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Model to study the technological process of separation of hard-to-separate granular mixtures and to adopt managerial decisions

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Model to study the technological process of separation of hard-to-separate granular mixtures and to adopt managerial decisions

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Abstract. The problem associated with the technological process of separation of granular mixtures is considered in the paper; the process is implemented with a separating unit, with the aim to improve its technical and economic indices. The paper presents a mathematical model of the process under investigation, described using a system of nonlinear partial differential equations with corresponding initial and boundary conditions of various kinds. To solve the problem, a variation of the finite difference method is used. The study of the responses of principal parameters of the technological process is carried out by a series of computer-aided computational experiments, analysis of the results obtained and conclusions.

1. Introduction

Separation and filtration of multicomponent granular mixtures with different physicomechanical properties and composition is a complex technological process (TP).

Modeling and control of the TP of separation of hard-to-separate mixtures, for example, cotton seeds of various downiness, are not well studied yet from theoretical and experimental points of view. In this regard, the task is to identify the principal factors that affect the complete separation of the inhomogeneous mass depending on linear dimensions of the particles of granular material and operating modes of a separating unit, as well as the characteristics of the sieve. It is necessary to ensure minimum losses of raw materials in the waste and an increase in technical and economic indices of the mechanism used in the implementation of the TP.

To achieve this goal, it is necessary to develop a mathematical model (MM), numerical algorithm, and software and tools that allow the computational experiments (CE) to be carried out by computer.

In recent years, a significant amount of scientific research has been carried out on the TP of separation and sorting of granular mixtures and important theoretical and practical results have been obtained. From the point of view of mathematical modeling of the object of study, a great scientific contribution has been made by such foreign and domestic scientists as J.Wang, J.Zhang, Yu.Zhihui, B.Remy, J.W.Dufty, D.Kocaefe, C.Andre, V.Gitisa, A.Safonyk, V.V.Beloborodov, I.I.Blekhman, Kh.Kh.Ataulaev, A.A.Klyuchkin, P.M. Zayko, G.Yu. Janilidze etc.

A statistical approach to the technological process of separation and division of granular mixtures is considered in [1]. In [2-5] the problems of mathematical modeling of the process of grain flow separation on the sieve and various studies on the theory of fluidization of a layer of granular material are systematized.

Simulation of the process of particles motion in a centrifugal separator with vertical and inclined axes of rotation is considered in [6–10]. The authors of the studies have shown the feasibility of using centrifugal separators with a vertical cylindrical drum, rotating with a pulsating change in speed, where the centrifugal, Coriolis and gravitational forces are simultaneously taken into account.

Experimental studies have shown that the separation, division, sorting of granular mixtures, along with the forces acting on the mixture layer as a result of intense oscillations of the sieve, are also affected by vertical forces due to the particles motion along the surface of the unit. Simultaneous motion of particles, both vertically and horizontally, creates optimal conditions for the run of particles of the granular mixture through the separation layer and the sieve mesh, resulting in increased productivity of the separating unit.

In some publications the process of sifting granular mixture through the sieve mesh is considered without taking into account the operation mode of the sieve, in others - the motion of granular mixture along the non-perforated surface of the sieve under vibration-translation oscillations at an angle α is considered. The process of separation of granular mixture, taking into account the particles motion along the layer thickness and the oscillations direction of the sieve, is not considered in a complex form.

An account of these factors in the MM development and their research are the main issues in the technology of separation of granular mixtures.

With account of the above-stated gaps, the process of separation of granular mixture under horizontal oscillation of the sieve is considered in present work. For this purpose, it is assumed that the separator's bunker, filled with a free-flowing mixture, oscillates at a certain angle β, and the angle of deflection across the sieve surface is α. The sieve surface oscillates horizontally with amplitude A_1 and frequency ω_1.

2. Statement of the problem

To derive the MM process assume that the probability of concentration distribution of granular mixture is equal to $\theta(x,z,t)$, the path of the granular mixture particles run from the upper layer to the surface of the sieve is L_2, and the separation time is t. The initial uniform distribution of granular mixture concentration is $\theta_{\circ}(x,z)$, so, we get [11-13]:

$$\frac{\partial\theta(x,z\ ,t)}{\partial t}=\frac{\partial}{\partial x}\left(b_c\frac{\partial\theta(x,z,t)}{\partial x}\right)+\frac{\partial}{\partial z}\left(b_c\frac{\partial\theta(x,z,t)}{\partial z}\right)+U\frac{\partial\theta(x,z,t)}{\partial x}+W\frac{\partial\theta(x,z,t)}{\partial z}. \quad (1)$$

