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RESEARCH OF HORIZONTAL SCREW CONVEYORS-MIXERS WITH ROTATING CASING

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Abstract. *The model of mixtures movement in screw conveyors-mixers with rotating body is considered in this paper. It is shown that the process of mixing the mixture occurs more intensively in the mode of operation, in which the load is lifted by rotating casing into the upper part of the conveyor, from where part of it spirals down, and part of it crumbles. above the shaft and enters another cell formed by adjacent turns of the screw operating body. At the same time, the mixture is shoveled and distributed along the length, which ensures high smoothing capacity of the mixer conveyor. To establish the kinematic parameters of the mixer conveyor in the cylindrical coordinate system, the equilibrium equation of the separate element of the mixture, which is acted upon by the reaction forces from the rotating body and the screw operating body, was considered. Ranges of values of the angular velocities of the shroud rotation, at which the stationary movement of the bulk cargo into the dumping zone occurs, were determined. Dependencies to determine the kinematic parameters of the mixer, which ensure the operating modes of the mixer under the condition of the specified quality of mixing were obtained.*

Key words: *screw-conveyor mixer; direct flow screw mixer; rotary casing; loose mixture; kinematics of the flow of bulk goods; equations of motion, drag body of bulk material.*

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1. INTRODUCTION

High reliability, environmental friendliness, the ability to work in flow production systems and relatively low cost of direct-flow screw conveyors-mixers are the reason for their wide use in agricultural production, food, chemical, pharmaceutical and other industries for the production of mixtures. The advantage of direct-flow mixers of continuous action is that the process takes place continuously ensuring high productivity of mixing the mixture components and easy automation. However, the intensity of mixing in such mixers, compared to periodic ones, is low and high homogeneity of the mixture is achieved by increasing the time when mixture stays in the operating area, which usually results in the increase in the length of the mixers, their material and energy consumption. The reduction of these indicators is ensured by the choice of rational parameters and modes of operation of screw conveyor-mixers, where the disruption of the screw flow of the mixture is realized and its shoveling is intensified. However, in order to reduce the length of screw mixers and, consequently, their material and energy consumption, it is necessary to resolve the contradiction which involves the ensuring of the proper number of mixing turns at low axial flow rate and, consequently, short length of the continuous screw conveyor.

The principle of operation of direct-flow screw conveyors-mixers is based on the peculiarities of transporting bulk cargo by screw conveyors, in which the layers are mixed as the mixture passes through the working space [1, 2]. It was shown in papers [3, 4] that such mixing occurs most intensively in screw conveyors under transient conditions, which are characteristic of the transition from slow to high-speed transport. The kinematics and dynamics

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of screw conveyors are also discussed in detail there. Features of the operation of screw conveyors-mixers are given in papers [5, 6]. Discrete element method (DEM) was used in paper [7] to identify the specifics of movement of various components in screw conveyors and analyze their kinematic and dynamic indicators, as well as productivity. Visualization of the particles movement in the flow of cargo of conveyors-mixers with their mixing is given in paper [8]. Numerical investigation of particle mixing in the screw mixer by discrete element method is shown in papers [9, 10]. The synthesis of mixers with screw operating bodies was carried out in paper [11]. Intensification of mixing processes by performing profiled screws and ensuring the proper quality of the mixture by changing the working space in telescopic mixers is considered in [12, 13]. Wide opportunities for intensifying the process of mixing components are provided by two-shaft screw conveyors, in which the flows from two screw operating bodies are mixed in the fluid layer [14]. In paper [15], the promising design of the screw conveyor-mixer with additional blades introduced for better capturing of the mixture in rotational motion was developed and studied by DEM method. The investigation of five different designs of special screw conveyors-mixers of different lengths using DEM is presented in papers [16, 17]. The analysis of known research results showed that one of the most promising directions for improving the quality of mixing, increasing process productivity, reducing the time spent by components in the working area, and reducing the material capacity of the equipment is the application of improved screw conveyors-mixers with a rotating casing. The mixture is captured by the rotating casing of the screw conveyor-mixer in the similar way as in tumbling mills, the features of which are described in detail in paper [18]. The investigation of new opportunities for qualitatively improving the operational characteristics of mixers and the quality of mixing components in the mixture in rotary casing screw conveyors is given in paper [19]. The study of the kinematics of bulk material in screw conveyor-mixer with rotating casing was considered in [19, 20]. Paper [22] presents the design of the experimental automated installation of the screw conveyor with rotating casing in order to specify the parameters of the mixing transport model. Most of the considered constructions and mixing methods can ensure high-quality distribution of components by volume, but not all of them provide their proper smoothing ability, i. e., the stability of the component ratio of over time. The investigation of the smoothing ability of screw conveyor-mixers with the development of the flow cell model is given in paper [23].

