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IMPROVING THE MECHANICAL-MATHEMATICAL MODEL OF GRAIN MASS SEPARATION IN A FLUIDIZED BED

Vadym Bredykhin
PhD, Associate Professor*
E-mail: vadimbr76@ukr.net
Petro Gurskyi
PhD, Associate Professor
Department of Equipment and Engineering of Processing and Food Production**
E-mail: gurskyi_petro@ukr.net
Oleksiy Alfyorov
Doctor of Technical Sciences, Associate Professor
Department of Operation, Reliability, Strength and Construction named after V. Anilovich**
E-mail: alfogor@i.ua
Khrystyna Bredykhina
Postgraduate Student
Department of Optimization of Technological Systems named after T. Yevsiukov**
E-mail: kristinabrdhn@gmail.com
Andrey Pak
Doctor of Technical Sciences, Associate Professor*
E-mail: pak.andr1980@khntusg.info
*Department of Physics and Theoretical Mechanics**
**Kharkiv Petro Vasylenko National Technical University of Agriculture
Alchevskykh str., 44, Kharkiv, Ukraine, 61002

This paper has substantiated the prospect of modeling the processes of separating grain mass into fractions as one of the tasks in the production of high-quality seed material. It has been determined that this could optimize the parameters of separation processes and design new working surfaces for its implementation. It is noted that modeling should take into consideration the influence of the structural and kinematic parameters of grain cleaning machines, the physical and mechanical properties of raw materials, the intralayer processes and forces.

The reported theoretical study has improved the mechanical-mathematical model of grain mass separation in a pseudo-fluidized bed according to its density. The model establishes a relationship between the effective coefficient of dynamic viscosity and the density of particles in the discrete and continuous phases and the volumetric concentration of discrete phase particles. At the same time, the porosity of a fluidized bed has been accounted for, as well as the longitudinal and transverse angles of inclination of the base surface to the horizontal plane, the amplitude and frequency of oscillations of the particles of the continuous phase; the direction angle of oscillations relative to the perpendicular to the base surface.

The adequacy of the improved mechanical-mathematical model has been confirmed by comparing the experimental and theoretical results of grain mass fractionation modeling. It was found that the differences in the density values of the separated fractions of GM did not exceed 7...8 %, that is, they were within the margin of error.

It has been established that the improved model of grain mass separation in a fluidized bed could be used to determine the rational values for the parameters of a pneumatic sorting table that is used for the fractionation of the corresponding seed material. The initial data, in this case, are the density of the continuous and solid phases of grain mass, the friction coefficient of the seeds, and the equivalent radius of the particle. The result of modeling is the rational values of the amplitude and oscillation frequency of the working surface of the pneumatic sorting table, and the angles of inclination of the working surface

Keywords: mechanical-mathematical model of separation, grain mass, seed material, fluidized bed

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1. Introduction

To ensure the food safety of the states engaged in the cultivation of grain crops, a steady increase in the annual volume of high-quality seed material (SM) is required [1]. The efficiency of the technological processes of seed production depends on the quality of the equipment executing these processes [2].

During the execution of technological processes to produce SM, the particles of the material (grains) are exposed to a repeated mechanical impact from the working bodies of grain harvesting and grain cleaning machines, which leads to injury to particles. Depending on the type of machines, injury to grains could reach critical values, which significantly reduces the biological activity of seeds. In this case, indicators of clogging of seeds with weeds, disease, and pest damage are of great importance. The basic role in the technological line of machines to produce SM belongs to machines for cleaning grain mass (GM) and separating it into fractions. The cleaning of GM and its separation into fractions occur according to the set of the physical and mechanical properties of grain and under the influence of the system of external forces on the grain particle [3].

Despite the variety of properties, actual separation mostly makes use of the differences in size, weight, and sailing. These attributes underlie air-sieve separation, which is most often used for GM separation. Other features, for example, the shape and nature of the surface of the grain, its specific mass, and elasticity are used less often, mainly for the processing and enrichment of GM that underwent an air-sieve separation. Despite the constraints inherent in the equipment applied in this case, as well as the limited scientific data related to such processes, the specified methods demonstrate the prospect of high-precision separation, especially involving heavy-to-separate GM.

2. Literature review and problem statement

Promising ways to improve the efficiency of SM separation by seed density are the use of an unevenly distributed airflow, blown through a layer of seeds, and the mechanical intensifiers of the separation process [4].

The airflow blown through the layer of seeds is pumped by a fan and distributed evenly over the entire working surface. However, the SM layer, due to the different physical and mechanical properties of particles, is unevenly distributed over the working surface. Thus, in different sectors of a pneumatic sorting table (PST), separation processes proceed with significant differences. At the most loaded sectors of the working surface, the airflow force is not sufficient for a high-quality segregation process while in the least loaded sectors the process of seed «boiling» could occur.

An earlier study has shown that changing the airflow force exerted a positive effect on the quality of a seed segregation process [5].