Initial and boundary conditions for equation (1) have the following form:

$$\begin{cases}\theta(x,z,t)\big|_{t=0}=\theta_0(x,z),\ \dfrac{\partial}{\partial x}\theta(x,z,t)\big|_{x=0}=0,\ \dfrac{\partial}{\partial x}\theta(x,z,t)\Big|_{x=L_x}=0,\\ \dfrac{\partial}{\partial z}\theta(x,z,t)\Big|_{z=0}=0,\quad \dfrac{\partial}{\partial z}\theta(x,z,t)\Big|_{z=L_z}=-\dfrac{k_0}{b_c}\theta A_1\omega_1^2\cos\gamma.\end{cases} \quad (2)$$

Here, θ is the concentration of granular mixture; k_0 is the coefficient of particles removal; $\delta=\frac{bt}{a_0}-\frac{1-be^{-a_0t}}{a_0^2}$ is the sieve angle; b_c is the separation factor; $\lambda=0.10,\ \gamma=0.006$ are the rates of horizontal and vertical motion of particles.

To determine the rate of horizontal u and vertical w motion of particles, we use the equations of hydrodynamics, taking into account cyclic horizontal and vertical excitations:

$$\begin{cases} \dfrac{\partial u}{\partial t}+u\dfrac{\partial u}{\partial x}+w\dfrac{\partial u}{\partial z}=g\sin\gamma-\dfrac{1}{\rho}\left(\dfrac{\partial P}{\partial x}-\mu\left(\dfrac{\partial^2 u}{\partial x^2}+\dfrac{\partial^2 u}{\partial z^2}\right)\right)+A_1\omega_1^2\sin\omega_1 t, \\ \dfrac{\partial w}{\partial t}+u\dfrac{\partial w}{\partial x}+w\dfrac{\partial w}{\partial z}=g\cos\gamma-\dfrac{1}{\rho}\left(\dfrac{\partial P}{\partial z}-\mu\left(\dfrac{\partial^2 w}{\partial x^2}+\dfrac{\partial^2 w}{\partial z^2}\right)\right)+A_2\omega_2^2\sin\omega_2 t. \end{cases} \tag{3}$$

Here λ, γ is the gravity acceleration; P is the pressure of granular mixture, which has a constant value; ρ, μ are the density and viscosity of granular mixture; $A_1, \omega_1, A_2, \omega_2$ are the amplitude and frequency of horizontal and vertical oscillations of the sieve, respectively.

For the closure and integration of the system of nonlinear differential equations (3) the initial and boundary conditions corresponding to the actual statement of the problem are set:

$$u(x,z,0)=u_0(x,z),\ w(x,z,0)=w_0(x,z) \ \text{ at } \ 0\le x\le L_x,\ 0\le z\le L_z, \tag{4}$$

$$\frac{\partial}{\partial x}u(0,z,t)=\frac{\partial}{\partial x}w(0,z,t)=0, \tag{5}$$

$$\frac{\partial}{\partial x}u(L_x,z,t)=\frac{\partial}{\partial x}w(L_x,z,t)=0,\ \frac{\partial}{\partial z}u(x,0,t)=\frac{\partial}{\partial z}w(x,0,t)=0, \tag{6}$$

$$\frac{\partial}{\partial z}u(x,L_z,t)=0, \quad \frac{\partial}{\partial z}w(x,L_z,t)=-k_0 w\cos\theta. \tag{7}$$

So, a mathematical model of the separation process for granular mixture, described by a system of nonlinear differential equations (1), (3) and the corresponding boundary conditions (2) - (7), has been built.

3. Method of solution

For numerical integration of equations with boundary conditions, the finite-difference method is used [13-14].

To ensure the stability of computational process, the terms

$$u\frac{\partial u}{\partial x},\ w\frac{\partial u}{\partial z},\ u\frac{\partial w}{\partial x} \text{ and } w\frac{\partial w}{\partial z}$$

of equation (3) are used according to the “against-the-flow” scheme.