However, due to the complexity of the process, in particular, the presence of rotational movements of both the screw spiral and the casing, and different phases of the mixture movement in the working space, and, accordingly, disruptions of homogeneous flows, the mixing process in screw conveyor-mixers has not been sufficiently investigated and requires further study of the kinematics and dynamics of transport and mixing, as well as the selection of optimal operating modes.

Objective of the paper is to ensure low material and energy consumption of direct-flow screw conveyors-mixers and high rates of mixture homogeneity and stability of the ratio of components over time by selecting and justifying their designs and rational operating modes. The above mentioned effect can be achieved by using direct-flow screw conveyors-mixers equipped with coaxially placed screw operating body and tubular casing, which rotate in the same direction, respectively, with angular velocities ω_1 and ω_2, where $\omega_1 > \omega_2$.

2. MATERIALS AND METHODS

Let us consider a horizontal straight-through screw conveyor-mixer with tubular cylindrical chamber with diameter D_0 and length L, where the mixture is transported by screw operating body (screw) with D outer diameter and T pitch. Let's choose cylindrical coordinate system $O\rho\varphi z$, where axis $O\rho$ is initially directed in the direction of the earth's gravity (downward), axis Oz is directed along the screw axis, and the location of arbitrary mixture particle is determined by the radial ρ, angular φ and axial z parameters.

The equation of helical surface (with left-hand winding) in the polar coordinate system in the parametric form, according to [1, 3], is as follows

$$\rho_1 = u_1;\ \varphi_1 = \upsilon_1;\ z_1 = -T\upsilon_1/(2\pi) = -c\upsilon_1. \tag{1}$$

Similar equation for the cylindrical surface of the casing

$$\rho_2 = D_0/2;\ \varphi_2 = \upsilon_2;\ z_2 = u_2. \tag{2}$$

Here u_i and υ_i are respectively linear and angular independent parameters of each of the surfaces; $c = T/(2\pi)$ is pitch parameter of the helical surface of the operating body.

Accordingly, the equations of the rotating helical surface of the conveying screw and the cylindrical surface of the casing

$$\rho_1 = u_1;\ \varphi_1 = \upsilon_1 + \omega_1 t;\ z_1 = -T\upsilon_1/(2\pi) = -c\upsilon_1. \tag{3}$$

$$\rho_2 = D_0/2;\ \varphi_2 = \upsilon_2 + \omega_2 t;\ z_2 = u_2, \tag{4}$$

where ω_1 and ω_2 are respectively, the angular speed of the screw operating body (spiral) and the tubular casing.

In the case of low-speed mixers with fixed casing and low filling factor φ_V of the mixer working volume, the main part of the cargo (mixture) with mass m will slide down the screw under the influence of gravity and will be transported in the low-speed conveyor mode at $v_Q = c\omega_1$ speed. The rotating casing will cause the drawing body to be caught in rotational motion and thrown over the shaft, which will contribute to mix the mixture and increase the mixer's smoothing ability, i.e. increase the uniformity of the distribution of components both in volume and in time. Let's denote the probability of capturing the arbitrary allocated volume of the mixture by the screw as p. Then, the probability that the allocated volume will be tipped over the shaft and not move forward is $q = 1 - p$. Due to the overturning of the load part through the shaft, the entire flow will have helical movement and the mediated angle of elevation of the flow line to the plane of the cross section of the screw mixer will be $\beta = \mathrm{arctg}(p/q)$.