The presence at the working surface of additional mechanical intensifiers of the process makes it possible to prolong the time when the material is at the working surface. That makes it possible to more fully separate the material into fractions that differ in seed density, and guide the fractions along optimized trajectories for dispatch [6]. To describe the SM separation process, the following is used:

– the analogies of moving a material point (particle);

– the analogies of movement of SM as the layered movement of a loose body;

– the theory of vibrational movement, the dynamics of seed movement;

– the theory of particle segregation in a seed layer;

– the theory of multiphase environments;

– hydrodynamic movements;

– the optimization of kinematic modes;

– the mechanics of solid media;

– a discrete-element method.

At the same time, these theoretical methods and procedures are not systemic in nature because they do not comprehensively consider the processes of SM separation by seed density in a fluidized bed of a multiphase medium. In addition, those models do not consider the intralayer interaction of mixture particles.

Using the concept of the hydrodynamics of multi-phase media in the modeling of processes has proven its effectiveness [7]. Given this concept, a pseudo-fluidized environment is characterized by dynamic viscosity, and SM is represented by a multiphase liquid consisting of two phases. One phase is discrete, formed by solid particles (seeds). Another phase is the continuous phase formed by the gaseous medium (air). The presented analogies to pseudo-fluids proved adequate in the modeling of various dynamic processes [8]:

– segregation (the redistribution of seeds particles in an SM layer according to the physical and mechanical properties);

– the stratification of SM according to the set of the physical and mechanical properties of seeds and the structural and kinematic parameters of the process (a two-phase environment – seeds, air).

However, the use of the above procedures to describe the process of separation of SM by seed density requires appropriate additions and clarifications [9].

A hypothesis was adopted in [10], and later confirmed in [11], which implies the representation of an SM layer as a multiphase pseudo-fluidized medium when modeling the process of separating SM by seed density.

This method makes it possible to maximally take into consideration the interaction of the physical and mechanical properties of SM and the structural and technological parameters of the seed separation process by density.

Thus, modeling the processes of GM separation into fractions is a promising task in producing high-quality SM, which could optimize the parameters of these processes and design new working surfaces for their implementation. During modeling, it is necessary to take into consideration the influence of the structural and kinematic parameters of grain cleaning machines, the physical and mechanical properties of GM particles, the intralayer processes, and forces acting on a layer of GM particles.

3. The aim and objectives of the study

The aim of this study is to improve the mechanical-mathematical model of raw material separation in a fluidized bed according to its density, which could improve the efficiency of grain mass separation processes into fractions to produce high-quality seed material.

To accomplish the aim, the following tasks have been set:

– to establish the defining parameters of the process of grain mass separation in a fluidized bed according to seed density and take them into consideration in the mechanical-mathematical model of this process;

– to derive the functional dependences between the defining parameters of the process of grain mass separation in a fluidized bed and the values of the parameters for setting a pneumatic sorting table to organize this process and prove the adequacy of the improved mechanical-mathematical model.

4. The study materials and methods

Vibratory pneumatic separators are usually used to separate GM into fractions according to the set of physical and mechanical features; they are categorized as separators of countercurrent, fan, and descending types.

In our experimental study of GM separation in a fluidized bed, a fan-type PST was used, whose physical appearance is shown in Fig. 1 (manufactured at Khorolskiy mechanical plant, Ukraine).

The separation of GM was carried out as follows.

An SM layer, moving on the flat (even) surface of the PST, under the influence of oscillations of the working surface and airflow, which is blown through the SM layer, acquires the properties of a pseudo-fluidized environment. The working surface of the PST (a deck) is located at adjustable angles of inclination, which contributes to the movement of the SM layer towards unloading. SM is pre-cleaned of impurities. The SM consists of many grains close in size, while different in density. In the process of PST operation, the SM delaminates into layers of seeds that move on their own trajectories towards the unloading trays. Depending on the quality of the material supplied to the working surface of the PST, the number of fractions may vary.

Fig. 1. PST general view (manufactured at Khorolskiy mechanical plant)

Determining the factors having a decisive influence on the parameters of the SM separation process and proving the adequacy of the improved mechanical-mathematical model were carried out based on the analysis of the results of an experimental study involving PST. These factors include the seed density that has been processed; the airflow rate blown through the SM layer. It is also necessary to take into consideration the longitudinal and transverse angles of inclination of the working surface; the amplitude of oscillations of the working surface; the coefficients of friction of SM and the working surface of the PST.

5. Results of the mechanical-mathematical modeling of grain mass separation in a fluidized bed

5. 1. Establishing the defining parameters of the process of grain mass separation in a fluidized bed according to seed density

To model the process of vibration-pneumatic separation of SM by seed density, an effective method is the method of multiphase media [12]. A multiphase structure consists of many particles that differ in their own density (a discrete component) and a gaseous environment (a continuous component). Such discrete and continuous components interacting with each other are considered as a solid environment [13].

Under the influence of an airflow force and the oscillations of the working surface, the SM layer enters a pseudo-fluidized state.

