THEORETICAL STUDY OF GRAIN PARTICLE MOVEMENT IN VIBRO-AERODYNAMIC FIELD

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Abstract. The article presents an in-depth theoretical study of the processes of sorting and cleaning grain materials. The primary focus is on analyzing the influence of various parameters, including the airflow velocity, working surface inclination angle, vibration frequency, and airflow pulsation, on the efficiency of seed material cleaning and sorting. A detailed mathematical model was developed in the study to describe the dynamics of grain particles in the air field. This model employs the Navier-Stokes equations to simulate the behavior of the gaseous phase and motion equations for individual solid particles. This approach enables a comprehensive assessment of the impact of inertial forces, friction forces, and airflow resistance on the movement of seed particles along the vibrating sieve surface, as well as the identification of conditions of the grain material transition into a fluidized state. The results of numerical modeling demonstrate that increasing the airflow velocity and the vibration frequency of the working surface significantly enhances the average movement speed of the grain material, which, in turn, improves the productivity of the cleaning process. Additionally, a substantial influence of the separator design parameters, such as the inclination angle and the geometric characteristics of the sieve, on the efficiency of grain material separation and cleaning was identified. The obtained results are of great importance for further optimizing technological processes for fractionation of grain crops. The proposed mathematical models can be used to improve existing and design new grain cleaning systems, ensuring maximum efficiency and productivity in agro-industrial production.

Keywords: grain sorting, separator, mathematical modeling, grain material cleaning.

Introduction

Grain sorting and cleaning are not merely production stages but the very foundation upon which the quality and safety of the final product are built [1]. Proper grain processing influences the yield, raw material storage, and subsequent processing, which in turn determines the overall economic efficiency of an agricultural enterprise [2].

Modern approaches in the agro-industrial sector have moved beyond traditional technologies, actively incorporating mathematical modelling [3-5]. This allows for the creation of detailed simulations of grain sorting and cleaning processes, helping to predict efficiency, identify potential bottlenecks, and develop optimal strategies. Mathematical models take into account the specifics of seeds, their physicochemical properties, and external factors, enabling more informed decisions for improving technological processes [6-8].

Amid increasing raw material quality standards and the need to reduce costs, mathematical modelling has become an indispensable tool for researchers and practitioners. It not only enhances the quality of the final product but also ensures economic stability for agricultural enterprises. The integration of modern scientific approaches into the analysis and optimization of production processes sets the stage for the innovative development of the agro-industrial sector and boosts product competitiveness both in domestic and international markets.

A number of scientific studies are dedicated to the research of grain material sorting and cleaning [9-11]. For example, the authors of [12] designed and optimized a rice screening system based on a CFD-DEM model. Their study identified the correlation between the filtration speed, inlet airflow velocity, and the width of the machine's outlet opening. As a result of the optimization, the most suitable values for the outlet cross-section, airflow velocity, and machine geometry were determined.

In [13], the authors investigated the processes of sorting and cleaning small impurities and safflower petals under different air flow angles. They developed a model of individual material particles. Experimental studies led to the identification of optimal values for the airflow velocity, airflow inclination angle, and dust removal angle. The study also demonstrated a strong correlation between the modeling results and experimental data.

Research [14] focused on the performance of an aspirator for separating dust and small impurities. The authors applied computational fluid dynamics (CFD) methods to refine the working parameters of the aspirator, achieving high efficiency in cleaning grain material. The study provides valuable insights for the further design of grain aspirators.

Thus, the relevance of research in applying mathematical methods to optimize grain sorting and cleaning processes is undeniably high. This approach not only ensures high product quality but also creates conditions for the sustainable development of the agricultural sector as a whole.

The aim of the study is to develop a mathematical model that describes the processes of sorting and cleaning grain materials in vibroaerodynamic environment.

Materials and methods

Let us consider the diagram shown in Fig. 1, where a seed in the grain medium moves along the surface of a non-collapsible sieve inclined at a certain angle to the horizon. The forces acting on the seed, which contribute to the formation of a pseudo-impulse fluidized seed layer, include: gravity $G = m \cdot g$; inertia force $F_i = \omega^2 \cdot R \cdot cos(\omega \cdot t)$; friction force $F_t = N \cdot \tan\gamma$; drag force of the pulsating airflow F_p; N_p – normal reaction force of the grain medium.

