(b)*

of the obtained mathematical dependencies. Therefore, it is necessary to consider a simplified scheme for the movement of both pure grain and impurities in the air flow of this air separator design before forming a mathematical description of the dynamics of the movement of grains in the air flow of the channel, and make simplifying assumptions.

Thus, the functioning of the zigzag separator is based on the principle of cascade-multiple separation of grains and impurities in the inclined elements of the pneumatic channel. In addition to the organization of the cascade separation principle in this separator, new schemes for the movement of material and air flows in each degree of separation were studied under the following assumptions.

Grains and impurities are elastic and have a constant ball shape. The air flow is assumed to be uniform, the speed of which is determined as the average flow rate: $v_a = Q_a / F$, where Q_a is the volume flow of air, F is the average cross-sectional area of the channel.

The deterministic impact or action of the air flow on a grain of arbitrary size $d = 2r$ were r is the radius of the grain is determined by the force of aerodynamic resistance R and the lateral force of the Magnus type (Zou et al., 2007).

The grain during flight rotates, the direction of rotation is random, one-way rotation is assumed in the calculations. The trajectories of movement of grain material components in a zigzag channel were determined by the numerical solution of differential equations of movement of a grain in the form of a material point in an inclined air channel in the MathCad software.

Since the direction of grain rotation is probable, the separation efficiency of grain cleaning was determined experimentally on a mock-up sample of the pneumatic separator (Figure 2).

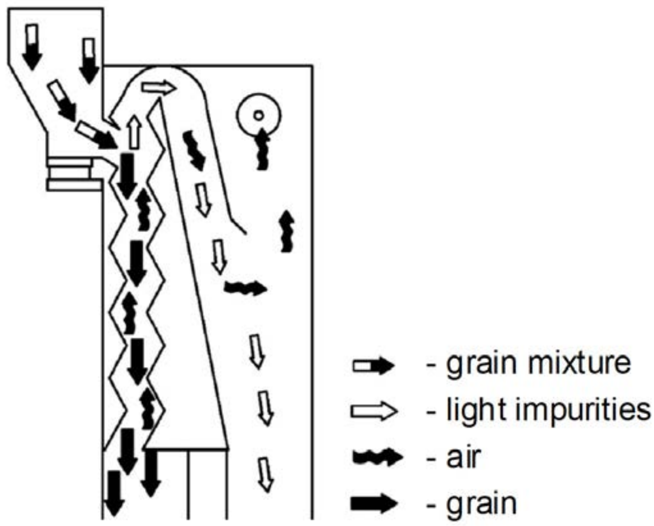

Figure 2. Technological scheme of the experimental mock-up sample of a pneumatic fractional separator of the zigzag type

To study the process of pneumatic fractional processing of grain, an experimental mock-up sample was made (Figure 3). The pneumatic separator has the following parameters: channel width 400 mm, depth 100 mm, height 820 mm, number of sections are 11, material feed is 35 kg per hour per 1 cm of width. A vibrating feeder fed the grain, the initial grain speed was provided by changing the frequency of the vibrating feeder drive.

The FlowVision software complex was used for numerical modeling of the air flow distribution in the pneumatic channel of a zigzag type separator. Calculation of the air flow is based on the use of the numerical method of finite volumes.

To simulate the air velocity field, geometric models of the calculation area of the air flow distribution in the pneumatic channel of a zigzag type separator with different values of the channel width were developed

Figure 3. General view of the experimental mock-up sample of the pneumatic fractional separator

(Figure 1b) and imported in ASCII (American Standard Code for Information Interchange) format with the STL (STereoLithography) files extension into the FlowVision software complex.

An experimental setup was developed and manufactured (Figure 4) to study the process of pneumatic fractionation during grain processing.

Research on the process of pneumatic fractionation was carried out by planning and conducting factorial experiments. The source material during the research was wheat grain with the content of impurities in the range of 1.8-2.2%. The source material was prepared by mixing 50 mass particles of pre-cleaned grain collected by a combine harvester and one mass part of impurities. The weight of the isolated impurities was determined by sampling and analysis of grain material fractions and impurities. The studies were carried out on an experimental setup and on a separator with a vertical channel to compare the results.