The discrete phase is considered as the finite number N of discrete components, each of which is formed by solid particles with their natural density:

$$\bar{\rho}_n, n = 1, 2 \ldots N.$$

In this case, the density of the set of particles of the n-th component of the discrete phase is equal to:

$$\rho_n = \delta_n \bar{\rho}_n, \quad n = 1, 2 \ldots N, \tag{1}$$

where δ_n is the volumetric share of particles of the n-th component in the pseudo-fluidized grain material.

The density of the discrete phase, in general, is defined as:

$$\rho_P = \sum_{n=1}^{N} \rho_n.$$

The density of the continuous phase is defined as:

$$\rho = \bar{\rho}\left(1 - \sum_{n=1}^{N} \frac{\rho_n}{\bar{\rho}_n}\right) = \bar{\rho}\left(1 - \sum_{n=1}^{N} \delta_n\right), \tag{2}$$

where $\bar{\rho}$ is the density of the gaseous medium (air).

Given (1) and (2), the density of a pseudo-fluidized NM layer is equal to:

$$\rho_c = \rho + \rho_P. \tag{3}$$

The speed of movement of the pseudo-fluidized SM layer is determined from the following equation:

$$\rho_c \vec{V}_c = \sum_{n=1}^{N} \rho_n \vec{V}_n + \rho \vec{V}, \tag{4}$$

where $\vec{V}_n$ is the speed of the n-th component of the discrete phase; $\vec{V}$ is the speed of the continuous phase.

Since the n-th component of the discrete phase is considered as a solid medium, the following continuity equation holds:

$$\frac{\partial \rho_n}{\partial t} + \nabla\left(\rho_n \vec{V}_n\right) = 0, \quad n = 1, 2 \ldots N. \tag{5}$$

Similarly, for a continuous phase:

$$\frac{\partial \rho_n}{\partial t} + \nabla\left(\rho \vec{V}\right) = 0. \tag{6}$$

The equation of inseparability for a pseudo-fluidized SM layer takes the following form:

$$\frac{\partial \rho_c}{\partial t} + \nabla\left(\rho_c \vec{V}_c\right) = 0. \tag{7}$$

The solid medium is simulated by Newtonian liquid moving on a flat air-permeable surface.

We shall introduce the Descartes $x_1 \times x_2 \times x_3$ coordinate system so that the flat air-permeable surface lies in the $x_1 \times x_2$ plane. In this case, the x_3 axis is perpendicular to this surface. The x_1 and x_2 axes are tilted at angles α_1 and α_2 to the horizontal plane. We shall assume that the air-permeable surface executes harmonic oscillations with a frequency of ω. Under the action of airflow and the oscillations of the supporting (working) air-permeable surface, the GM layer is in a pseudo-fluidized state. The motion equation for a multiphase system that simulates the movement of SM can be represented as:

$$\rho_n\left(\frac{\partial V_{ni}}{\partial t}+\left(\nabla,\vec{V}_n\right)V_{ni}\right)=$$
$$=\frac{\partial}{\partial x_j}\left[-P_n\delta_{ij}+\mu_n\left(\frac{\partial V_{ni}}{\partial x_j}+\frac{\partial V_{nj}}{\partial x_i}\right)\right]+$$
$$+\rho_n F_{ni}+\rho_n\sum_{n=1}^{N}F_{nm}\left(V_{mi}-V_{ni}\right),$$
$$n=1,2,\ldots,N;\quad i=1,2,3, \tag{8}$$

where V_{ni} is the i-th component of the speed $\vec{V}_n$ of the n-th component of the discrete phase; μ_n is the effective coefficient of the dynamic viscosity of the n-th component in SM; F_{ni} is the i-th component of mass force, acting on the unit of mass of the n-th component of the mixture; P_n is the partial static pressure of the n-th component of SM; δ_{ij} is the Kronecker symbol (for repeating symbols, addition is implied).

The last term of the right-hand side of expression (8) is introduced to take into consideration the interaction of the n-th component with another m-component of GM. In this case, the values of F_{nm} characterize this interaction and satisfy the following condition:

$$\rho_n F_{nm}=\rho_m F_{mn}.$$

The effective viscosity coefficients μ_n, $n=1,2,\ldots,N$ of the n-th component of the discrete phase are determined according to the following equation:

$$\mu_n\left(\frac{\partial V_{ni}}{\partial x_j}+\frac{\partial V_{nj}}{\partial x_i}\right)=\mu\frac{\rho_n}{\rho_c}+$$
$$+\frac{\mu}{\rho_c}\left[\left(V_{ni}-V_j\right)\frac{\partial\rho_n}{\partial x_j}+\left(V_{nj}-V_j\right)\frac{\partial\rho_n}{\partial x_j}\right]+$$
$$+\rho_n\left(V_{ni}-V_i\right)\left(V_{nj}-V_j\right), \tag{9}$$

where μ is an effective viscosity coefficient of the material.