It should be noted that, since the direction of the inertia force and the friction force changes depending on the direction of the deck's angular acceleration, differential equations will be formulated separately for different intervals. Thus, the effect of forces on the grain medium located on the surface of the deck, which performs oscillatory motion in the positive interval, is shown in Fig. 1.

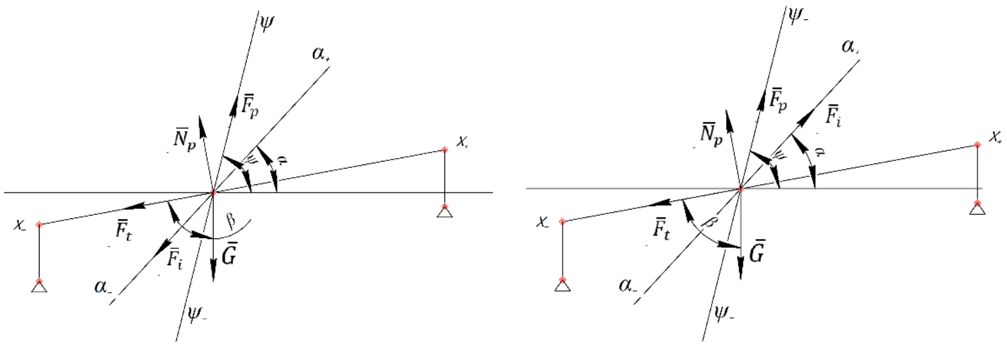

Fig. 1. **Diagram of forces acting on the grain medium in:** a – the positive interval of the deck's angular acceleration direction; b – the negative interval of the deck's angular acceleration direction

It is clear that the inertia force in this case is directed opposite to the angular acceleration, meaning that in the first case the force is directed to the right and tends to shift the grain material upward along the length of the non-collapsible surface of the deck. The differential equation of relative displacement of a seed in the grain material on the vibrating surface, according to the d'Alembert-Lagrange principle [15; 16], takes the following form:

$$m \cdot \frac{d^2 x_{(+)}}{dt^2} = F_i \cdot \cos(\alpha - \beta) - m \cdot g \cdot \sin(\beta) - [-F_i \cdot \sin(\alpha - \beta) + $$
$$+ m \cdot g \cdot \cos(\beta) - F_p \cdot \sin(\psi - \beta)] \cdot \tan(\gamma) + F_p \cdot \cos(\psi - \beta). \quad (1)$$

In the second interval, the inertia force will be directed to the left (as shown in the figure) and downward along the sieve, while the seed in the grain material will tend to move downward along the deck surface, as shown in Fig. 1.

According to the diagram in Fig. 1, the differential equation of relative displacement of the seed in the grain medium on the deck surface will take the following form:

$$m \cdot \frac{d^2 x_{(-)}}{dt^2} = \left[F_i \cdot \sin(\alpha - \beta) + m \cdot g \cdot \cos(\beta) - F_p \cdot \sin(\psi - \beta)\right] \cdot \tan(\gamma) -$$
$$-F_i \cdot \cos(\alpha - \beta) - m \cdot g \cdot \sin(\beta) + F_p \cdot \cos(\psi - \beta). \quad (2)$$

After mathematical transformations, the differential equations of relative displacements will take the form:

$$\frac{d^2x_{(+)}}{dt^2}\cdot\frac{1}{\xi} = \omega^2\cdot R\cdot\cos(\omega\cdot t) - g\cdot\frac{\sin(\beta+\gamma)}{\cos(\alpha-\beta-\gamma)} + k_p\cdot\left(V_{pn}\cdot[1-\sin(\omega_1\cdot t)]\right)^2\cdot\frac{\sin(\psi-\beta+\gamma)}{\cos(\alpha-\beta-\gamma)}. \quad (3)$$

$$\frac{d^2x_{(-)}}{dt^2}\cdot\frac{1}{\lambda} = \omega^2\cdot R\cdot\cos(\omega\cdot t) - g\cdot\frac{\sin(\beta+\gamma)}{\cos(\alpha-\beta-\gamma)} - k_p\cdot\left(V_{pn}\cdot[1-\sin(\omega_1\cdot t)]\right)^2\cdot\frac{\sin(\psi-\beta+\gamma)}{\cos(\alpha-\beta-\gamma)}. \quad (4)$$

To determine the relative displacement velocity of the seed along the deck surface, we integrate differential equations (3) and (4).

