THEORETICAL STUDY OF PNEUMATIC SEPARATION OF GRAIN MIXTURES IN VORTEX FLOW

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Abstract. The article presents the results of the research on the justification of the pneumatic centrifugal method and design of the device for separation of grain mixtures in the grain-cleaning unit (module) of pneumatic centrifugal grain separators. The grounded initial requirements for the technological indicators and design-kinematic parameters of such a device would provide the productivity of the unit up to 60 $t\cdot h^{-1}$ and the qualitative indicators on the primary purification of the wheat grain, which is the basis for a family of universal grain separators of new generation with productivity 50, 100 and 200 $t\cdot h^{-1}$. For the developed design of the pneumatic centrifugal separator with the created vortex flow the equivalent scheme of interaction of the material particle of the grain mixture with the pneumatic vortex flow during its movement in the specified flow was made. The conditions of its motion and forces acting during this interaction were determined for the material particle. The components of its velocities during its motion in radial and vertical directions have also been determined. The necessary coordinate systems were introduced. To describe the motion of a material particle along a curvilinear trajectory the system of differential equations was composed. As a result of differential equations system solving the conditions of material particle distribution in three directions of motion depending on the physical and mechanical properties of the material particles have been determined. Constructed graphical dependences allowed to determine the design and kinematic parameters of the developed new design of the pneumatic centrifugal separator with vortex flow.

Keywords: grain mixture, pneumoseparation, vortex flow, model, efficiency.

Introduction

Grain production in Ukraine, Latvia and other Eastern European countries is constantly increasing. An important point in the technology of growing grain is its cleaning and separation [1-3]. Studies [3] aimed at justification of promising full-flow post-harvest processing of grain in agricultural enterprises prove the need to introduce in each large enterprise or in a group of relatively small enterprises (on the basis of cooperation) specialized grain cleaning-drying and storing complexes, which should provide reception, direct pre-treatment, accumulation for temporary storage and primary treatment of the grain with productivity of the machines for primary treatment of wheat grain with humidity up to 17% and clogging of the separated impurity up to 8% – 25, 50, 100 and 200 $t\cdot h^{-1}$.

Thus, in order to successfully ensure timely post-harvest processing of grain in agricultural enterprises with a significant increase in gross grain yield, there is a problem of creating primary cleaning machines (grain separators) with the capacity up to 200 $t\cdot h^{-1}$. The solution to this problem, taking into account the development of such separator design based on the modular principle, can be achieved through creation of a new design of the grain-cleaning unit (module) with the capacity 50 $t\cdot h^{-1}$.

In known universal grain vibrocentrifugal separators of BCS type pneumatic centrifugal devices are used [4], the separation process in which cannot provide a significant increase in separation efficiency, as particles of the grain mixture by rotary spreader are sent into the pneumatic separation channel perpendicular to the direction of air movement, which acts on the particles in the radial-vertical direction, which limits the interaction time and, therefore, the possibility of increasing the efficiency of such a separator. The works [5-9] and others are devoted to the problem of increasing the efficiency of pneumatic separation of grain mixtures by pneumatic centrifugal devices of air-lattice vibrating separators. Studies were aimed at improving the quality of pneumatic separation in the grain-cleaning unit with the capacity of 25 $t\cdot h^{-1}$. The results of these studies confirmed an insignificant improvement of pneumatic separation quality without increasing the capacity of the grain-cleaning unit, which did not solve the problem. Accordingly, there is a need for a more thorough study of the working process of this type of separators. The purpose of the research is to increase the efficiency of pneumatic separation of grain mixtures in air-lattice pneumatic-vibrating centrifugal separators by increasing the productivity and quality of separation of grain mixtures into components. To solve this problem, it is necessary to develop a new, most accurate and complete model of the movement of a grain mixture particle that will justify the design and kinematic parameters of the pneumatic vibro-centrifugal separator, which will make it possible to more clearly separate the fractions of the grain mixture in the pneumatic vortex chamber during the separation process.

Materials and methods

The investigation was conducted using the provisions of analytical geometry and differential calculus, the theory of agricultural machines, methods of compiling programs for numerical calculations on a PC [10-12].