As one can see, the i-th component of the force F_{ni}, which acts on the unit of mass of the n-th component of the discrete phase of the material, can be represented in the following form:

$$F_{ni}=\frac{1}{2}\frac{\bar{\rho}}{\bar{\rho}_n}\left[\begin{array}{l}\frac{\partial}{\partial t}\left(V_i-V_{ni}\right)+\\+\left(\nabla,\vec{V}-\vec{V}_n\right)\left(V_i-V_{ni}\right)\end{array}\right]+$$
$$+F_n\left(V_i-V_{ni}\right)+\frac{9\bar{\rho}\sqrt{\nu}}{2\sqrt{\pi}a_n\bar{\rho}_n}\times$$
$$\times\int_0^t\left[\frac{d}{dt}\left(V_i-V_{ni}\right)\left(t-\tau\right)^{-1/2}\right]d\tau+f_{ni},\ i=1,2,3\ldots, \tag{10}$$

where $\bar{\rho}_n$ is the density of particles forming the n-th component of the discrete phase; $\bar{\rho}$ and v are, respectively, the density and coefficient of the kinematic viscosity of the continuous phase; a_n is the equivalent radius (by volume) of particles of the n-th component of the discrete phase; f_{ni} is the i-th component of the external force acting on the particles of the n-th component; F_n is a coefficient that characterizes the interaction of a continuous phase with particles of the n-th component of the discrete phase.

The above equations (5), (8) for the components of the discrete phase of the pseudo-fluidized grain material characterize them as continuous interacting environments.

In addition to equations (5), (8), we shall use the equation of motion of the continuous phase of grain material, derived by direct addition of (8) taking into consideration (2).

$$\rho\left[\frac{\partial V_i}{\partial t}+\left(\nabla,\vec{V}\right)V_i\right]=-\left(1-\sum_{n=1}^{N}\frac{\rho_n}{\bar{\rho}_n}\right)\frac{\partial P}{\partial x_i}+$$
$$+\frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial V_i}{\partial x_j}+\frac{\partial V_j}{\partial x_i}\right)\right]+\rho F_i-0.5\bar{\rho}\times$$
$$\times\sum_{n=1}^{N}\frac{\rho_n}{\bar{\rho}_n}\left[\begin{array}{l}\frac{\partial}{\partial t}\left(V_i-V_{ni}\right)+\\+\left(\nabla,\vec{V}-\vec{V}_n\right)\left(V_i-V_{ni}\right)\end{array}\right]-\frac{9\sqrt{\nu\bar{\rho}}}{2\sqrt{\pi}}\times$$
$$\times\sum_{n=1}^{N}\frac{\rho_n}{\bar{\rho}_n a_n}\int_0^t\left[\frac{d}{d\tau}\left(V_i-V_{ni}\right)\left(t-\tau\right)^{-1/2}\right]d\tau-$$
$$-\sum_{n=1}^{N}\rho_n F_n\left(V_i-V_{ni}\right),\ i=1,2,3. \tag{11}$$

The terms of the right-hand side of equation (11) characterize the interaction of discrete and continuous phases of pseudo-fluidized grain material. For example, the fourth term takes into consideration the acceleration of the mass of particles of the discrete phase in relation to the continuous phase, the fifth term is due to the Bosse force and expresses instantaneous hydrodynamic resistance, the last term describes the resistance of discrete phase particles.

Equations (8) to (11), which describe a change in the amount of movement of the discrete and continuous phases of pseudo-fluidized grain material, are important; however, no less interesting are the processes that lead to a change in the energy of the grain mass. In order to derive this equation, we shall introduce the following energy characteristics of the grain material: T and T_n are the absolute temperatures of the continuous phase and the n-th component of the discrete phase, respectively.

The equation describing the energy change in grain material takes the following form:

$$\rho\left[\frac{\partial}{\partial t}\left(\frac{V_i^2}{2}+cT\right)+\left(\nabla,\vec{V}\right)\left(\frac{V_i^2}{2}+cT\right)\right]+$$
$$+\sum_{n=1}^{N}\rho_n\left[\frac{\partial}{\partial t}\left(\frac{V_{ni}^2}{2}+c_nT_n\right)+\left(\nabla,\vec{V}_n\right)\left(\frac{V_{ni}^2}{2}+c_nT_n\right)\right]=$$
$$=\frac{\partial P}{\partial t}+\frac{\partial}{\partial x_j}\kappa\frac{\partial T}{\partial x_j}+$$
$$+\sum_{n=1}^{N}\frac{\partial}{\partial x_j}\kappa_n\frac{\partial T_n}{\partial x_j}+\frac{\partial}{\partial x_j}V_i\left[\mu\left(\frac{\partial V_i}{\partial x_j}+\frac{\partial V_j}{\partial x_i}\right)\right]+$$
$$+\sum_{n=1}^{N}\frac{\partial}{\partial x_j}V_{nj}\left[\mu_n\left(\frac{\partial V_{ni}}{\partial x_j}+\frac{\partial V_{nj}}{\partial x_i}\right)\right]+\Phi_E+\sum_{n=1}^{N}\Phi_{nE}, \tag{12}$$

where the Φ_{nE} quantities describe the heating of particles due to viscous dissipation (dispersion).