Using the “against-the-flow” derivatives, the convective terms of the equations are compactly written as:

$$A_u^{n+\frac{1}{2}}=u_{i,j}^n\left(\frac{\partial u_{i,j}}{\partial x}\right)^{n+\frac{1}{2}}+w_{i,j}^n\left(\frac{\partial u_{i,j}}{\partial z}\right)^n=\frac{u_{i,j}^n+\left|u_{i,j}^n\right|}{2}\frac{u_{i,j}^{n+\frac{1}{2}}-u_{i-1,j}^{n+\frac{1}{2}}}{h_x}+$$

$$+\frac{u_{i,j}^n-\left|u_{i,j}^n\right|}{2}\frac{u_{i+1,j}^{n+\frac{1}{2}}-u_{i,j}^{n+\frac{1}{2}}}{h_x}+\frac{w_{i,j}^n+\left|w_{i,j}^n\right|}{2}\frac{u_{i,j}^n-u_{i,j-1}^n}{h_z}+\frac{w_{i,j}^n-\left|w_{i,j}^n\right|}{2}\frac{u_{i,j+1}^n-u_{i,j}^n}{h_z},$$

$$A_w^{n+\frac{1}{2}}=u_{i,j}^n\left(\frac{\partial w_{i,j}}{\partial x}\right)^{n+\frac{1}{2}}+w_{i,j}^n\left(\frac{\partial w_{i,j}}{\partial z}\right)^n=\frac{u_{i,j}^n+\left|u_{i,j}^n\right|}{2}\frac{w_{i,j}^{n+\frac{1}{2}}-w_{i-1,j}^{n+\frac{1}{2}}}{h_x}+$$

$$+\frac{u_{i,j}^{n}-\left|u_{i,j}^{n}\right|}{2}\frac{w_{i+1,j}^{n+\frac{1}{2}}-w_{i,j}^{n+\frac{1}{2}}}{h_x}+\frac{w_{i,j}^{n}+\left|w_{i,j}^{n}\right|}{2}\frac{w_{i,j}^{n}-w_{i,j-1}^{n}}{h_z}+\frac{w_{i,j}^{n}-\left|w_{i,j}^{n}\right|}{2}\frac{w_{i,j+1}^{n}-w_{i,j}^{n}}{h_z},$$

$$A_u^{n+1}=u_{i,j}^{n+\frac{1}{2}}\left(\frac{\partial u_{i,j}}{\partial x}\right)^{n+1}+w_{i,j}^{n+\frac{1}{2}}\left(\frac{\partial u_{i,j}}{\partial z}\right)^{n+1}=\frac{u_{i,j}^{n+\frac{1}{2}}+\left|u_{i,j}^{n+\frac{1}{2}}\right|}{2}\frac{u_{i,j}^{n+\frac{1}{2}}-u_{i-1,j}^{n+\frac{1}{2}}}{h_x}+$$
$$+\frac{u_{i,j}^{n+\frac{1}{2}}-\left|u_{i,j}^{n+\frac{1}{2}}\right|}{2}\frac{u_{i+1,j}^{n+\frac{1}{2}}-u_{i,j}^{n+\frac{1}{2}}}{h_x}+\frac{w_{i,j}^{n+\frac{1}{2}}+\left|w_{i,j}^{n+\frac{1}{2}}\right|}{2}\frac{u_{i,j}^{n+1}-u_{i,j-1}^{n+1}}{h_z}+\frac{w_{i,j}^{n+\frac{1}{2}}-\left|w_{i,j}^{n+\frac{1}{2}}\right|}{2}\frac{u_{i,j+1}^{n+1}-u_{i,j}^{n+1}}{h_z},$$

$$A_w^{n+1}=u_{i,j}^{n+\frac{1}{2}}\left(\frac{\partial w_{i,j}}{\partial x}\right)^{n+1}+w_{i,j}^{n+\frac{1}{2}}\left(\frac{\partial w_{i,j}}{\partial z}\right)^{n+\frac{1}{2}}=\frac{u_{i,j}^{n+\frac{1}{2}}+\left|u_{i,j}^{n+\frac{1}{2}}\right|}{2}\frac{w_{i,j}^{n+\frac{1}{2}}-w_{i-1,j}^{n+\frac{1}{2}}}{h_x}+$$
$$+\frac{u_{i,j}^{n+\frac{1}{2}}-\left|u_{i,j}^{n+\frac{1}{2}}\right|}{2}\frac{w_{i+1,j}^{n+\frac{1}{2}}-w_{i,j}^{n+\frac{1}{2}}}{h_x}+\frac{w_{i,j}^{n+\frac{1}{2}}+\left|w_{i,j}^{n+\frac{1}{2}}\right|}{2}\frac{w_{i,j}^{n+1}-w_{i,j-1}^{n+1}}{h_z}+\frac{w_{i,j}^{n+\frac{1}{2}}-\left|w_{i,j}^{n+\frac{1}{2}}\right|}{2}\frac{w_{i,j+1}^{n+1}-w_{i,j}^{n+1}}{h_z}.$$