The cargo consumption in such mixer will be determined similarly to the screw conveyors [1–3]

$$Q = 0{,}25\pi\varphi_V \psi c\omega_1 (D^2 - d^2), \tag{5}$$

where d is screw shaft diameter; ψ is coefficient that takes into account the overflow of the mixture through the screw shaft and in the gaps between the screw and the casing, $\psi = p$.

When switching to screw transportation, the mixture is drawn into a screw movement. In this case, each selected i th element (particle of the mixture) with ΔV_i volume will have velocity

$$\bar{v}_i = \bar{v}_{\rho i} + \bar{v}_{\tau i} + \bar{v}_{zi} = \frac{d\rho_i}{dt}\bar{e}_\rho + \frac{\rho d\varphi_i}{dt}\bar{e}_\tau + \frac{dz_i}{dt}\bar{e}_z \,, \qquad (6)$$

where $\bar{e}_\rho$, $\bar{e}_\tau$, та $\bar{e}_z$ are respectively, radial, circular and axial orthoi of the cylindrical coordinate system $O\rho\varphi z$.

Let us assume the hypothesis of layer-by-layer motion of particles (selected volumes ΔV_i), in which for arbitrary particle with running angular parameter $\varphi = \theta_i$, the radial parameter $\rho_i = \text{const}$ is constant, whence $d\rho_i / dt = 0$. Let us consider the motion of the particle (of the selected volume ΔV_i) along fixed cylindrical surface (on casing $\rho_i \approx R$) under the action of a screw, which will impose a constraint on the parameters of the particle z and φ, given by the dependence $z_i = c \cdot \varphi_i$. Then the trajectory of the particle can be uniquely described by the running angular parameter $\beta_i = \beta_i(t)$ - the angle of elevation of the trajectory to the cross-sectional plane

$$tg[\beta_i(t)] = dz_i/(\rho d\varphi_i) = v_{zi} / v_{\tau i} \,, \qquad (7)$$

where v_{zi} and $v_{\tau i}$ are, respectively, axial and circular components of the particle helical velocity.

Provided that the appropriate viscosity from the screw and casing are imposed on the selected elementary mixture volume ΔV_i it will have only one degree of freedom. The angular location θ_i of the selected elementary volume $\theta_i = \upsilon_{1i} + \omega_1 t$, where υ_{1i} is the angular parameter of the point of the screw surface that contacts it, is taken as an independent parameter.

Taking into account the superimposed viscosity, the coordinates of the selected volume will be $\rho_i = R$, $\varphi_i = \theta_i$, $z_i = z_i(\theta) = c(\omega_1 t - \theta)$. Under the condition of constant angular velocity of the screw, the dependence (6) for determining the total velocity of the allocated volume is ΔV_i, will be $\bar{v}_i = R\dot{\theta}_i \cdot \bar{e}_\tau + c(\omega_1 - \dot{\theta}_i) \cdot \bar{e}_z$, where $\dot{\theta}_i$ is the angular velocity of the helical motion of the particle.

The differential equations of particle motion for the screw conveyor are given in papers [1–3]. Similar equations of motion can be written for the allocated elementary volume ΔV_i, which moves along the surfaces of the casing and the screw under the rotation of the latter. To ensure the connection of the particle with each surface, we assume that $D = D_0$.

Using D'Alembert principle, the equation of motion for the selected elementary volume is as follows

$$\bar{N}_{1i} + \bar{F}_{1i} + \bar{N}_{2i} + \bar{F}_{2i} + \Sigma\bar{P}_{ij} + \bar{G}_i - m_i \bar{a}_i = 0 \,, \qquad (8)$$

where $\bar{N}_{1i}$, $\bar{N}_{2i}$ та $\bar{F}_{1i}$, $\bar{F}_{2i}$ are, respectively, the vectors of forces of normal reactions of the screw helix and casing surfaces and friction forces from their action (Fig. 1), $F_{1i} = \mu_1 N_{1i}$, $F_2 = \mu_2 N_2$;

m_i is particle mass; $\bar{a}$ is absolute particle acceleration;

$\bar{G}_s$ - vector of the earth's gravity;

ΣP_{ij} – the sum of external influences from the solid cargo on the surface of the allocated volume. Here μ_1 and μ_2 are coefficients of friction of the particle sliding along the surfaces of the screw and the casing, respectively.