The Φ_E value characterizes the radiation of a unit of grain material volume and takes into consideration the external sources of heat:

$$\Phi_{nE}=\rho_n F\left(\vec{V}-\vec{V}_n\right)^2+\rho_n\sum_{m=1}^{N}F_{nm}\left(\vec{V}-\vec{V}_n\right)^2,\quad n=1,2,\ldots,N.$$

Thus, equations (5), (6), (8) to (12) describe the dynamics and energy characteristics of the movement of grain material.

As can be seen from (8), (11), and (12), during the hydrodynamic modeling of the movement of pseudo-fluidized grain material, it is necessary to introduce such important characteristics of grain material as the coefficients of dynamic viscosity of the discrete and continuous phases. Determining these values is a rather complex task. Its solution makes it possible to assess the adequacy of the mathematical model to the actual physical processes that accompany the intralayer movement of SM.

The relative velocity of discrete phase particles changes harmoniously over time depending on the oscillation frequency of the working surface. Its amplitude depends in a complex way on the physical and mechanical parameters of SM, the airflow rate on the free surface of the fluidized bed, and the effective coefficient of dynamic viscosity.

$$-\frac{\pi g\cos\alpha_1\cos\alpha_2}{\delta_1}+\frac{4\sqrt{2}\bar{\rho}_1^2\delta_1^2A\omega^{3/2}\cos\alpha_2\cos\alpha_3F_1}{9\bar{\rho}\sqrt{\nu}\sqrt{\left(1+B_1\right)^2+\left(1+B_2\right)^2}}=$$

$$=\frac{\pi}{2}\left(1-\varepsilon\right)^{1/3}\left(\begin{array}{l}\dfrac{g^2\cos^2\alpha_1\cos^2\alpha_2}{\delta_1^2F_1^2}-\\ -\dfrac{8\sqrt{2}g\cos\alpha_1\cos^2\alpha_1\cos\alpha_3\rho_1^2A\omega^{3/2}}{9\delta_1F_1\bar{\rho}\sqrt{\nu}\sqrt{\left(1+B_1\right)^2+\left(1+B_2\right)^2}}+\\ +\dfrac{4\bar{\rho}_1^4\delta_1^4A^2\omega^3\cos^2\alpha_2\cos^2\alpha_3}{81\bar{\rho}^{2}\nu\left[\left(1+B_1\right)^2+\left(1+B_2\right)^2\right]}\end{array}\right).\quad(13)$$

Equation (13) establishes a relationship between the effective coefficient of dynamic viscosity and the following parameters of grain material and the characteristics of the support surface and an airflow rate. These include the density $\bar{\rho}_1$ and $\bar{\rho}$ of particles of the discrete and continuous phases of grain material; δ_1 and ε is the volumetric concentration of discrete phase particles and the porosity of the fluidized bed.

In addition, the model takes into consideration the following: α_1 and α_2 are the longitudinal and transverse angles of inclination of the support surface in relation to the horizontal plane; the amplitude A and the circular frequency ω of the oscillations of particles of a continuous phase; α_3 is the angle of oscillation direction relative to the axis directed perpendicular to the support surface. Equation (13) underlies the improved mechanical-mathematical model of raw material separation in a fluidized bed according to its density.

5. 2. The results of modeling the trajectories of SM particles movement using the improved mechanical-mathematical model

Based on the improved mechanical-mathematical model (equation (13)), we determined the initial data for modeling the trajectories of SM particle movement.

Changing coordinates over time is determined from the following formulas:

$$x_1=x_{1(0)}+\int_0^t V_1(t)\mathrm{d}t;$$

$$x_2=x_{2(0)}+\int_0^t V_2(t)\mathrm{d}t;$$

$$x_3=x_{3(0)}+\int_0^t V_3(t)\mathrm{d}t,\quad(14)$$

where

$$V_1(t)=-\frac{4ga\bar{\rho}_1\left(1-\delta^2\right)}{\bar{\rho}\left(1.75V_0+\dfrac{75\delta\nu}{a}\right)}\sin\left(\alpha_1\right)+$$

$$+\frac{gf_k\delta}{\pi h\nu k_p}\int_0^\infty e^{-x^2t}F\left(x,x_3\right)\mathrm{d}x;$$

$$V_2(t)=-\frac{4ga\bar{\rho}_1\left(1-\delta^2\right)}{\bar{\rho}\left(1.75V_0+\dfrac{75\delta\nu}{a}\right)}\cos\left(\alpha_1\right)\sin\left(\alpha_2\right)+$$

$$+\frac{gf_k\delta}{\pi h\nu k_p}\int_0^\infty e^{-x^2t}F\left(x,x_3\right)\mathrm{d}x;$$

$$V_3(t)=V_0-\frac{2ga\bar{\rho}_1\left(1-\delta^2\right)\left(\cos\left(\alpha_1\right)\cos\left(\alpha_2\right)-\delta\right)}{\bar{\rho}\left(1.75V_0+\dfrac{75\delta\nu}{a}\right)}+$$

$$+\frac{9\bar{\rho}\sqrt{\nu}}{\pi\bar{\rho}_1a}\int_0^\infty\frac{e^{-x^2t}}{A_2^2x^2+\left(A_3-A_1x^2\right)^2}\mathrm{d}x.\quad(15)$$