The initial hypothesis in this study was the assumption that, if a thin layer of loose grain mixture is introduced into artificially created air rotational flow in the direction of its movement from the middle by ascending cone-like flow, then this mixture will be subjected to effective volumetric redistribution due to creation of qualitative uniformity of particle distribution in the volumetric space of the air flow (porosity) – under the action of centrifugal forces: heavier particles will move away from the axis of rotation of the air-grain mixture, and lighter particles will move closer to the middle of the flow. In this case, the holding time of particles of the grain mixture in the air vortex flow will be significantly increased due to its movement along the arc trajectories of increased length compared to the time of passage of particles through the air flow of pneumatic channels of known pneumocentrifugal separating devices. It will provide increase of the quality of separation, and accordingly, efficiency of the separating pneumocentrifugal device. In theoretical and experimental studies, the optimal parameters of the air flow and the angle of its swirl to achieve the efficiency of separation of grain material were taken according to studies [9].

To formulate the initial requirements for a pneumatic centrifugal separator, the BCS-50 serial separator was studied, which provides 80% efficiency in preliminary cleaning of a heap of wheat with a bulk density of 0.75 t · m-3, moisture up to 11% and contamination up to 10% [8].

Based on this, we have developed a design diagram of the pneumatic centrifugal device, which is shown in Fig. 1.

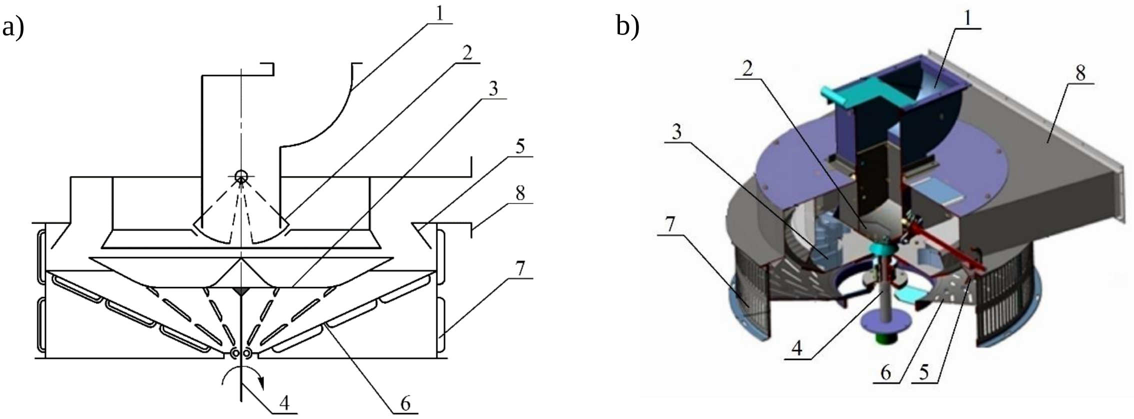

Fig. 1. **Pneumatic centrifugal separating device: a – design diagram; b – 3D model:** 1 – loading grain duct; 2 – dosing device; 3 – rotary spreader of grain mixture; 4 – drive shaft; 5 – wall of pneumatic separating duct; 6 – louvered cone; 7 – louvered cylindrical wall; 8 – suction pipe

The technological process of this pneumatic centrifugal device is as follows. Grain mixture through the charging conduct 1, at the opening of dosing device spigots 2 is fed strictly in the center of the rotary spreader 3, which is driven in rotation through the shaft 4. Spreader 3 directs the grain mixture into the pneumatic separation channel bounded by the outer wall 5. The angular rotation speed of the spreader 3 is equal to the angular speed of the louvered cone of the separator. Pneumatic vortex flow is created by introducing air into the pneumatic separation channel through the holes in the louver cone 6 and holes in the louver cylindrical wall 7 in the direction of rotation of the rotary spreader 3, the value of speed V_n which provides regulation is considered constant. The air is sucked in through the suction branch 8. An experimental setup (Fig. 2) was developed for preliminary studies of separation processes in a vortex flow. The experimental unit (Fig. 2) consists of a frame on which the grain-cleaning unit is installed. In the upper part of the block is placed the pneumatic vortex chamber, and inside – centrifugal sieves, which are attached to the frames, which in turn are mounted on the frame with the help of lever-hinged hangers. Also on the frame are fixed: the drive pulley with the frame, the grain mixture divider of the pneumoseparating channel, the grain mixture divider on the inner surface of the sieve, which are placed in the casing with trays of fraction outlet, the drives of rotor rotation and oscillatory motion of the sieve. Pneumatic vibration separator with pneumatic vortex chamber works as follows. Grain mixture, which is to be separated into fractions, through the dispenser with open chokes symmetrically to the axis of rotation goes to the grain mixture spreader, which is driven in a rotational motion in the direction that coincides with the direction of motion of air jets arising from the passage of air through the slits of the louver cone and louver cylindrical wall. The air is sucked from the aspiration system through the settling chamber connected to the pneumoseparating fan.