Instead of (3) we get the following system of finite-difference equations:

$$\frac{u_{i,j}^{n+\frac{1}{2}}-u_{i,j}^{n}}{\tau/2}+A_u^{n+\frac{1}{2}}=\frac{\mu}{\rho}\Delta_{1x}+\frac{g_{1,i,j}}{2},\quad \frac{u_{i,j}^{n+1}-u_{i,j}^{n+\frac{1}{2}}}{\tau/2}+A_u^{n+1}=\frac{\mu}{\rho}\Delta_{1z}+\frac{g_{1,i,j}}{2},$$
$$\frac{w_{i,j}^{n+\frac{1}{2}}-w_{i,j}^{n}}{\tau/2}+A_w^{n+\frac{1}{2}}=\frac{\mu}{\rho}\Delta_{2x}+\frac{g_{2,i,j}}{2},\quad \frac{w_{i,j}^{n+1}-w_{i,j}^{n+\frac{1}{2}}}{\tau/2}+A_w^{n+1}=\frac{\mu}{\rho}\Delta_{2z}+\frac{g_{2,i,j}}{2}.$$

Here

$$g_{1,i,j}=g\sin\gamma-\frac{1}{\rho}\frac{P_{i,j}-P_{i-1,j}}{h_x}+A_1\omega_1^2\sin\omega_1 t,$$
$$g_{2,i,j}=g\cos\gamma-\frac{1}{\rho}\frac{P_{i,j}-P_{i,j-1}}{h_z}+A_2\omega_2^2\sin\omega_2 t,$$

$$\Delta_{1x}=\frac{u_{i+1,j}^{n+\frac{1}{2}}-2u_{i,j}^{n+\frac{1}{2}}+u_{i-1,j}^{n+\frac{1}{2}}}{h_x^2}+\frac{u_{i,j+1}^{n}-2u_{i,j}^{n}+u_{i,j-1}^{n}}{h_z^2},$$

$$\Delta_{1z}=\frac{u_{i+1,j}^{n+\frac{1}{2}}-2u_{i,j}^{n+\frac{1}{2}}+u_{i-1,j}^{n+\frac{1}{2}}}{h_x^2}+\frac{u_{i,j+1}^{n+1}-2u_{i,j}^{n+1}+u_{i,j-1}^{n+1}}{h_z^2},$$

$$\Delta_{2x}=\frac{w_{i+1,j}^{n+\frac{1}{2}}-2w_{i,j}^{n+\frac{1}{2}}+w_{i-1,j}^{n+\frac{1}{2}}}{h_x^2}+\frac{w_{i,j+1}^{n}-2w_{i,j}^{n}+w_{i,j-1}^{n}}{h_z^2},$$

$$\Delta_{2z}=\frac{w_{i+1,j}^{n+\frac{1}{2}}-2w_{i,j}^{n+\frac{1}{2}}+w_{i-1,j}^{n+\frac{1}{2}}}{h_x^2}+\frac{w_{i,j+1}^{n+1}-2w_{i,j}^{n+1}+w_{i,j-1}^{n+1}}{h_z^2}.$$

After re-grouping the terms and some transformations, the following form of the system of linear algebraic equations with a three-diagonal matrix is obtained.

$$\begin{cases} a_{1i}u_{i+1}^{n+\frac{1}{2}}-b_{1i}u_i^{n+\frac{1}{2}}+c_{1i}u_{i-1}^{n+\frac{1}{2}}=-d_{1i}, \\ a_{2i}w_{i+1}^{n+\frac{1}{2}}-b_{2i}w_i^{n+\frac{1}{2}}+c_{2i}w_{i-1}^{n+\frac{1}{2}}=-d_{2i}, \\ \bar{a}_{1j}u_{j+1}^{n+1}-\bar{b}_{1j}u_j^{n+1}+\bar{c}_{1j}u_{j-1}^{n+1}=-\bar{d}_{1j}, \\ \bar{a}_{2j}w_{j+1}^{n+1}-\bar{b}_{2j}w_j^{n+1}+\bar{c}_{2j}w_{j-1}^{n+1}=-\bar{d}_{2j}. \end{cases} \tag{8}$$