The variable factors were the specific material supply and the average air velocity of the air in the channel. The quality indicator of the process of pneumatic fractionation was separation efficiency.

The separation efficiency in the experiments was determined as the ratio of the weight of impurities removed from the grain to the weight of impurities in the initial grain mixture that can be removed by air flow.

RESULTS AND DISCUSSION

A computer mathematical model was created in the MathCad 13 application package to determine the parameters of the zigzag aspiration channel. This model describes the influx of parameters in the channel (width, height, cut of the zigzag ledge to the horizon, edge of the zigzag ledge) on the nature of the grain trajectory. The grain is affected by the force of gravity, the force of resistance to the air, and the Magnus force when

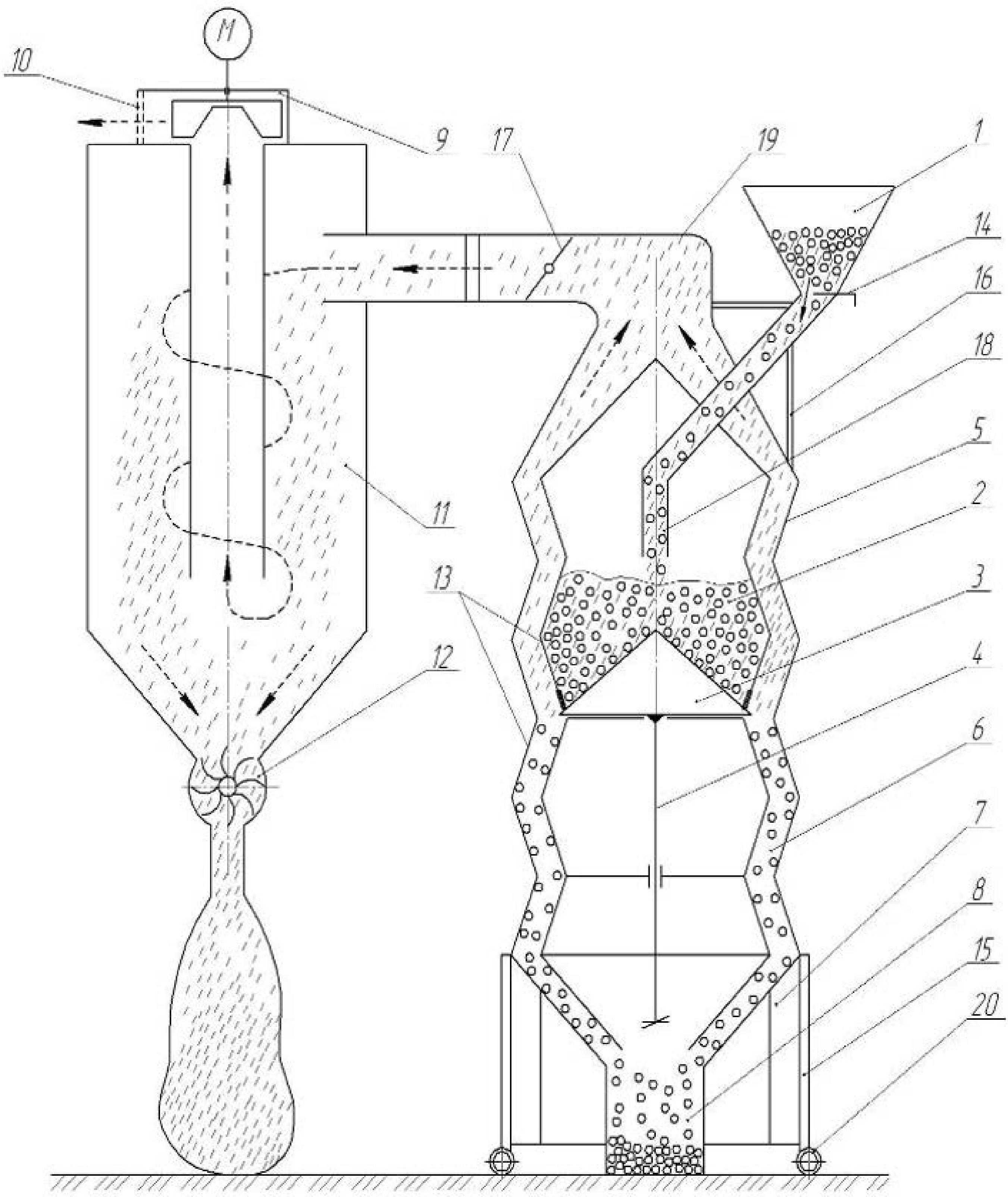

Figure 4. Scheme of the experimental setup, where 1 is the receiving hopper; 2 is storage hopper; 3 is dispenser cone; 4 is adjusting rod; 5 is annular V-shaped aspiration channel; 6 is segmental inserts; 7 is outlet pipe; 8 is storage box for cleaned seeds; 9 is suction fan; 10 is air filter; 11 is cyclone; 12 is dispenser for light impurities; 13 is viewing window; 14 is sliding door; 15 is frame; 16 is support frame; 17 is regulating valve; 18 is directional outlet nozzle; 19 is transitional diffuser; 20 are wheels.