Fig. 2. **General view of the experimental setup for investigation of the pneumatic vortex separation process**

A swirling upward air flow is created in the pneumoseparating channel, in which the grain mixture layer is thinned down to the state of movement of individual grains. Due to aerodynamic forces, the light particles are carried into the settling chamber, where they settle and are removed by gravity outside the separator when the valve is opened. The grain mixture purified from light impurities along the inner surface of the cut cone from the slits, which simultaneously create an aerodynamic conveying process, are sent to the separator, which feeds the grain mixture to the inner surface of the centrifugal sieve, where the fine waste is separated. Similarly, the sieve separates crushed and fine grains, the sieve separates the grain of the main crop, and large impurities come off the sieve. Separated fractions by blades are sent to the trays. Grain of the main crop in the tray is re-treated by the air flow, which through the slits of the louvers through the air duct goes to the settling chamber, and the final purified grain by gravity is taken out of the separator by opening the valve. Grain mixture is divided into 5 fractions: fine waste, chopped and fine grain, cleaned grain, large impurities, light impurities, the gentle mode of operation of the pneumatic vortex chamber reduces the trauma of the grain. Studies [8] found that the cause of unsatisfactory cleaning of the grain mixture from light impurities is irrational feeding of grain into the ascending air flow by the grain mixture spreader. During the working process, the spreader feeds the grain mixture in a dense layer into the air flow. Since the bottom part of the serial spreader has blades, it contributes to uneven (along the perimeter) grain supply into the aspiration channel due to the fact that the blades direct the grain in the form of jets, thereby creating zones with higher density of grain. Another disadvantage of pneumatic separator's pneumatic vibration separator part is whirling in the connection zone of the air duct with the upper cylindrical part of the aspiration chamber, which reduces the air flow rate in some areas of the chamber.

In [9], hypotheses have been put forward that allow to eliminate the above drawbacks. Their essence is reduced to feeding the grain perpendicular to the direction of the air flow. This is provided by inclining the walls of the aspiration channel at an angle close to 45°, so that the aspiration channel takes the form of a truncated hollow cone, coaxial to which the grain mixture spreader, made in the form of a truncated cone, installed with its larger base upwards, is installed inside. Thus, in the theoretical study [8] the main indicators of the operating mode of the pneumatic separator pneumatic vibration separator were substantiated. Nevertheless, most of the provisions require theoretical and experimental verification.

Therefore, for theoretical study of this grain separator, first of all, let us build an equivalent diagram (Fig. 3). Let us show the grain mixture particle in the form of a material particle *M*, located in the separator working space, and the forces acting on it, occurring in the pneumatic vortex flow. It should be noted that the grain mixture is introduced into the pneumatic vortex flow by the centrifugal spreader under the action of centrifugal force, which acts on the grain mixture particles located on the working surface of the rotating spreader. Each particle *M*, depending on its mass and the resistance of the air flow, after leaving the surface of the manure spreader, after flying a certain distance, hangs for a very short time in a certain point of the working space of the pneumoseparating channel. Under the influence of the air flow the light particle immediately rises up and enters the zone of light impurities removal. The heavy particle, after a short hover, under the action of the weight force, overcoming the force of air flow resistance, goes down, eventually getting into the zone of withdrawal of the valuable heavy fraction. As it is for this case the most important and interesting, let us build an equivalent scheme. Thus, let us consider in the equivalent diagram the behavior of a heavy particle *M*, mass *m*, located in an air stream at an arbitrary time moment *t*.