The elements of a three-diagonal matrix are calculated as:

$$a_{1i}=\frac{\mu}{\rho h_x^2}-\frac{u_{i,j}^n-\left|u_{i,j}^n\right|}{2h_x},\ b_{1i}=\frac{2\mu}{\rho h_x^2}+\frac{2}{\tau}+\frac{\left|u_{i,j}^n\right|}{h_x},\ c_{1i}=\frac{\mu}{\rho h_x^2}+\frac{u_{i,j}^n+\left|u_{i,j}^n\right|}{2h_x},$$

$$d_{1i}=\frac{g_1}{2}-\left(\frac{w_{i,j}^n-\left|w_{i,j}^n\right|}{2h_z}-\frac{\mu}{\rho h_z^2}\right)u_{i,j+1}^n-\left(\frac{2\mu}{\rho h_z^2}-\frac{2}{\tau}+\frac{\left|w_{i,j}^n\right|}{h_z}\right)u_{i,j}^n+\left(\frac{w_{i,j}^n+\left|w_{i,j}^n\right|}{2h_z}+\frac{\mu}{\rho h_z^2}\right)u_{i,j-1}^n,$$

$$a_{2i}=\frac{\mu}{\rho h_x^2}-\frac{u_{i,j}^n-\left|u_{i,j}^n\right|}{2h_x},\ b_{2i}=\frac{2\mu}{\rho h_x^2}+\frac{2}{\tau}+\frac{\left|u_{i,j}^n\right|}{h_x},\ c_{2i}=\frac{\mu}{\rho h_x^2}+\frac{u_{i,j}^n+\left|u_{i,j}^n\right|}{2h_x},$$

$$d_{2i}=\frac{g_2}{2}-\left(\frac{w_{i,j}^n-\left|w_{i,j}^n\right|}{2h_z}-\frac{\mu}{\rho h_z^2}\right)w_{i,j+1}^n-\left(\frac{2\mu}{\rho h_z^2}-\frac{2}{\tau}+\frac{\left|w_{i,j}^n\right|}{h_z}\right)w_{i,j}^n+\left(\frac{w_{i,j}^n+\left|w_{i,j}^n\right|}{2h_z}+\frac{\mu}{\rho h_z^2}\right)w_{i,j-1}^n,$$

$$\bar{a}_{1j}=\frac{\mu}{\rho h_z^2}-\frac{w_{i,j}^{n+\frac{1}{2}}-\left|w_{i,j}^{n+\frac{1}{2}}\right|}{2h_z},\ \bar{b}_{1j}=\frac{2\mu}{\rho h_z^2}+\frac{2}{\tau}+\frac{\left|w_{i,j}^n\right|}{h_z},\ \bar{c}_{1j}=\frac{\mu}{\rho h_z^2}+\frac{w_{i,j}^{n+\frac{1}{2}}+\left|w_{i,j}^{n+\frac{1}{2}}\right|}{2h_z},$$

$$\bar{d}_{1j}=\frac{g_1}{2}-\left(\frac{u_{i,j}^{n+\frac{1}{2}}}{2h_x}-\frac{\mu}{\rho h_x^2}\right)u_{i+1,j}^{n+\frac{1}{2}}-\left(\frac{2\mu}{\rho h_x^2}-\frac{2}{\tau}\right)u_{i,j}^{n+\frac{1}{2}}-\left(\frac{u_{i,j}^{n+\frac{1}{2}}}{2h_x}-\frac{\mu}{\rho h_x^2}\right)u_{i-1,j}^{n+\frac{1}{2}},$$

$$\bar{a}_{2j}=\frac{\mu}{\rho h_z^2}-\frac{w_{i,j}^{n+\frac{1}{2}}-\left|w_{i,j}^{n+\frac{1}{2}}\right|}{2h_z},\quad \bar{b}_{2j}=\frac{2\mu}{\rho h_z^2}+\frac{2}{\tau}+\frac{\left|w_{i,j}^{n+\frac{1}{2}}\right|}{h_z},\quad \bar{c}_{2j}=\frac{\mu}{\rho h_z^2}+\frac{w_{i,j}^{n+\frac{1}{2}}+\left|w_{i,j}^{n+\frac{1}{2}}\right|}{2h_z},$$