Vectors $\overline{N}_{1i}$ and $\overline{N}_{2i}$ are directed, respectively, perpendicular to the surfaces of the screw and the rotating casing, and the vectors $\overline{F}_{1i}$ and $\overline{F}_{2i}$ are placed, respectively, in the planes tangent to the surfaces of the spiral and the casing at the point of their contact with the particle and are directed opposite to the vectors of the relative velocity of the particle with respect to each of the surfaces, Fig. 1. Vector $\overline{G}$ of gravity on the system's orthos $O\rho\varphi z$ for horizontal placement of the conveyor will be decomposed into components $\overline{G}_i = m_i g(\cos\theta_i \cdot \bar{e}_\rho - \sin\theta_i \cdot \bar{e}_\tau)$.

Vectors of the equivalent normal reactions of each of the surfaces and their components due to friction in cylindrical coordinates $O\rho\varphi z$ are $\overline{R}_i = \overline{N}_i + \overline{F}_i = \{\alpha_{\rho i}N_i; \alpha_{\tau i}N_i; \alpha_{zi}N_i\}$, where $\alpha_{\rho i}, \alpha_{\tau i}$ and α_{zi} are the corresponding coefficients (sums of the guiding cosines of the vectors $\overline{N}_i$ and $\overline{F}_i$, to the orthoi of the coordinate system).

$$\alpha_1 = \{\alpha_{\rho 1}; \alpha_{\theta 1}; \alpha_{z1}\} = \{0; \sin\alpha + \mu_1\cos\alpha; \cos\alpha - \mu_1\sin\alpha,\};$$
$$\alpha_2 = \{\alpha_{\rho 2}; \alpha_{\theta 2}; \alpha_{z2}\} = \{1; -\mu_2\cos\beta_{i2}; -\mu_2\sin\beta_{i2}\}, \tag{9}$$

where α is the elevation angle of the spiral helical line at $\rho = R$; β_{2i} is the inclination angle of the trajectory of the relative particle motion (relative velocity vector $\bar{v}_p$) along the surface of the rotating casing.

$$\sin\beta_{2i} = c(\omega_1 - \dot{\theta}_i)/v_p; \qquad \cos\beta_{2i} = \rho(\dot{\theta}_i - \omega_2)/v_p;$$
$$\operatorname{tg}\beta_{2i} = [(\omega_1 - \omega_2)/(\dot{\theta}_i - \omega_2) - 1]\cdot\operatorname{tg}\alpha. \tag{10}$$

Accordingly, the inclination angle of the trajectory β_i (Fig. 2) in the absolute coordinate system $O\rho\varphi z$ is determined similarly to the screw conveyor with fixed casing [1, 2] by the known angular velocity of the particle $\dot{\theta}$.

$$\sin\beta_i = c(\omega_1 - \dot{\theta}_i)/v; \qquad \cos\beta_i = \rho\dot{\theta}_i/v_i; \qquad \operatorname{tg}\beta_i = (\omega_1/\dot{\theta}_i - 1)\operatorname{tg}\alpha. \tag{11}$$

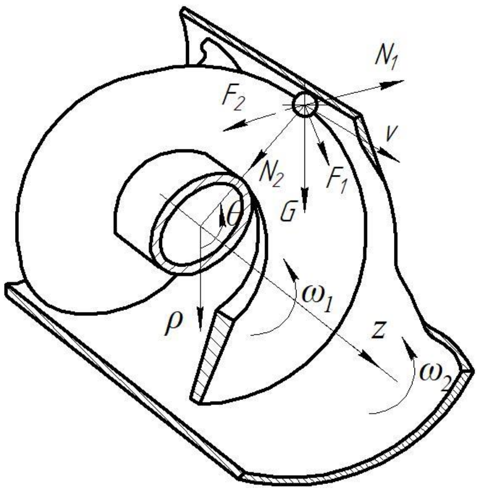

Figure 1. Scheme for calculating the equation of particle motion in the screw conveyor-mixer with rotating casing