In this case, the generalized forces are determined as:

$$F(x,0)=\frac{2x\sin\left(2h\lambda_2\right)}{\mathrm{ch}\left(2h\lambda_1\right)-\cos\left(2h\lambda_2\right)};\quad(16)$$

$$F\left(x,x_3\right)=\frac{2x\left(e^{-\lambda_1x_3}\sin\left(\lambda_2x_3\right)\mathrm{ch}\left(2h\lambda_1\right)+ch\left(\lambda_1x_3\right)\sin\left(\lambda_2\left(2h-x_3\right)\right)\right)}{\mathrm{ch}\left(2h\lambda_1\right)-\cos\left(2h\lambda_2\right)}.\quad(17)$$

The amplitudes along the coordinate axes are calculated as:

$$A_1=1+\frac{\bar{\rho}}{2\bar{\rho}_1};\quad A_1=1+\frac{\bar{\rho}}{2\bar{\rho}_1};\quad A_3=\frac{\bar{\rho}\left(1.75V_0+75\delta\nu/a\right)}{2a\bar{\rho}_1\left(1-\delta^2\right)};\quad(18)$$

where

$$D_1=A_3+A_2x\sqrt{2}-A_1x^2;\quad D_2=\frac{A_2x}{\sqrt{2}}.\quad(19)$$

In this case,

$$\lambda_1=\sqrt{\frac{D_1+\sqrt{D_1^2+D_2^2}}{2\nu}};\quad\lambda_2=\sqrt{\frac{-D_1+\sqrt{D_1^2+D_2^2}}{2\nu}}.\quad(20)$$

The effective coefficient of the kinematic viscosity of the continuous phase is calculated as:

$$\nu=\bar{\rho}(1-\delta)b_0^2, \quad (21)$$

where b_0 is the point of function's zero:

$$\Psi(x, A, \omega, V_0, \delta, a, f_k, \alpha_1, \alpha_2, \alpha_3)=0. \quad (22)$$

The function zero search boundaries (22): $a<x<b$, where $a=0$; $b=1$.

The result of modeling using the devised mechanical-mathematical model is the established trajectories of seed layers consisting of particles of different densities. An example of the resulting trajectories is shown in Fig. 2.

A layer of seed material was modeled by a set of wheat grains of different density: 680 kg/m^3; 720 kg/m^3; 830 kg/m^3; 960 kg/m^3; 1,183 kg/m^3; 1,200 kg/m^3.

Fig. 3 shows the result of the experimental stratification of GM at PCS (manufactured at Khorolskiy mechanical plant, Ukraine).

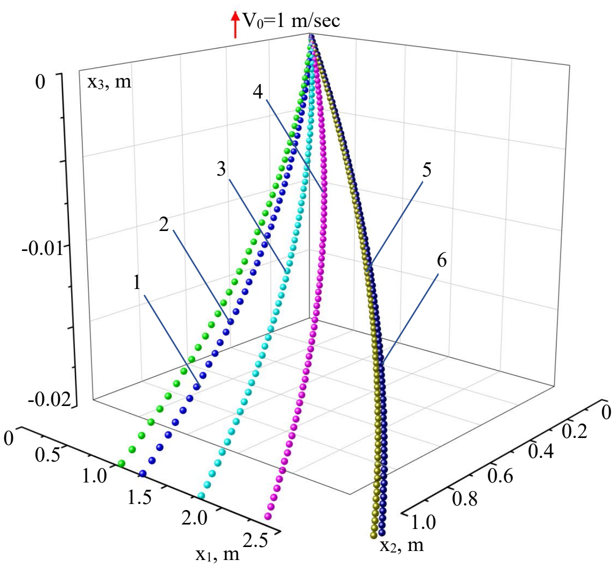

Fig. 2. Trajectories of seed layers consisting of particles of different density, kg/m^3: 1 – 680; 2 – 720; 3 – 830; 4 – 960; 5 – 1,183; 6 – 1,200