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$$\bar{d}_{2j} = \frac{g_2}{2} - \left(\frac{u_{i,j}^{n+\frac{1}{2}} - \left| u_{i,j}^{n+\frac{1}{2}} \right|}{2h_x} - \frac{\mu}{\rho h_z^2} \right) u_{i,j+1}^{n+\frac{1}{2}} - \left(\frac{2\mu}{\rho h_z^2} - \frac{2}{\tau} + \frac{\left| u_{i,j}^n \right|}{h_z} \right) u_{i,j}^{n+\frac{1}{2}} + \left(\frac{u_{i,j}^{n+\frac{1}{2}} + \left| u_{i,j}^{n+\frac{1}{2}} \right|}{2h_z} + \frac{\mu}{\rho h_z^2} \right) u_{i,j-1}^{n+\frac{1}{2}}.$$

To integrate the system of equations (8), we use the sweep method. Since the task is described using the systems of nonlinear differential equations in partial derivatives, an iterative method is used to solve it, the convergence of which is checked using the conditions:

$$\left| U_{i,j}{}^{(S-1)} - U_{i,j}{}^{(S)} \right| < \varepsilon, \quad \left| W_{i,j}{}^{(S-1)} - W_{i,j}{}^{(S)} \right| < \varepsilon,$$

where ε is the accuracy of the iteration method.

Now determine the changes in the concentration of the target product of granular mixture. To do this, the method of variable directions is used. Then equation (1) after applying the approximation takes the following form:

$$\begin{cases} \dfrac{\theta_{i,j}^{n+\frac{1}{2}} - \theta_{i,j}^n}{\tau} = \dfrac{\mu}{h_x^2} \left(\theta_{i+1,j}^{n+\frac{1}{2}} - 2\theta_{i,j}^{n+\frac{1}{2}} + \theta_{i-1,j}^{n+\frac{1}{2}} \right) + \dfrac{u_{i,j}}{2h_x} \left(\theta_{i+1,j}^{n+\frac{1}{2}} - \theta_{i-1,j}^{n+\frac{1}{2}} \right) + \\ \qquad + \dfrac{\mu}{h_z^2} \left(\theta_{i,j+1}^n - 2\theta_{i,j}^n + \theta_{i,j-1}^n \right) + \dfrac{w_{i,j}}{2h_z} \left(\theta_{i,j+1}^n - \theta_{i,j-1}^n \right), \\ \dfrac{\theta_{i,j}^{n+1} - \theta_{i,j}^{n+\frac{1}{2}}}{\tau} = \dfrac{\mu}{h_z^2} \left(\theta_{i,j+1}^{n+1} - 2\theta_{i,j}^{n+1} + \theta_{i,j-1}^{n+1} \right) + \dfrac{w_{i,j}}{2h_z} \left(\theta_{i,j+1}^{n+1} - \theta_{i,j-1}^{n+1} \right) + \\ \qquad + \dfrac{\mu}{h_x^2} \left(\theta_{i+1,j}^{n+\frac{1}{2}} - 2\theta_{i,j}^{n+\frac{1}{2}} + \theta_{i-1,j}^{n+\frac{1}{2}} \right) + \dfrac{u_{i,j}}{2h_x} \left(\theta_{i+1,j}^{n+\frac{1}{2}} - \theta_{i-1,j}^{n+\frac{1}{2}} \right). \end{cases}$$

Proceed to the abbreviated notations [14]:

$$\begin{cases} a_i \theta_{i+1,j}^{n+\frac{1}{2}} - b_i \theta_{i,j}^{n+\frac{1}{2}} + c_i \theta_{i-1,j}^{n+\frac{1}{2}} = -d_i, \\ \bar{a}_j \theta_{i,j+1}^{n+1} - \bar{b}_j \theta_{i,j}^{n+1} + \bar{c}_j \theta_{i,j-1}^{n+1} = -\bar{d}_j. \end{cases} \tag{9}$$

The elements of a three-diagonal matrix have the following form:

$$a_i = \frac{\mu}{h_x^2} + \frac{u_{i,j}}{2h_x}, \quad b_i = \frac{2\mu}{h_x^2} + \frac{1}{\tau}, \quad c_i = \frac{\mu}{h_x^2} - \frac{u_{i,j}}{2h_x},$$

$$d_i = \left(\frac{\mu}{h_z^2} + \frac{w_{i,j}}{2h_z} \right) \theta_{i,j+1}^n - \left(\frac{2\mu}{h_z^2} - \frac{1}{\tau} \right) \theta_{i,j}^n + \left(\frac{\mu}{h_z^2} - \frac{w_{i,j}}{2h_z} \right) \theta_{i,j-1}^n,$$