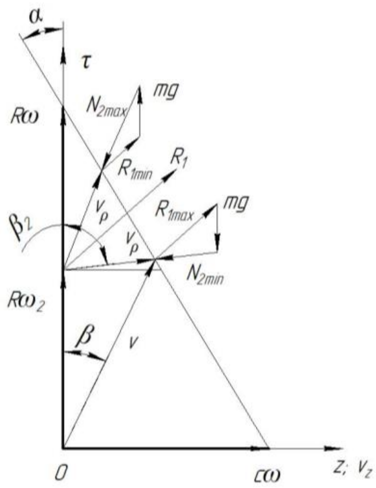

Figure 2. Calculation scheme for determining the kinematic parameters of the screw conveyor-mixer with rotating casing

The absolute velocity vector of the particle is defined as $\bar{v} = \bar{v}_T + \bar{v}_p$ where $\bar{v}_T$ is the transferred velocity corresponding to the casing's circular velocity; $\bar{v}_T = \bar{v}_\tau = R\omega_2 \cdot \bar{e}_\tau$.

For the model of a single material particle for slow-moving conveyors with fixed casing, its stationary motion is possible with the parameter $\beta_i = \pi/2$, angular velocity $\dot{\theta} = 0_i$, linear velocity $v_{zi} = c\omega_1$ and constant angle θ_i, which in the selected coordinate system will be as follows

$$\theta_i = \mathrm{arctg}[\mu_2 \,\mathrm{tg}(\alpha + \varphi_{\mu 1})], \tag{12}$$

where $\varphi_{\mu 1}$ is friction angle of the particle on the spiral surface $\varphi_{\mu 1} = \mathrm{arctg}\,\mu_1$.

The components of the absolute acceleration of the particle when it moves along the surface of rotating casing under the action of the spiral are

$$a_{\rho i} = -\rho\dot{\theta}_i^2; \qquad a_{\varphi i} = \rho\ddot{\theta}_i; \qquad a_{zi} = \ddot{z}_i = T(\omega_1 - \dot{\theta}_i)'_t/(2\pi) = c(\dot{\omega}_1 - \ddot{\theta}_i), \tag{13}$$

where ρ is radial parameter of the particle, $\rho = D/2$; $\theta, \dot{\theta}$ and $\ddot{\theta}$ are, respectively, the angular parameter, velocity and acceleration of the particle in the system $O\rho\varphi z$.

By decomposing vector equation (8) of the particle's motion on the coordinate axes, we obtain the system of equations similar to that for screw conveyors

$$\begin{gathered} -N_{2i} + m_i g\cos\theta_i + mR\dot{\theta}_i^2 = 0; \\ (\sin\alpha + \mu_1\cos\alpha)\cdot N_{1i} - \mu_2\cos\beta_{2i}\cdot N_{2i} + \Sigma P_{\varphi i} + m_i g\sin\theta_i - m_i R\ddot{\theta}_i = 0; \\ (\cos\alpha - \mu_1\sin\alpha)\cdot N_{1i} - \mu_2\sin\beta_{2i}\cdot N_2 + \Sigma P_{zi} - m_i c(\dot{\omega}_1 - \ddot{\theta}_i) = 0. \end{gathered} \tag{14}$$

where $\Sigma\bar{P}_i$ is the total effect of external influences from other particles; for the case of a single particle $\Sigma\bar{P}_i = 0$, for the case of many particles, the internal forces are balanced in the centre of gravity.