moving inside the aspiration channel. Let's imagine a zigzag pneumatic separator in the form of a flat model, the separator itself is referred to a fixed relative to the horizontal surface of the coordinate system (Figure 5).

Let us direct the X axis vertically and the Y axis horizontally for convenience in describing the separation process. A particle with an initial velocity V_0 and at an angle to the horizon is introduced into the air stream. To determine the nature of the flow around the particle, we determine the relative velocity of entry into the air flow

$$V_{REL} = \sqrt{{V_b}^2 + V_0^2 + 2 \cdot V_0 \cdot sin(\alpha + \beta)} \qquad (1)$$

where V_b is the air flow velocity, m/s; β is the angle of inclination of the walls of the zigzag aspiration channel, rad.

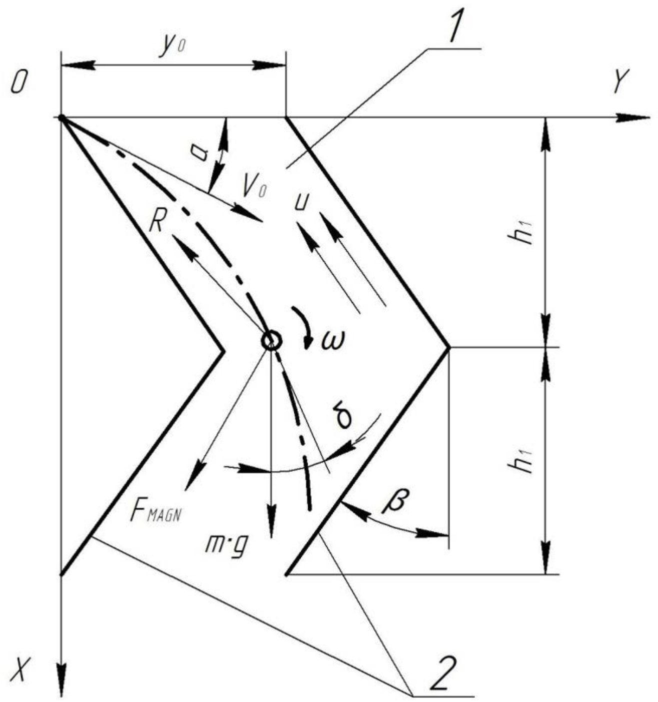

Figure 5. Scheme of the forces acting on a particle in a zigzag channel where 1 is aspiration channel, 2 is zigzag shelves

A number of assumptions were made to simplify the construction of a mathematical model of grain movement in an annular zigzag pneumatic separator and the analytical derivation of differential equations as well as a system analysis of grain movement in a zigzag channel.