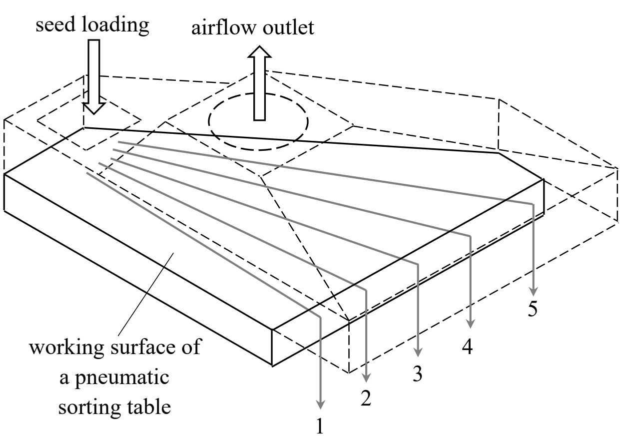

Fig. 3. PST-based GM stratification into fractions with the following density, kg/m^3: 1 – 730...740; 2 – 790...800; 3 – 900...950; 4 – 1,120...1,200; 5 – 1,350...1,450

Parameters for separation are the rational parameters obtained using the improved mechanical-mathematical model of grain mass separation in a fluidized bed.

6. Discussion of results of the mechanical-mathematical modeling of grain mass separation in a fluidized bed

The result of this study is the improvement of the mechanical-mathematical model of GM separation in a pseudo-fluidized state. Underlying the model built is the method of multi-phase environments when a multiphase structure consists of many particles interacting with each other, being considered as a solid medium.

The improved mechanical-mathematical model takes into consideration the interaction of discrete and continuous phases of pseudo-fluidized grain material. Specifically, the acceleration of the mass of discrete phase particles relative to a continuous phase, the instantaneous hydrodynamic resistance, the resistance of discrete phase particles.

It should be noted that during the hydrodynamic modeling of the movement of pseudo-fluidized GM, such characteristics of the grain material as the coefficients of dynamic viscosity of the discrete and continuous phases were introduced. Solving such a problem makes it possible to assess the adequacy of the mathematical model to the actual physical processes that accompany the intralayer movement of SM.

Solving the model's equations makes it possible to determine that the characteristics of the separation process are influenced by the oscillation frequency of the working surface and the speed of airflow. Since with an increase in the oscillation frequency of the working surface the layer of seed material begins to move along the trajectories shifted along the x_1 axis, in this case, a greater proportion of grains with a lower density enter the trays, which are designed for grains with a higher density. Thus, the characteristics of separation are significantly deteriorating.

With a decrease in the speed of airflow, the layer of material moves in a dense flow and the process of pseudo-liquefaction occurs within insignificant limits, and with an increase in the speed of airflow, the process of «boiling» of seed material occurs, and the separation process stops.

The rational parameters for the improved mechanical-mathematical model of grain mass separation in a fluidized bed are as follows: the amplitude and oscillation frequency of the working surface $A=35\cdot10^{-5}$ m, $\omega=15.6$ rad/s; the angles of inclination of the working surface: longitudinal=2 degrees, transverse=5 degrees. At the same time, it is assumed that the friction coefficient of seeds is $f=0.45$; the reduced material density (seeds+air) is $\rho=246.84$ kg/m^3; the equivalent particle radius is $a=2\cdot10^{-3}$ m. Under such parameters, there is a possibility to separate GM into 5 fractions of the following density, kg/m^3 – 740; 820; 960; 1,181; 1,400.

We have experimentally separated GM into fractions (Fig. 3) at PST, configured according to the parameters determined by modeling using the improved mechanical-mathematical model; the fractions' density, kg/m^3: 1 – 730...740; 2 – 790...800; 3 – 900...950; 4 – 1,120...1,200; 5 – 1,350...1,450. These results prove the adequacy of the improved mechanical-mathematical model since the differences in the density values of fractions obtained from the experimental (Fig. 2) and theoretical modeling (Fig. 3) are within the limits of error. Differences in the density values of fractions do not exceed 7...8 %.

Works [10] and [11] do not take into consideration such defining parameters of the process of GM separation in a fluidized bed as the density of the solid phase of GM [10] and its friction coefficient [11]. The result is an increase in the difference between the density values of fractions obtained from the experimental and theoretical modeling. The deviation is 15...21 %. The disregard for other defining parameters of the mechanical-mathematical model of GM separation in a fluidized bed likely entails an increase in the deviation between the theory and the experiment.

Thus, the improved mechanical-mathematical model of GM separation in a fluidized bed could be used to determine the rational values for the parameters of PST used for the fractionation of the corresponding SM. At the same time, the initial data for the improved model are the density of the continuous and solid phases of GM, the seed friction coefficient, and the equivalent particle radius. The result of modeling are the rational amplitude values and the oscillation frequency of the working surface of PST, and the angles of inclination of the working surface.

It should be noted that under industrial conditions the configuration of PST for GM separation is typically carried out empirically. That is, the setting requires a series of experiments to achieve the necessary difference in the density of the separated fractions of GM. That entails an increase in labor intensity, material, and energy costs. It is obvious that the use of the improved mechanical-mathematical model reduces the duration of PST configuration, reducing the material costs of experimental research to minimum values.

