MODELLING OF AERODYNAMIC SEPARATION OF GRAIN MATERIAL IN COMBINED CENTRIFUGAL-PNEUMATIC SEPARATOR

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Abstract. One of the ways to improve the efficiency of post-harvest processing of grain is the preliminary fractionation of the grain mass, that is, the distribution into fractions for food, seed and fodder purposes. The use of airflows at the initial stage of separation ensures the preliminary formation of grain flows with minimal energy consumption and ensures the receipt of grain for various commodity operations. The high correlation of indicators of the technological properties of the components of the grain material allows the use of airflow at various stages of post-harvest processing of the crop. In most constructions of separators, the airflow is used to clean the lightest impurities. In this work, it is proposed, based on the integration of pneumatic separating working bodies, to develop a combined centrifugal and pneumatic gravity separator for separating components from the grain mixture that differ in mass and aerodynamic properties. The technology for separating the components of the grain material consists of preliminary removal of light impurities using a centrifugal-pneumatic method and dividing the grain into fractions using a pneumatic gravity method in an annular channel with an additional outpouring of radial airflow. The parameters of the combined wind separator are determined using additional mathematical models with trajectory analysis, computational fluid dynamics (CFD) methods and experimental verification. The results of experimental studies confirmed the possibility of dividing the grain material into two fractions with a percentage of fractions in the output of 39% to 61%.

Keywords: separation, airflow, grain material, mathematical model.

Introduction

In agricultural production, the separation of the grain heap into fractions is performed on machines of various types, the principle of operation of which is based on the difference in the physical and mechanical properties of impurities and various components of the grain material, such as size, weight, density, aerodynamic resistance, etc. Separation of thegrain material by an airflow has a number of advantages over other separation methods. This is a simple design, high specific productivity, minor grain injury, the possibility of removing inferior grain to the forage fraction.

Pneumatic separating channels are used in all types of air grid separators [1-3] to remove light impurities before feeding the grain to the sieve, which increases the productivity of the sieve working bodies [4]. Vertical pneumatic channels [5], inclined air channels [6] and grain separators with horizontal airflow [7-8] are widely used in grain cleaning practice. In addition to cleaning, they make it possible to divide the grain material into several fractions according to aerodynamic characteristics. The efficiency of grain cleaning in pneumatic channels largely depends on the properties of the initial grain material, parameters of the grain flow [9], the thickness of the grain layer, its porosity, the distribution of impurities in the volume of the flow [10-11].

The operation of air separators is significantly complicated by the uneven air speed in the channels and the uneven supply of grain into the channels [12].

Existing methods of increasing the productivity and efficiency of air grain separation involve increasing the size of the channels, using additional devices that change the air velocity fields, tiered feeding of grain into the channels [13], the application of an electric field [14], the use of preliminary pneumatic stratification of the grain flow before feeding into the channel [15]. In the work [16], a cylindrical insert is proposed in a vertical channel, which is given forced rotational oscillations.

However, most of the analysed innovations, despite certain improvements in the material separation process, significantly complicate the design of separators and do not solve the main problem of ensuring complete separation of the grain material due to the overlapping values of the signs of separation of grain and impurity particles. They do not allow separating grain materials into more than two components: pure grain and light impurities. At the same time, when using the lower part of the vertical channel as a working zone, there is a promising opportunity to separate the material into separate fractions based on aerodynamic characteristics that are qualitatively correlated with the biological properties of grains [17].

Fractionation of the grain material by an airflow at the initial stage of post-harvest processing ensures the preliminary formation of grain flows, which with minimal energy consumption allow obtaining grain of food, seed and fodder conditions [18-19].

A significant number of works are devoted to theoretical studies using mathematical modelling of the process of grain movement in air separation plants, which substantiate the possibility of taking into account the action on grain of previously unaccounted Magnus-type forces [20], Zhukovsky and centrifugal forces in air channels of various sections and shapes [21]. The development of new modelling approaches reveals the possibility of the development of new aerodynamic schemes for organizing the process of cleaning and separating grain into separate fractions.

A promising trend in the development of the design of grain separating machines is the integration of several separating working bodies into one machine, which makes it possible to implement the entire complex of technological operations from the purification of grain material to its separation into commodity factions. The study of such combined grain-separating units has received insufficient attention. In this work, the authors tried, based on a set of developed mathematical models, to study the trajectories of movement of the components of grain material at different stages of separation and evaluate their effectiveness theoretically and experimentally.