– grain particle, to which the forces acting in the "grain mixture–air flow" system are applied, different in specific gravity from all other particles of the grain mixture;
– when moving inside the aspiration channel (Figure 5), the grain is affected by gravity, determined as, $F = m \cdot g$, where m is the mass of grain, kg; g is the free fall acceleration, m/s^2;
– air flow sucked from the working area of the air separator, stable over the cross-sectional area of the channel and acting on the particle with force

$$R = f(Re) \cdot F_m \cdot \frac{\rho_n}{2} \cdot (V - V_b)^2 \qquad (2)$$

where $f(Re)$ is the resistance coefficient, which is a Reynolds function; F_m is the midsection of grain, m^2; ρ_n is air flow density, kg/m^3; V and V_b are grain speed and air flow speed in the grain layer respectively, m/s.

The resistance coefficient, which is a Reynolds function, is determined

$$f(Re) = \frac{13}{\sqrt{4.8 \cdot \varepsilon^{2.6} \cdot \frac{V_b}{\nu} \cdot d}} \qquad (3)$$

where ε is the porosity of the layer in the static state; d is equivalent grain diameter, m; ν is kinematic coefficient of viscosity, m^2/s.

The Magnus force arises when a grain particle rotates around its axis, which can be described according to the Zhukovsky rule

$$F_{MAGN} = Vb \cdot \rho n \cdot Q \qquad (4)$$

where Q is the volumetric flow rate around the spherical grain, m^3/s

$$Q = S_{SUR} \cdot V_1 \qquad (5)$$

where S_{SUR} is the body surface area, m^2; V_1 is circumferential speed, m/s.

As know, the surface area of the body is equal to

$$S_{SUR} = 4 \cdot \pi \cdot R^2 \qquad (6)$$

where R is the equivalent radius of the sphere, m;

Substituting the obtained equations (5-6) into equation (4) and taking into account that the circular speed is equal to $(\omega \cdot R)$, we obtain the general equation for calculating the Magnus force:

$$F_{MAGN} = 4 \cdot \pi \cdot V_b \cdot \rho_n \cdot R^3 \cdot \omega \qquad (7)$$

According to the scheme of force interaction between a particle and a medium (Figure 5), the particle motion equation will have the general form

$$m \cdot \bar{a} = \bar{F} + \bar{R} + \bar{F}_{MAGN} \tag{8}$$

The resulting equation differs from the known ones by the presence of a component that takes into account the effect of rotation of a grain particle around its axis in the grain material.

Taking into account the accepted assumptions, having projected the equation (8) respectively on the *X* and *Y* axes, the motion of the particle between the walls of the aspiration zigzag channel can be described by the system of differential equations:

$$\begin{cases} m \cdot \ddot{x} = m \cdot g - \dfrac{13}{\sqrt{4.8 \cdot \varepsilon^{2.6} \cdot \frac{V_b}{\nu} \cdot d}} \cdot F_m \cdot \dfrac{\rho_n}{2} \cdot (\dot{x} - V_b \cdot \cos\beta)^2 + 4 \cdot \pi \cdot \rho_n \cdot R^3 \cdot \omega \cdot (\dot{x} - V_b \cdot \sin\beta) \\ m \cdot \ddot{y} = \pm \dfrac{13}{\sqrt{4.8 \cdot \varepsilon^{2.6} \cdot \frac{V_b}{\nu} \cdot d}} \cdot F_m \cdot \dfrac{\rho_n}{2} \cdot (\dot{y} \pm V_b \cdot \sin\beta)^2 \pm 4 \cdot \pi \cdot \rho_n \cdot R^3 \cdot \omega \cdot (\dot{y} \pm V_b \cdot \cos\beta) \end{cases} \tag{9}$$

By making the following substitutions in the differential equations:

$$Z = \frac{13}{\sqrt{4.8 \cdot \varepsilon^{2.6} \cdot \frac{V_b}{\nu} \cdot d}} \cdot F_m \cdot \frac{\rho_n}{2 \cdot m};\; L = \frac{4 \cdot \pi \cdot \rho_n \cdot R^3 \cdot \omega}{m};\; V1 = V_b \cdot \cos\beta;\; V2 = V_b \cdot \sin\beta$$

we obtain a second-order differential equations in a simplified form

$$\begin{cases} \ddot{x} + Z \cdot \dot{x}^2 - L \cdot \dot{x} - 2 \cdot V1 \cdot \dot{x} \cdot Z = g - L \cdot V2 - Z \cdot V1^2 \\ \ddot{y} - Z \cdot \dot{y}^2 + \dot{y} \cdot (2 \cdot Z \cdot V2 - L) + L \cdot V1 - Z \cdot V2^2 = 0 \end{cases} \tag{10}$$