The obvious limitation of the improved mechanical-mathematical model is taking into consideration the parameters of the selected PST only via its coefficient k_p. This coefficient is determined by the design of the selected PST, its performance, and large-scale size; it is provided by a manufacturer. Taking into consideration these features of PST in the mechanical-mathematical model of GM separation in a fluidized bed is a possible area for further research. In addition, the potential prospect of future work is to automate the configuration of PST to rational parameters for the separation of various SM.

7. Conclusions

1. We have improved the mechanical-mathematical model of GM separation in a pseudo-fluidized state, which is based on a method of the multiphase media. The mechanical-mathematical model considers the interaction of the discrete and continuous phases of pseudo-fluidized grain material according to the following parameters: the acceleration of the mass of discrete phase particles relative to the continuous phase; the instantaneous hydrodynamic resistance; the resistance of discrete phase particles; the coefficients of dynamic viscosity of the discrete and continuous phases of GM.

2. Functional dependences have been established between the defining parameters of the grain mass separation process in a fluidized bed and the values of the parameters for setting a pneumatic sorting table for managing this process. The adequacy of the improved mechanical-mathematical model has been confirmed by comparing the experimental and theoretical results of the simulation of GM fractionation. It was found that the differences in the density values of the separated fractions of GM do not exceed 7...8 %, that is, fall within the margin of error.

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ANALYSIS OF THE EFFECT OF STIRRER AND CONTAINER ROTATION DIRECTION ON MIXING INDEX (Ip)

Sugeng Hadi Susilo
Doctor of Mechanical Engineering*
E-mail: sugeng.hadi@polinema.ac.id
Asrori Asrori
Doctor of Mechanical Engineering*
E-mail: asrori@polinema.ac.id
Gumono Gumono
Senior Lecture of Mechanical Engineering*
E-mail: gumono@polinema.ac.id
*Department of Mechanical Engineering
State Polytechnic of Malang
Jl. Soekarno Hatta No. 9,
Lowokwaru, Malang, Indonesia, 65141

The paper discusses the effect of the stirrer and container rotation direction on the mixing index (Ip). The chaos theory is the result of an in-depth study of various problems that cannot be answered by the two previous major theories, namely quantum mechanics and the theory of relativity. Effective mixing of the flow area does not depend on rapid stirring.

This study uses a container with a double stirrer, camera, programmable logic controller, tachometer, 6 A adapter, and a computer. DC electric motor (25 V) for turning stirrers and housings. The diameter of the primary and secondary stirrers is Dp=38 mm and Ds=17 mm. The diameter of the container made of transparent plastic is Dw=160 mm and height is 170 mm. Primary stirrer rotation (np)=10 rpm, secondary stirrer rotation (ns)=22.3 rpm, and container rotation (nw)=13 rpm, the angular velocity of the container is Ωw=360° while the angular speed of the primary stirrer is Ωp=180°. The liquid consists of a mixture of water and paint (white). For dye, a mixture of water and paint (red) is used. For testing the Brookfield viscometer, the viscosity of the liquid and dye is used. The results showed that turning the stirrer in the opposite direction to the container, there will be stretching, bending, and folding around the stirrer, and the smallest mixing index was P2V-b (0.94). In addition, based on the mixing index value above, the highest mixing effectiveness level is obtained, namely: P2V-b, P2S-b, P2B-b, P2V-a, P2B-a, and finally P2S-a. The mixing index is inversely related to the effectiveness level. So the highest effectiveness level is given by the following treatment: variation rotation (between opposite rotating mixers); opposite rotation (stirrer rotation opposite direction to the container); unidirectional rotation (stirrer rotation in the direction of the container)

Keywords: mixing index, chaos, stirrer, container, mixing effectiveness, rotation direction

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1. Introduction

The chaos theory is the result of an in-depth study of various problems that cannot be answered by the two previous major theories, namely quantum mechanics and the theory of relativity. Chaos conditions have started to be mathematically modelled since the late 1800s by Henri Poincare. The development of this theory in the 20th century was not as fast as the theory of quantum mechanics and the theory of relativity [1].

The chaos flow-based numerical and mathematical approaches have recently been widely used in various fields of science, including social, economic, political, biotechnology, meteorology, mechanical engineering, even in the entertainment world. For robotics experts, chaos-based modelling is used to identify the evolutionary process of life, understand genetic algorithms, simulate artificial life for how the brain works, or create intelligent machines. In the entertainment world, many games have been developed from chaos research such as the computer game series SimAnt, SimLife, SimCity and so on. In the medical field, chaos theory is used for the mixing of medicinal substances [2].

The stirring process in laminar flow with low Reynolds numbers can produce a very complex flow pattern [3]. The complexity of the flow pattern consists of many particles (microstructures) whose changes are influenced by fluid flow [4]. This phenomenon is called advection. In this motion, the velocity of the particles is the same as the velocity of the fluid [5].

During chaotic motion, the fluid and particles are stretched, thereby expanding the contact area and reducing the diffusion distance between them [6]. The strain occurs exponentially with time, resulting in efficient stirring [7]. In the mixing process, efficient strain distribution is a major factor [8].