$$\bar{a}_j = \frac{\mu}{h_z^2} + \frac{w_{i,j}}{2h_z},\ \bar{b}_j = \frac{2\mu}{h_z^2} + \frac{1}{\tau},\ \bar{c}_j = \frac{\mu}{h_z^2} - \frac{w_{i,j}}{2h_z},$$

$$\bar{d}_j = \left(\frac{\mu}{h_x^2} + \frac{u_{i,j}}{2h_x}\right)\theta_{i,j+1}^{n+\frac{1}{2}} - \left(\frac{2\mu}{h_x^2} - \frac{1}{\tau}\right)\theta_{i,j}^{n+\frac{1}{2}} + \left(\frac{\mu}{h_x^2} - \frac{u_{i,j}}{2h_x}\right)\theta_{i,j-1}^{n+\frac{1}{2}}.$$

4. Discussion of results and conclusions

Based on the above algorithm, a software tool has been developed for computer experiments. The results of numerical experiments are given in Figs. 1-3.

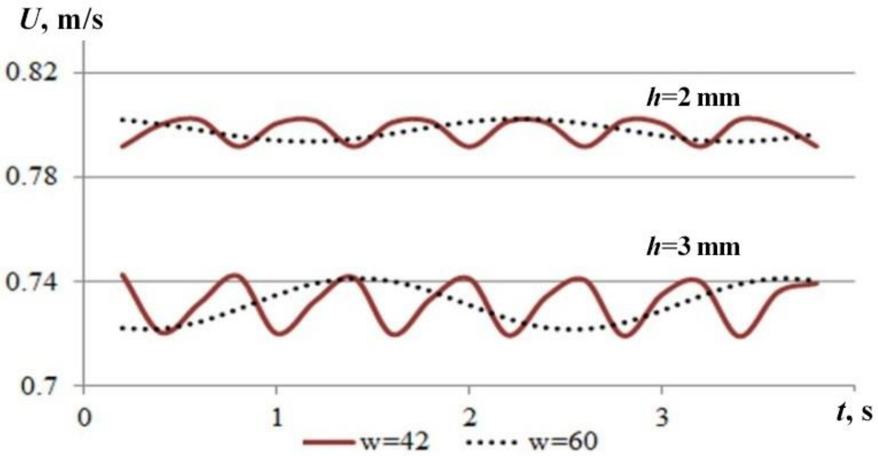

Figure 1. Change in motion rate of granular particles depending on the frequency of oscillation of the sieve surface.

According to the curves in Fig. 1, with an increase in the frequency of sieve oscillations, the particle oscillations along the sieve surface of the aggregate decrease, as well as the rate of particle track. When its values are excessively large, firstly, there is a lack of sifting through the sieve mesh; secondly, there occurs the violation of the regime of stable operation of the separating unit.

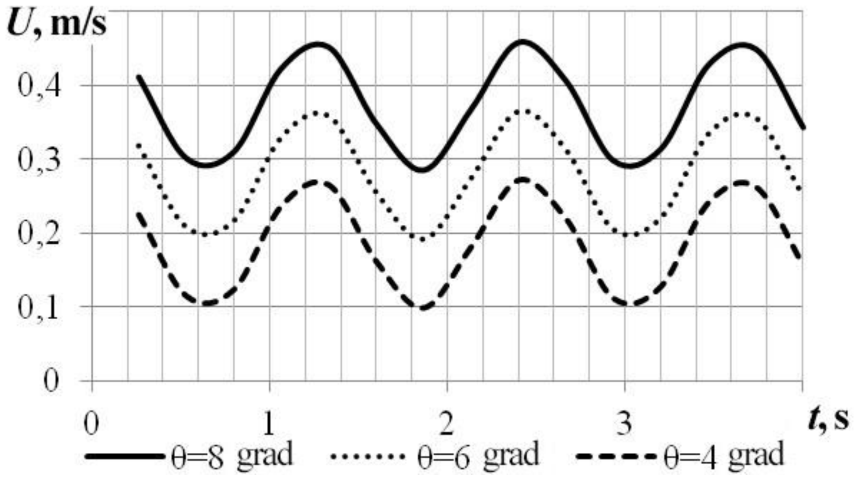

Figure 2. Change in motion rate of the particles of granular mixture depending on the constituent angle of the sieve surface relative to the horizontal.

Fig. 2 shows the changes in the motion rate of particles of granular medium depending on the angle of the sieve surface to the horizon. From the results it is seen that with increasing sieve inclination, the value of the rate of particles on the sieve surface increases.