After making substitutions:

$K = L + 2 \cdot V1 \cdot Z; F = g - L \cdot V2 - V1^2 \cdot Z; K1 = 2 \cdot V2 \cdot Z - L; F1 = L \cdot V1 - V2^2 \cdot Z$

we finally get:

$$\begin{cases} \ddot{x} + Z \cdot \dot{x}^2 - K \cdot \dot{x} - F = 0 \\ \ddot{y} - Z \cdot \dot{y}^2 + K1 \cdot \dot{y} + F1 = 0 \end{cases} \tag{11}$$

Mathematica software was used to simplify the solution of the system of equations. In the results of the calculations, a graphical interpretations of equation (11) were obtained in general form at different values of the angular velocity of rotation of a grain fraction around its axis (Figure 6 and 7). To plot the movement of a grain particle in the working channel of a pneumatic separator in the vertical and horizontal planes, the following values of its structural and kinematic parameters were taken: $d_G = 4 \cdot 10^{-3}$ m; $\rho_в = 1.21$ kg/m^3; kinematic coefficient of air viscosity at 20 °C, $\nu = 1.51 \cdot 10^{-5}$ m^2/s; $\eta = 1.82 \cdot 10^{-5}$ N·s/m^2; $V_{B\ wheat} = 9\text{-}11.5$ m/s; $m_{wheat} = (40\text{-}50) \cdot 10^{-6}$ kg; $V_{B\ oats} = 8\text{-}9$ m/s; $m_{oats} = (35\text{-}38) \cdot 10^{-6}$ kg; $g = 9.81$ m/s^2; $\varepsilon = 0.5$; $\beta = 20°$; $Y(0) = 0$.

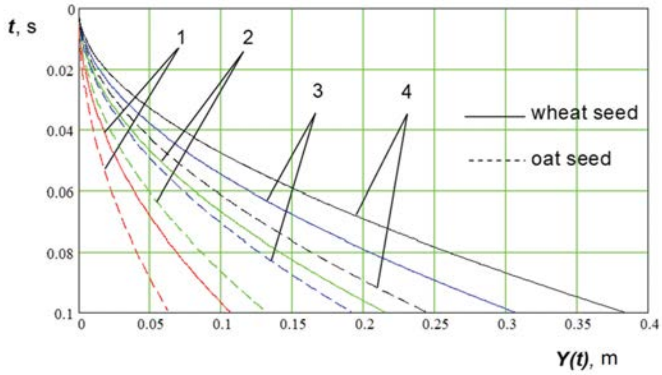

Figure 6. Dependences of the grain particle movement along the Y axis in a non-uniform air flow on the separation time at different values of the angular velocity ω, where 1 is $\omega = 20$ s^{-1}; 2 is $\omega = 30$ s^{-1}; 3 is $\omega = 40$ s^{-1}; 4 is $\omega = 50$ s^{-1}

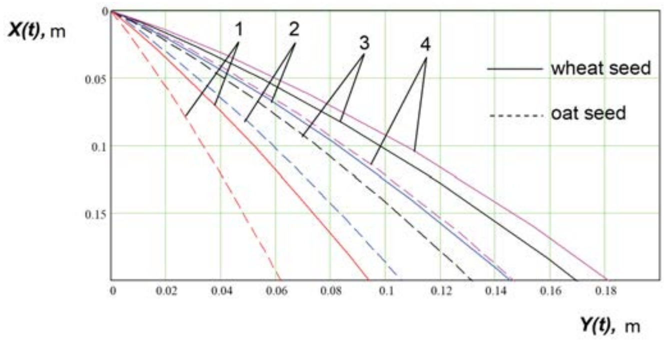

Figure 7. Dependences of particle movement trajectories along the X-axis and the Y-axis at different values of the angular speed of particles rotation around their axis, where 1 is $\omega = 20$ s^{-1}; 2 is $\omega = 30$ s^{-1}; 3 is $\omega = 40$ s^{-1}; 4 is $\omega = 50$ s^{-1}