Materials and methods

The work proposes a technological scheme and design for simultaneous purification of the grain material from impurities and its separation into fractions according to aerodynamic properties, which is implemented using the pneumatic base of the BCSM industrial separator.

The technological process diagram and general view of the new design of the combined centrifugal-pneumatic separator are presented in Figure 1.

Fig. 1. **General view of the combined air separator**

To determine the influence of the main factors on the separation processes implemented in various zones of the combined unit, it is necessary to apply mathematical modeling of the movement of individual components of the grain material under the influence of forces caused by the airflow, and experimentally determine the final separation indicators. The method of modeling the movement of material in the airflow is described in detail in [22]. Projecting the forces of the equation on the axis of rectangular coordinates, we have a system of differential equations that describe the movement of grain in uniform air flows of a vertical annular channel:

$$\begin{aligned} \frac{d^2x(t)}{dt} &= -k_v\left(V_{ax}(x) - \frac{dx(t)}{dt}\right)\sqrt{\left(V_a(x) - \frac{dx(t)}{dt}\right)^2 + \left(V_a(y) + \frac{dy(t)}{dt}\right)^2} \\ \frac{d^2y(t)}{dt} &= -k_v\left(V_{ay}(y) - \frac{dy(t)}{dt}\right)\sqrt{\left(V_a(x) - \frac{dx(t)}{dt}\right)^2 + \left(V_a(y) + \frac{dy(t)}{dt}\right)^2} + g \end{aligned}, \tag{1}$$

where $V_{ay}(y) = V_{a0} - b \cdot y(t)$; $V_a(x) = \frac{Q_a}{2 \cdot \pi \cdot H} \left(\frac{1}{r_0} - \frac{1}{x}\right)$; $V_{ax} = V_0 - \frac{a}{\alpha}$; $a = \frac{Q_a}{2\pi H}$ at $(x > r)$;

x – distance across the annular channel, m;
y – distance along the annular channel, m;
k_v – coefficient of aerodynamic drag, m^{-1};
V_{a0} – air velocity at the point of grain introduction into the channel, $m \cdot s^{-1}$;
b – half the channel width, m;
H – channel height, m;
Q_a – volume flow of air in the channel. $m^3 \cdot s^{-1}$;
r_0 – radius of the inner wall of the cylindrical channel, m.

Initial and boundary conditions are:

$$t = 0; x = -b; y = 0; \frac{dy}{dt} = -V_0 \cdot \cos\alpha_0; \frac{dx}{dt} = V_0 \cdot \sin\alpha_0 \tag{2}$$

where V_0 – grain velocity at the entrance to the channel, $m \cdot s^{-1}$;
α_0 – angle of grain introduction into the airflow.

The coefficient of aerodynamic drag was used as a sign of the separation of components:

$$K_v = g/V_t^2 \tag{3}$$

where g – free fall acceleration, $m \cdot s^{-2}$;
V_t – grain terminal velocity, $m \cdot s^{-1}$.

Modelling of the airflow field in a vertical channel was carried out using computational fluid dynamics (CFD) methods by solving the unsteady Navier-Stokes equations [23]. To identify the possibilities of changing the pattern of the velocity field of the airflow in a vertical annular channel, the distribution of the air velocity was studied using the FlowVision software.

Experimental studies were carried out on a laboratory bench made based on an industrial separator BTSM-50A (Fig. 1). Conical spreaders with radial blades are used as rotary spreaders. The air speed in the aspiration channel was 4-9 $m \cdot s^{-1}$; disk speed 100-160 rpm. The flow speed in the pneumatic gravity channel is 4-9 $m \cdot s^{-1}$.

Changing the supply of the seed mixture was carried out by adjusting diaphragms with different cross-sections, which were installed at the base of the loader hopper and pre calibrate on the experimental material.

The experimental material was an artificially prepared mixture of wheat and barley seeds in a ratio of 9:1 by weight and with up to 5% impurities. The air speed was changed by throttling the discharge section of the fan. The separation efficiency was determined depending on the speed of the airflow and the rotation frequency for the rotary spreader.