When the values of the angle of inclination from the horizon exceed 9°, the rate increases sharply and time of the particles track decreases. In this case, there is a lack of sifting of the target product.

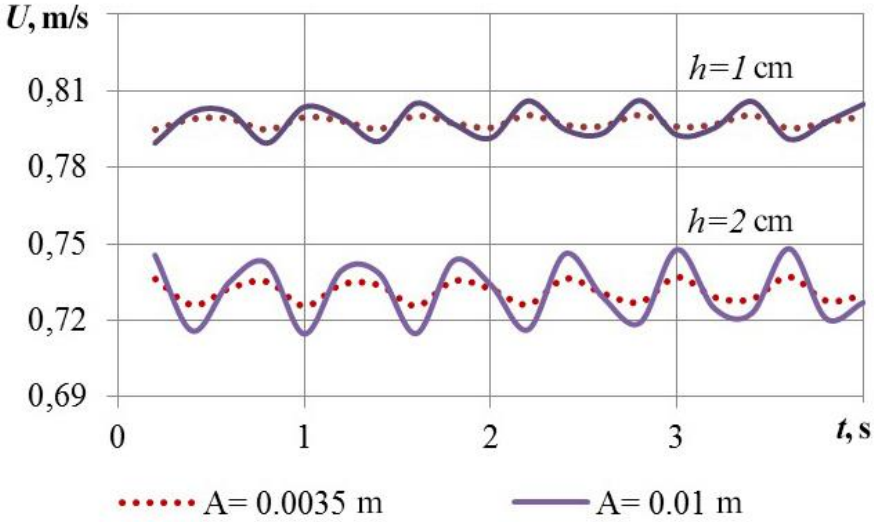

Figure 3. Change in motion rate of particles of granular mixture depending on the amplitude of vertical oscillations of the sieve.

The change in the rate of motion of the particles of granular mixture at different values of oscillations amplitude of the sieve is shown in Fig. 3. As seen from the figure, the change in oscillation amplitude of the sieve does not lead to a significant change in the rate of motion of the particles of granular mixture. With a decrease in the amplitude of the sieve oscillations, a gradual change in the rate of motion of particles on the sieve surface occurs. This is especially noticeable in the upper layers of granular mixture.

To study the effect of density of the mixture on the rate of the particles, computer calculations have been conducted. As follows from the carried out numerical computer calculations, the horizontal and vertical rates of particles increase with increasing density of granular mixture. This is especially noticeable at an increase in the angle of inclination of the separator sieve relative to the horizon and is explained by the increase in the proportion of gravity in the equation.

Studies have been conducted to determine the effect of the coefficient of vibration viscosity of mixture on the separation process. The results have shown that with an increase in this coefficient the rate of granular material motion on the surface of the separator sieve decreases proportionally. It is established that the coefficient of vibration viscosity directly depends on the frequency and amplitude of oscillations of the sieve of a separating unit.

By a numerical experiment, it is found that the rate of particles motion in different layers of mixture along the thickness is different. The maximum rate of granular mixture is observed in the upper layers of the material being separated. It is seen that in the lower layers the rate of motion of particles changes in a zigzag manner, and in the upper layer - smoothly, which is characteristic of deep waves.

Numerical calculations carried out at different inclination angles of the sieve of the aggregate relative to the horizon have shown that 9° increase in the inclination angle of the sieve leads to a sharp increase in particles rate and to a reduction in the run time of the particles. As a result, there is a lack in sifting of granular material and a loss of valuable product. It is stated that with an increase in the

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frequency of the sieve oscillation, a gradual change in the rate of particles on the surface of the sieve of the aggregate occurs.

According to the carried out numerical calculations, the concentration of granular mixture at the initial stages of the separation process (t = 10–12 s) decreases sharply, and then the rate slows down. With an increase in the amplitude of the sieve oscillation, the run of granular mixture increases linearly. This increase, in turn, leads to a dramatic change in the concentration of granular mixture on the surface of the sieve. The decrease in the run rate of granular mixture in time is related to the clogging of the sieve mesh and compaction of mixture layer.

The analysis of computational experiments at different thickness of the separation layer has shown that the process of separating granular mixture from impurities at 22-24% of clogging of granular material occurs more evenly and efficiently at the layer thickness of L_3 = 3.2–3.6 cm. An increase in the thickness of the layer to be separated by more than 3.8 cm leads to an increase in the difference in vertical concentration of granular mixture, and this, in turn, leads to a lack in sifting of the seed kernels through the sieve mesh.

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