To determine the velocity at any arbitrary moment in time T, integration must be performed within the limits from the start of the displacement T_0 to T. The velocity during the downward movement of the seed is determined by the following equation:

$$\frac{1}{\lambda}\cdot\int_{T_0}^{T}\frac{d^2x_{(-)}}{dt^2}dt = \int_{T_0}^{T}\omega^2\cdot R\cdot\cos(\omega\cdot t)dt - \\ -\int_{T_0}^{T}\left[g\cdot\frac{\sin(\beta+\gamma)}{\cos(\alpha-\beta-\gamma)}\right]dt - \int_{T_0}^{T}\left[k_p\cdot\left(V_{pn}\cdot[1-\sin(\omega_1\cdot t)]\right)^2\cdot\frac{\sin(\psi-\beta+\gamma)}{\cos(\alpha-\beta-\gamma)}\right]dt \quad (5)$$

The relative velocity of the seeds when the grain material moves in the opposite direction can be determined in a similar manner:

$$\frac{1}{\xi}\cdot\frac{dx_{(+)}}{dt} = \omega\cdot R\cdot[\sin(\omega\cdot T)-\sin(\omega\cdot T_0)] - g\cdot[T-T_0]\cdot\frac{\sin(\beta+\gamma)}{\cos(\alpha-\beta-\gamma)} + \\ + \frac{k_p\cdot V_{pn}^2}{\omega_1}\cdot\frac{\sin(\psi-\beta+\gamma)}{\cos(\alpha-\beta-\gamma)} \cdot\left[\begin{array}{c} 2\cdot[\cos(\omega_1\cdot T)-\cos(\omega_1\cdot T_0)] - \\ -\frac{1}{4}\cdot[\sin(2\cdot\omega_1\cdot T)-\sin(2\cdot\omega_1\cdot T_0)] + \frac{3}{2}\cdot\left[\frac{\omega_1\cdot T}{2}-\frac{\omega_1\cdot T_0}{2}\right]\end{array}\right] \quad (6)$$

The initial conditions for CFD modelling of the airflow passing through the air-permeable deck are shown in Fig. 2. As a result, pressure contours, velocity vector fields, and airflow trajectories (in the form of streamlines) were obtained.

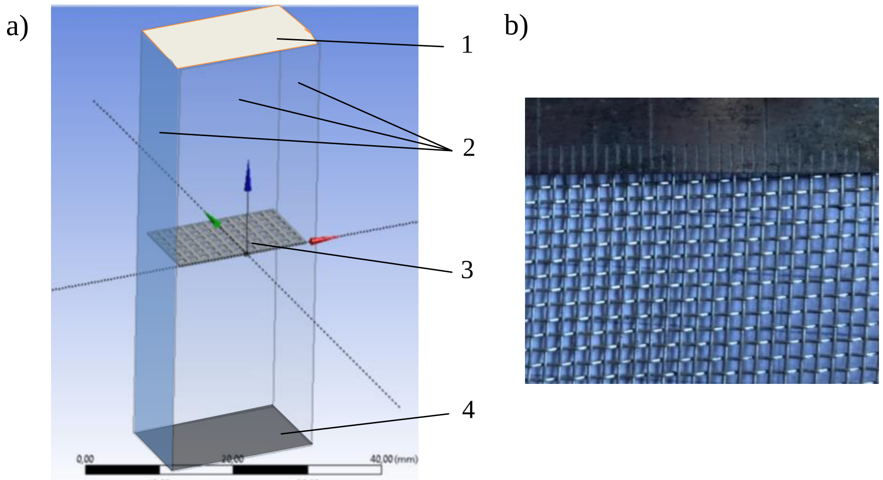

Fig. 2. **Initial conditions of modelling (a) and the non-collapsible sieve made of woven steel mesh with a rod diameter of 0.3 mm (b):** 1 – outlet; 2 – symmetry; 3 – solid; 4 – inlet

The ANSYS Fluent package was used for modelling, which is based on an explicit method for solving the problem. It is also noteworthy that the similar CFX model is not optimized for further integration with DDPM. The *k-ε* turbulence model was chosen because this model provides data processing speed and stability.