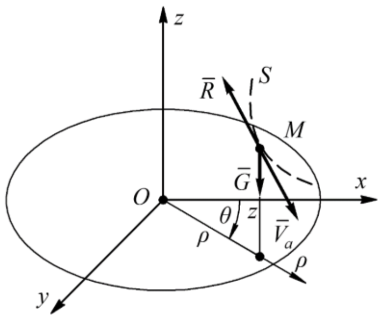

Fig. 3. **Equivalent scheme of interaction of pneumatic vortex flow with material particle of grain mixture**

Its assumed trajectory of motion in the absolute Cartesian coordinate system *Oxyz* is denoted by *S*. The *Oz* axis of this coordinate system is located on the rotor rotation axis and is directed vertically upward, the O*x* axis is directed to the right, and the *Oy* axis is perpendicular to the *zOx* plane. As shown in the equivalent diagram, the material particle *M* in this case is acted by the force of its weight *G* and the force *R* of air resistance. In this case, the force of weight *G* of the material particle *M* is directed vertically downwards, and the force *R* of air resistance, provided that the material particle moves downwards, is directed in the direction opposite to the direction of its movement. Further, since we consider the rotational motion of the rotor around its own axis *Oz*, the most appropriate to describe the motion of the particle *M* of the grain mixture is to use the cylindrical coordinate system, in which the equations of motion of the particle will have a simpler and easier to solve form than in the Cartesian coordinate system *Oxyz*. So, we will consider the motion of the material particle *M* of the grain mixture in the cylindrical coordinate system *Ozρθ*, *Oz* axis of which is directed vertically upwards and coincides with the rotor rotation axis (common axis with Cartesian coordinate system *Oxyz*), *Oρ* axis is located in horizontal plane *xOy*, oriented in radial direction from the point *O* and deviated from the horizontal *Ox* axis by an angle , that is, in the *Oxy* plane the parameters ρ and θ form a polar coordinate system *Oρθ* and are the coordinates of the material particle *M* in the horizontal plane *Oxy*. In space, in the cylindrical coordinate system *Ozρθ*, the particle *M* has coordinates *M* (*z*, *ρ*, *θ*).

The resistance force of the air flow *R* to the motion of the material particle is determined by the well-known formula:

$$R = m \cdot k_n \cdot V^2, \tag{1}$$

where k_n – sailing coefficient;
V – relative velocity of the particle in the air stream.

In this case, the magnitudes of the components of the airflow resistance force on the axis of the cylindrical coordinate system will be equal:

$$\left.\begin{aligned} R_\rho &= m\cdot k_n\left(\dot{\rho} + V_{n.\rho}\right)^2, \\ R_\theta &= m\cdot k_n\left(\rho\cdot\dot{\theta} + V_{n.\theta}\right)^2, \\ R_z &= m\cdot k_n\left(\dot{z} + V_{n.z}\right)^2. \end{aligned}\right\} \tag{2}$$

Differential equations of absolute motion of a particle in an ascending vortex airflow in the cylindrical coordinate system will have the following form:

$$\left.\begin{aligned} &m\left(\ddot{\rho} - \rho\cdot\dot{\theta}^2\right) = -R_\rho, \\ &m\left(2\cdot\dot{\rho}\cdot\dot{\theta} + \rho\cdot\ddot{\theta}\right) = -R_\theta, \\ &m\ddot{z} = R_z - mg\ . \end{aligned}\right\} \tag{3}$$

Results and discussion

Substituting the value of air resistance force components (2) into the system of equations (3), we obtain a mathematical model of particle motion in the investigated pneumoseparating channel:

$$\left.\begin{aligned} &\ddot{\rho} = \rho\cdot\dot{\theta}^2 - k_n\left(\dot{\rho} + V_{n.\rho}\right)^2, \\ &\ddot{\theta} = \frac{-k_n\left(\rho\cdot\dot{\theta} + V_{n.\theta}\right)^2 - 2\dot{\rho}\cdot\dot{\theta}}{\rho}, \\ &\ddot{z} = k_n\left(\dot{z} + V_{n.z}\right)^2 - g\ . \end{aligned}\right\} \tag{4}$$