Figure 8 shows the trajectories of the movement of grains, calculated according to equations (9) with constant structural and kinematic parameters, which are given above with the initial conditions: t = 0; x = 0; x´ = dx/dt = 0; y = 0; y´ = dy/dt = 0; and variable values of the grains terminal velocity (2.0 m/s; 2.5 m/s; 3.0 m/s).

Analyzing the graphical dependencies (Figure 6-8), it can be concluded that the effect of particle rotation significantly depends on the initial angular velocity and the angle of introduction of the grain mixture into the aspiration channel. It was also established that if the speed of the air flow in the separation zone of the grain mixture and the relative speed of the particle are changed, it is possible to achieve looseness of the material over the area of the aspiration channel, and turn the stochastic movement of particles with oscillating rotation in the volume of the channel into full rotation of the particles around their axis.

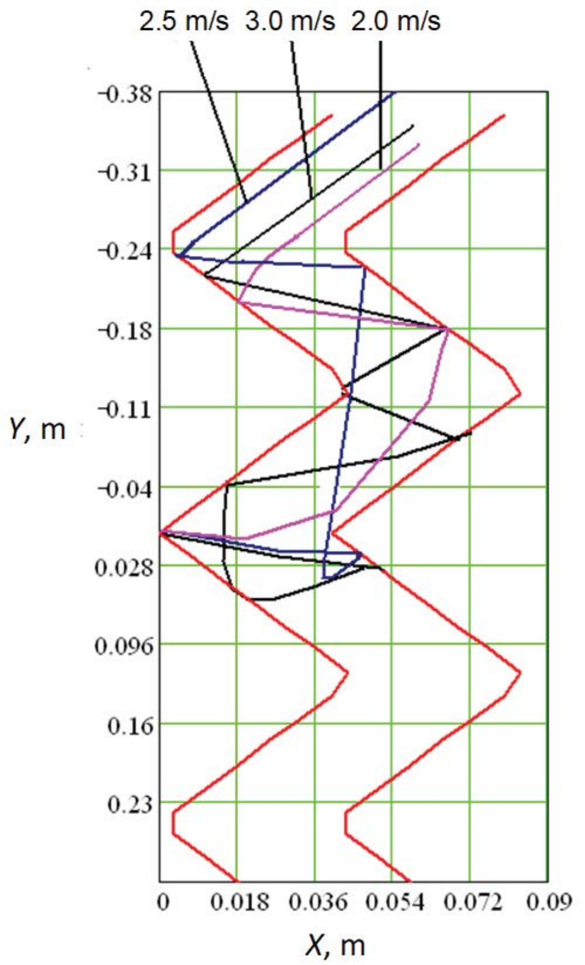

Figure 8. Generalizing graphical dependence of grain movement trajectories for different values of their terminal velocity

When the particles are given rotation at the beginning of their movement, it leads to a reduction in the effect of stochastic scattering over the area of the channel.

Dependencies for determining the trajectory of movement depending on the angular velocity were obtained, and an increase in the effect of pneumatic separation during the separation of grain mixtures due to the influence of the Magnus effect was obtained.

As a result of the conducted research, plots were obtained in the form of the velocity field (Figure 9) of the air flow at different values of the channel width and average air velocity of the air in the channel.