The efficiency of separation was determined in the traditional way according to the formula:

$$E = (A - B)/C, \tag{4}$$

where E – separation efficiency;
A – amount of the light fraction in the sedimentation chamber;
B – amount of heavy impurities in the light fraction of the separation in the sedimentation chamber;
C – amount of light impurities in the original grain material.

The efficiency of pneumatic gravity separation was estimated by the mass of 1000 grains in each grain sampler.

Results and discussion

As a result of solving the system of equations (1) with limit conditions (2), in the MathCad software, the grain movement trajectories in the annular channel of the pneumatic gravity separator were obtained (Fig. 2).

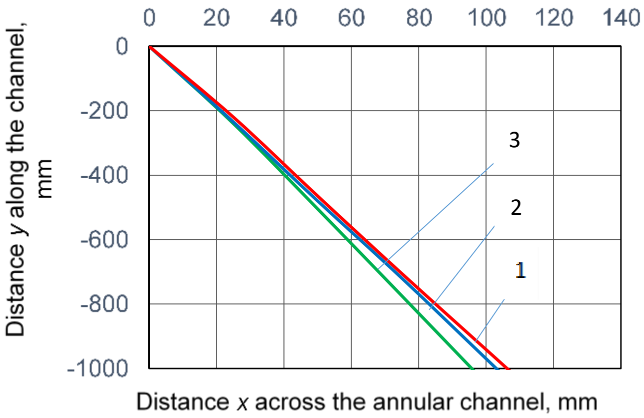

Fig. 2. **Trajectories of movement of grains in the annular channel of the pneumatic gravity separator under the condition of convergence from a conical distributor at different values of the terminal velocity of particles**: 1 – 3.4 m·s^{-1}; 2 – 5 m·s^{-1}; 3 – 9 m·s^{-1}

The analysis of the trajectories of the grains, which differ in their aerodynamic properties, makes it possible to evaluate the possibilities of increasing the efficiency of the separation of the grain material into fractions using additional radial air movement. It also makes it possible to establish the influence of the input airflow parameters on the amount of smoothing of trajectories and the efficiency of separation. The maximum difference in grain movement trajectories (at the exit from the channel) was obtained with the parameters of grain introduction into the airflow: introduction angle $\alpha = 70°$, initial speed $V_0 = 0.4$ m·s^{-1}, trajectory-splitting coefficient $\Delta x = 0.04$– 0.05 m, and the porosity criterion $\varepsilon = 0.3$.

To ensure the condition of uniformity, modelling of the airflow distribution in the vertical annular channel of the gravitational pneumatic separator was carried out at different heights of the air intake slots. When the air intake slits were placed only on the outer cylindrical wall of the annular channel (Fig. 3), a significant increase in the vertical component of the airflow velocity was observed to 7.5 m·s^{-1} at the inner wall of the annular channel. In this case, a zone of air turbulence formed at the outer wall.

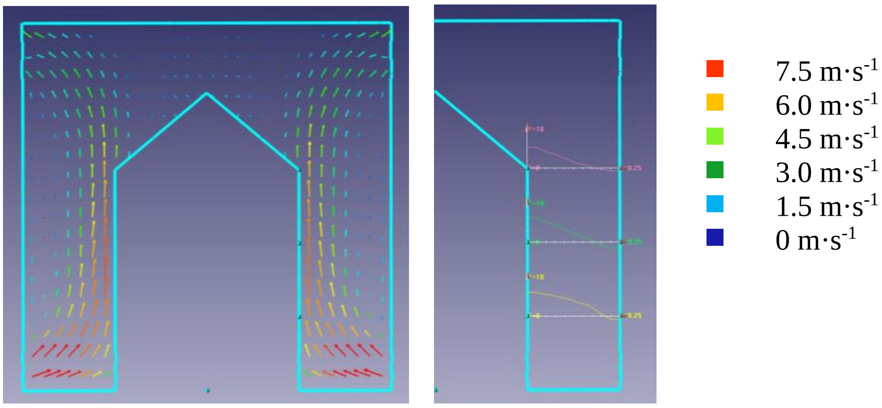

Fig. 3. **Distribution of the air velocity in the vertical annular channel of the pneumatic gravity separator when an air intake slot is placed on the outer wall with a height of 75 mm**

Placing an additional slot on the inner wall of the annular channel led to a change in the airflow field in the annular vertical channel of the pneumatic gravity separator. In this case, a change in the ratio between the height of the air suction slots on the outer and inner walls leads to a change in the velocity diagram in the sections of the channel.