In this case, the velocity $\bar{V}_n$ of the air flow in the first approximation will be considered constant, i.e. V_n = const. Then the angles between the axes ρ, θ, z and the vector $\bar{V}_n$ will also be constant. However, in order to calculate the constructed mathematical model, they must be given. As a result, we can determine the components of the air flow velocity on the axis of the cylindrical coordinate system:

$$\begin{aligned} V_{n.\rho} &= V_n\cdot\cos\left(\bar{V}_n, \rho\right), \\ V_{n.\theta} &= V_n\cdot\cos\left(\bar{V}_n, \theta\right), \\ V_{n.z} &= V_n\cdot\cos\left(\bar{V}_n, z\right). \end{aligned} \tag{5}$$

and substitute the obtained values into the system of equations (4).

The result will be:

$$\left.\begin{aligned} &\ddot{\rho} = \rho\cdot\dot{\theta}^2 - k_n\left[\dot{\rho} + V_n\cdot\cos\left(\bar{V}_n, \rho\right)\right]^2, \\ &\ddot{\theta} = \frac{-k_n\left[\rho\cdot\dot{\theta} + V_n\cdot\cos\left(\bar{V}_n, \theta\right)\right]^2 - 2\dot{\rho}\cdot\dot{\theta}}{\rho}, \\ &\ddot{z} = k_n\left[\dot{z} + V_n\cdot\cos\left(\bar{V}_n, z\right)\right]^2 - g\ . \end{aligned}\right\} \tag{6}$$

The presence of components $V_{n.\rho}$, $V_{n.\theta}$, and $V_{n.z}$ in the equations provides an increase of particle velocity components in radial and vertical directions of its movement, which provides for heavy particles the movement along curvilinear trajectories with approach to the axis of the air channel at simultaneous slowing down of their fall. For light particles this contributes to their more rapid removal from the separation zone beyond the borders of the separating device.

Using the developed program for numerical calculations, as well as the parameters of the process under consideration, the system of differential equations (6) was solved using a PC. Based on the results of the solution, graphical dependences of the changes in the specified coordinates were plotted, which made it possible to plot the trajectories of motion of grain mixture particles in the vortex flow (Fig. 4).

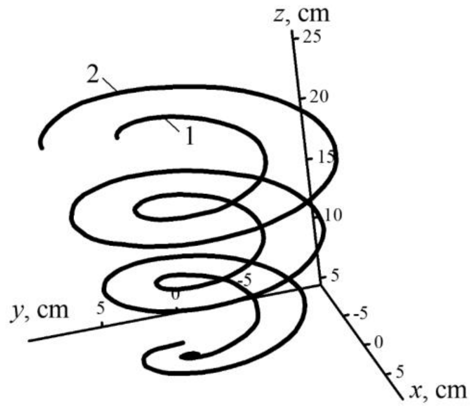

Fig. 4. **Simulation of grain trajectories in a pneumatic vortex air flow:**
1 – heavy fraction; 2 – light fraction

In the separating zone of the pneumoseparating channel, depending on their aerodynamic properties, the particles are distributed in three dimensions of space, and due to the constant counter flow in the radial direction and accompanying in the tangential direction, the grain mixture is exposed to a longer impact of the air flow on the particles, which contributes to improving the clarity of their sorting by aerodynamic properties. The solution of the system of equations cannot be represented in the form of an analytical function, so it is solved using the MathCad software package, which implements the software method of numerical integration of the equations on the interval (0; 0.1) at $\bar{V}_n = 7$ m·s^{-1}.

For the convenience of perception of the obtained graphical relationships, the transition from polar coordinates to Cartesian coordinates was made by the known formulas:

$$\begin{aligned} x &= \rho \cdot \cos\theta, \\ y &= \rho \cdot \sin\theta. \end{aligned} \tag{7}$$

In this case, using the function *Odesolve*, the solution of the system of equations is presented in the form of a parametric trajectory of movement of fractions in two planes *zOx*, *zOy* (Fig. 5).