The successive approximation method involves calculating phase values at each iteration step until the difference between the previous and current values becomes smaller than the specified accuracy required achieving the solution.

Results and discussion

The obtained dependencies are graphically represented in (Fig. 3) and illustrate the dependence of seed velocity in both directions over time for different values of the drag coefficient.

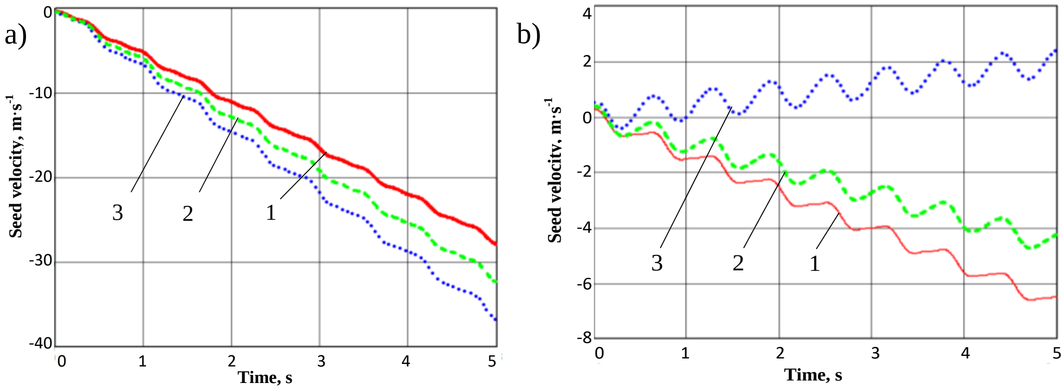

Fig. 3. **Seed velocity during displacement: a) in the negative direction over time for different values of the drag coefficient; b) in the positive direction over time for different values of the drag coefficient:** $1 - k_p = 0.074$; $2 - k_p = 0.105$, $3 - k_p = 0.136$

According to the obtained data, the first graph, where the seed moves in the negative direction, shows that as the sail coefficient k_p increases, the velocity decreases more steeply, indicating increased resistance from the medium. In contrast, on the second graph, where the movement occurs in the positive direction, periodic velocity fluctuations are observed at the same k_p values, suggesting the presence of possible unstable airflow patterns or variable external influences.

To avoid confusion regarding the moments when vibrational disturbances begin during movement in the positive (T) and negative (T) directions, it is necessary to introduce the definitions of the phase of the onset of vibrational disturbances for movement in the positive ($\omega \cdot T_0 = \theta_1$) and negative ($\omega \cdot T_0 = \theta_2$) directions of material displacement.

Taking into account the given notations, the final version results in graphical dependencies that reflect the values of the third integral of the initial equation for determining the numerical values of seed displacements in both the positive and negative directions (Fig. 4).

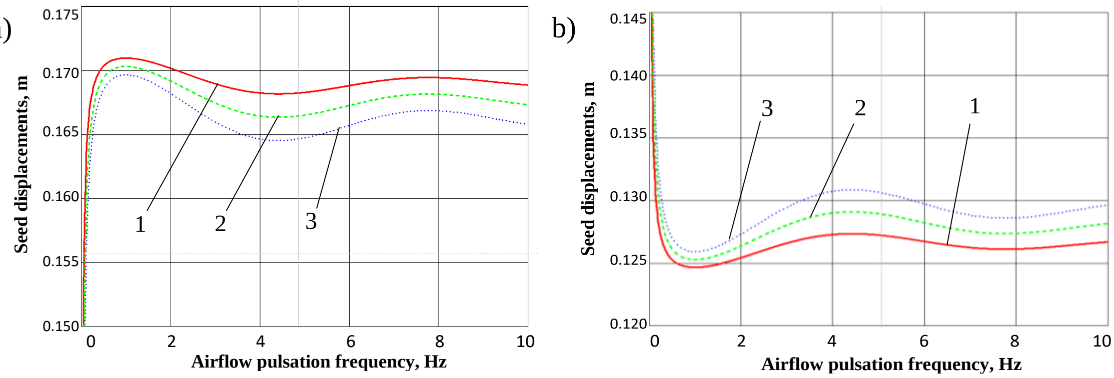

Fig. 4. **Dependence of the numerical values of seed displacements:** a – $x_{(-)}$ on the air flow pulsation value ω_1 in the negative direction for different values of the sail coefficient; b – $x_{(+)}$ on the air flow pulsation value ω_1 in the positive direction for different values of the sail coefficient ($1 - k_p = 0.074$; $2 - k_p = 0.105$; $3 - k_p = 0.136$)