The analysis of the obtained vector fields of air flow velocities proved a significant influence of the channel width on Distribution of air velocity in the zigzag

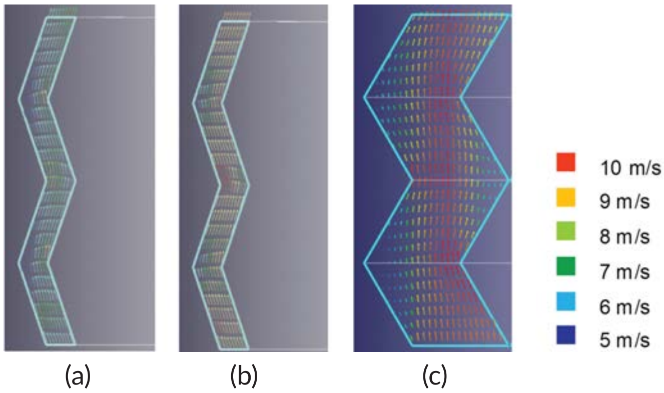

Figure 9. Distribution of air velocity in the zigzag channel of the separator when the average air velocity *V* and channel width *b* change: a) *V* = 7 m/s, *b* = 100 mm; b) *V* = 9 m/s, *b* = 100 mm; c) *V* = 9 m/s, *b* = 300 mm

channel of the separator. When the width B increases to 300 mm, a narrow air flow is formed in the center of the channel in the chamber with the formation of dead zones in the corners of the channel. When the channel width is 100 mm, the velocity field is redistributed along the length and width of the channel, which will provide favorable conditions for the separation of grain mixtures. This channel width was chosen for the gravity zigzag pneumatic separator.

In the process of modeling the technological process of separating grains in the zigzag channel of the separator and based on the analysis of Fig. 8 and 9, the rational parameters of the sieveless fractionation process were determined, taking into account the distribution of the air velocity field along the height and perimeter of the zigzag channel of the separator. So for wheat grain: the angle of material supply β = 20 – 25°; the speed of introducing material into the zigzag channel V_0 = 0,35 – 0,45 m/s; the average flow rate of air V = 7.45 – 8.67 m/s, which ensured an increase in the material separation coefficient by 0.02–0.05 m and the dependence of the cleaning efficiency on the specific load of the zigzag pneumatic separator by 15–20%.

On the basis of the conducted research, the design of the zigzag separator with the annular section of the channel was improved (Figure 10).

Figure 10. General view of an annular gravity zigzag pneumatic separator

The conducted experimental studies made it possible to establish the dependences of the influence of grain material loading on the separation effect in devices with an annular zigzag channel and a straight vertical channel (Figure 11).

Analysis of the obtained dependencies shows an increase in the separation effect in the separator with an annular zigzag channel. At the same time, the specific productivity of the annular gravity zigzag pneumatic separator is expected to increase by 15-20% compared to the separator with a vertical channel.

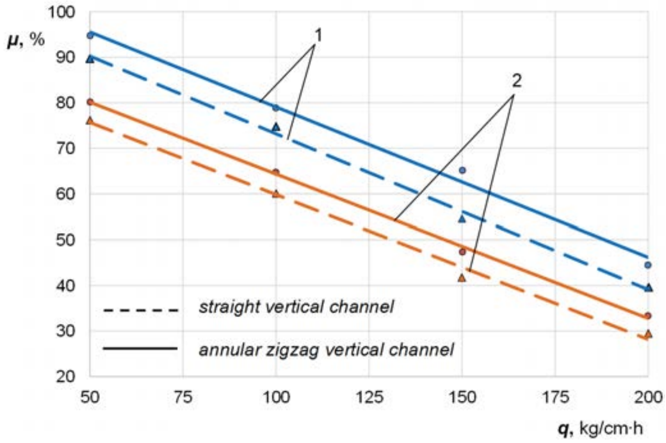

Figure 11. Dependence of cleaning efficiency on loading and air flow speed where 1 is V = 7.5 m/s; 2 is V = 6.5 m/s

CONCLUSIONS

Greater efficiency of the branching of trajectories during the pneumatic separation of grain mixtures can be expected with a variable speed of the air flow in the direction of movement. It is advisable to use zigzag-shaped separator with an annular channels for this method of intensification of separation.

The conducted research allowed proposing new technological schemes for the processing of grain materials with the widespread use of air structures which make it possible to increase the efficiency of fractionation and purification of grain materials. The use of variable air flow structures made it possible to implement the separation of grain mixtures with a more complete consideration of the properties of grain materials.

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