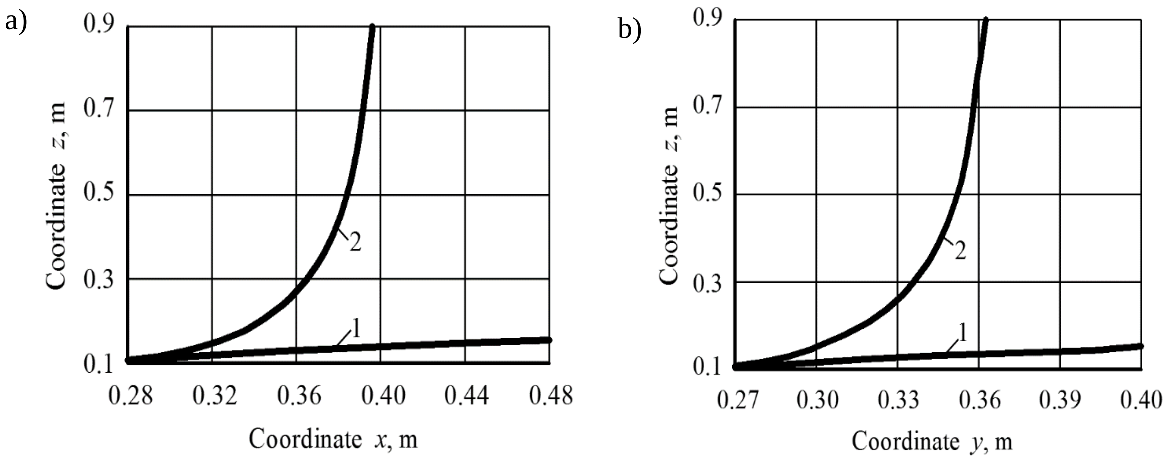

Fig. 5. **Trajectory of movement of fractions inside the aspiration channel:**
a – in the *zOx* plane; b – in the *zOy* plane: 1 – heavy fraction; 2 – light fraction

Fig. 5 shows that grain mixture particles with different specific gravity or aerodynamic properties are quite clearly separated in the pneumatic vortex chamber during the separation process. Therefore, as a result of theoretical studies we can say that a pneumatic vortex chamber with diameter 0.8-1.0 m and height 0.5-0.6 m is enough to obtain satisfactory results. Thus, the kinematic mode of the pneumatic separator in the developed mathematical model corresponds to the kinematic mode of the industrial models of BCS-type separators, which, when using the device in the new model of separators, will increase their unification. In the process of preliminary experimental studies of the pneumoseparating device in the experimental model of the pneumatic centrifugal separator of BCSM-50A type with the capacity 50 $t \cdot h^{-1}$ for primary purification of wheat grain the completeness of separation of light impurities was increased by 15-20%.

In most studies of separators for grain cleaning there is conducted an experimental assessment of the efficiency of the existing installations [2; 3; 6], or prototypes [7; 13]. The second part of the research is aimed at a theoretical study of the impact of individual structural elements of the separating devices upon productivity or efficiency [13-15], as well as determining the loss of whole grain [6]. There are also articles on how to determine the aerodynamic characteristics of grain [5], but there are no universal mathematical models that for particular air flow parameters could help determine the behavior of seeds in an ascending vortex flow.

Conclusions

1. The mathematical model of grain mixture particle motion based on the physical model scheme of the pneumatic centrifugal device was developed and investigated.
2. As a result of solving the developed mathematical model graphical dependences of changes in the coordinates of a particle in a vortex flow were built, which made it possible to construct trajectories of the movement of particles of the grain mixture.
3. Analysis of the obtained dependences showed that to obtain satisfactory results in the separation of the grain mixture, a pneumatic vortex chamber with a diameter of 0.8-1.0 m and a height of 0.5-0.6 m is sufficient. Preliminary experimental studies showed that the use of such a pneumatic vortex chamber can increase the efficiency of pneumatic separation by 15-20%, when achieving the performance of the grain cleaning unit (module) for cleaning wheat grain up to 50 $t \cdot h^{-1}$.
4. The experimental model created on the basis of the theoretical studies is adapted to the design of industrial separators of BCS type, which allows to create a new generation of separators, which have a capacity of 50, 100 and 200 $t \cdot h^{-1}$ in wheat purification when bringing it to basic conditions.

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