According to the above dependences, the rational parameters of the movement of grain particles in a vibro-aerodynamic field process are substantiated, namely the surface inclination angle to the horizon $\alpha = 6^\circ$; oscillation direction angle $\beta = 5^\circ$; crank radius $R = 0.01$ m; airflow pulsation frequency $\omega_1 = 6$ Hz.

As a result of the CFD study (Fig. 5), a model was obtained that serves as a starting point for developing a more advanced model, which will take into account the pulsation of the airflow and the vibration of the air-permeable deck.

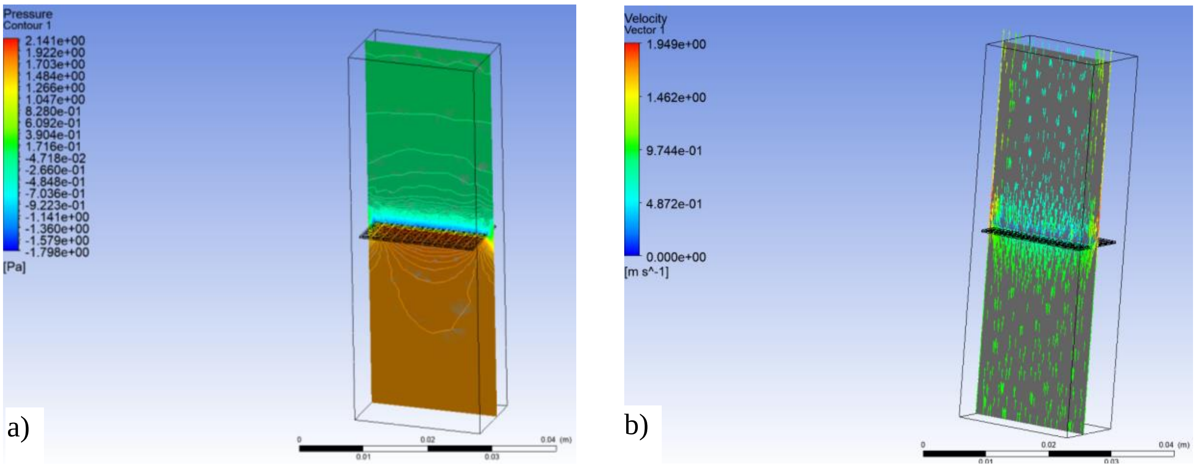

Fig. 5. **Modelling results are presented in the form of pressure contours (a) and the velocity vector field (b) of the airflow in cross-section**

The modelling was conducted under the assumption of a continuous laminar regime and the placement of the studied sample parallel to the horizon (with gravity acting perpendicular to the sieve in the direction opposite to the outgoing airflow). The obtained data indicate the presence of a pressure differential in the investigated area. In general, the direction and velocity of the airflow are satisfactory for bringing the grain material layer into a pseudo-fluidized state. The next step will be to study the surface for any deformation when subjected to the pulsating airflow. Surfaces with a high value of the cross-section have satisfactory air permeability, but due to this design, they may not be sufficiently rigid for prolonged operation under load.

Conclusions

Based on the results of theoretical studies, the dependences of the speeds of movement of grain material along the working surface of the separator with different air flow rates were obtained and the rational parameters of the process movement of grain particles in a vibro-aerodynamic field were substantiated. The obtained regularities can be used to evaluate the theoretical results of studying the parameters of seed movement in an improved fluidized pulsating seed layer on the separator deck.

Using CFD modelling and theoretical studies of the process of seed movement on a perforated surface exposed to an inclined air flow, the average speeds of material movement on the surface of the deck were calculated depending on various factors. It was found that with an increase in the air flow velocity, deck vibration frequency, and air flow pulsation frequency, the average speed of seed movement increases, which contributes to an increase in the specific productivity. It was determined that the air permeability of the working surface made of woven mesh is 10-15% higher than that of the working surface made of solid metal with punched holes.

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Author contributions

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

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