When modelling the airflow distribution in the annular channel of the pneumatic gravity separator, it was found that the closest approach to the straight airflow distribution scheme is observed at the height of the air absorption slits on the outer wall of 75 mm, and on the inner wall of 100 mm (Fig. 4). At the same time, the maximum value of the airflow speed is within 4.0-5.0 m·s^{-1}.

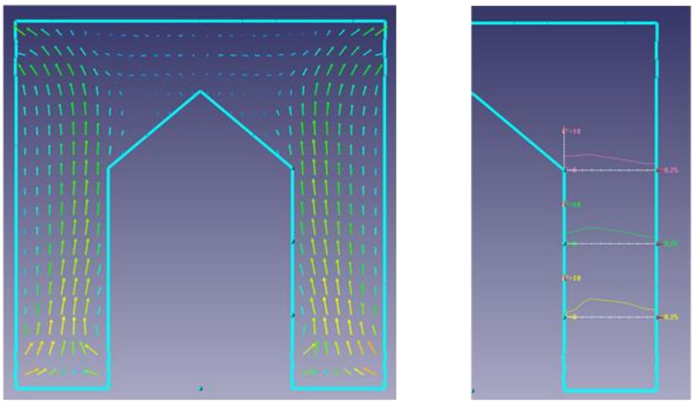

Fig. 4. **Distribution of the air velocity in the vertical annular channel of the pneumatic gravity separator when air intake slits are placed on the outer wall with a height of 75 mm and the inner wall with a height of 100 mm**

According to the results of the experimental studies, it was established that the use of a combined air separator provides an effective process of seed fractionation with a free cross-section of 0.38-0.44. At the same time, the effect of separating impurities is 75-77%, and the removal of whole grain into waste is 0.5-0.9%. The maximum value of the cleaning effect of 79.4-80.7% and minimum grain losses of 0.5% are achieved when using air flows in the zone of the exit window from the channel and the location parameters of the edge of the dividing wall of fractions x = 0.21-0.23 m and y = 0.16-0.18 m.

The results of the experimental studies confirmed the possibility of dividing the grain material into two fractions: heavy with a mass of 1000 grains of 36 g (terminal velocity = 9.7 $m \cdot s^{-1}$) and light – 30.2 g (terminal velocity = 8.7 $m \cdot s^{-1}$) with percentage fractions at the output from 39% to 61%. The standard error during the research did not exceed 5%.

The use of the developed technical means makes it possible to isolate a fraction of seed material with increased sowing properties, in particular seed density. This was achieved through the use of a uniform air flow velocity diagram in the aspiration channel.

Conclusions

1. Increasing the efficiency of fractionation of components of the grain material in airflows is ensured by the use of variable directional speeds of airflows and changes in their intensity over time. Changing the air speed in the direction of movement in the vertical channel allows to increase the trajectory-splitting coefficient by 15-25%, the efficiency coefficient by 17-21%.
2. Models of the process of fractionation of components of the grain material were obtained, with the use of which it was established that the most effective fractionation process in pneumatic separating channels with an intensifying device for introducing the grain material into the channel is ensured with a free cross-sectional of 0.38-0.44. The maximum value of the cleaning effect of 79.4-80.7% and the minimum grain loss of 0.5% are achieved when using air streams in the area of the exit window from the channel and the placement parameters of the edge of the dividing wall of fractions x = 0.21-0.23 m and y = 0.16-0.18 m.
3. The results of the experimental studies confirmed the possibility of dividing the grain material into two fractions: heavy with a mass of 1000 grains of 36 g and light – 30.2 g with percentage of fractions in the output of 39% to 61%.

Author contributions

Conceptualization, S.S., B.K., A.K., I.D. and V.M.; methodology, S.S., A.K., I.D. and V.M.; software, D.V.; investigation, S.S., A.K., V.M and D.V.; data curation, S.S. and V.M.; writing – original draft preparation, V.M.; writing – review and editing, S.S. and A.K.; project administration, S.S. All authors have read and agreed to the published version of the manuscript.

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