3. RESULTS AND DISCUSSION

For the case of stationary process, it is possible to accept $\dot{\omega}_1 = 0$, $\dot{\omega}_2 = 0$, $\ddot{\theta}_i = 0$. Then

$$\begin{gathered} N_{2i} = m_i(R\dot{\theta}_i^2 + g\cos\theta_i); \\ \mu_2 N_{2i}\cos(\alpha + \varphi_1 + \beta_{2i}) = m_i g\sin\theta_i\cos(\alpha + \varphi_1); \\ N_{1i} = \frac{\mu_2\sin\beta_{2i}\cdot N_{2i}}{\cos\alpha - \mu_1\sin\alpha}. \end{gathered} \tag{15}$$

From the second equation in system (15)

$$\beta_{2i} = \arccos\left[\frac{g\sin\theta_i\cos(\alpha + \varphi_1)}{\mu_2(R\dot{\theta}_i^2 + g\cos\theta_i)}\right] - \alpha - \varphi_{\mu 1}. \tag{16}$$

In the lower part of the conveyor-mixer ($\theta_i = 0$), the gravity vector is directed along the axis $O\rho$ and the angle $\beta_{2i} = \pi/2 - \alpha - \varphi_{\mu 1}$. As the casing rotates and angle θ_i increases, the value of angle β_{2i} increases to 90^0, when the particle moves along the generative of the rotating casing (Fig. 2 and Fig. 3), and with further increase of angle θ_i, angle β_{2i} will increase until angle β_i in the basic coordinate system reaches the value $\beta_i \to \pi/2$ and single particle is not be pulled into the rotating motion by the casing (Fig. 3), but moves horizontally.

In order to assess the mutual influence of particles on the process of their movement as a system, let us consider two side-by-side load elements (particles) of equal mass $m_1 = m_2$ with angular parameters φ_1 and φ_2, respectively, and represent them as $\varphi_1 = \theta + \Delta_1$ and $\varphi_2 = \theta - \Delta_2$; where θ is the angular parameter of the intermediate (middle) point located on the casing between the particles; Δ_1 and Δ_2 is the angular displacement of each of the particles relative to the intermediate point, let us assume $\Delta_1 = \Delta_2 = \Delta$.

Let us consider coordinate system $O_C ntu$ the centre of which is located at the centre of mass C of the system of two particles with mass $m = m_1 + m_2$, axis $O_C n$ is normal to the surface of the casing, axis $O_C t$ is tangent to the circle passed through C, and axis $O_C u$ is collinear to axis $O_C z$ of the system $O\rho\varphi z$. Accordingly, the angular parameter of the centre O_C coincides with the angular parameter of the centre of masses θ_C. For cohesive mixture, the elevation angles of close particles will be practically the same ($\beta_{21} = \beta_{22}$), and therefore, in equation (14), the coefficients (9) for each of the two particles are taken to be the same α_{11}=α_{12} and α_{21}≈α_{22} The centrifugal acceleration of each particle is $a_{\rho 1} = a_{\rho 1} = -\rho\dot{\theta}_i^2$. For stationary process, let us assume $a_{\rho 1} = a_{\rho 1} = -\rho\dot{\theta}_i^2$, and for neighbouring particles $N_{11} = N_{12}$, $N_{21} = N_{22}$.

Then for the system of two particles ($i \in \{1,2\}$) the equation of motion is as follows

$$\begin{gathered} -N_{2i}\cos(\pm\Delta) + m_i g[\cos(\theta \pm \Delta)] + m_i R(\dot{\theta} \pm \dot{\Delta})^2 \cos(\pm\Delta) = 0; \\ (\sin\alpha + \mu_1 \cos\alpha) N_{1i} - \mu_2 \cos\beta_{i2} \cdot N_{2i} \pm P_i \sin\alpha + m_i g \sin(\theta \pm \Delta) = 0; \\ (\cos\alpha - \mu_1 \sin\alpha) N_1 - \mu_2 \sin\beta_{2i} \cdot N_2 \mp P_i \cos\alpha = 0. \end{gathered} \tag{17}$$

Let us sum over the corresponding coordinates the components of the system of equations for each of the particles $i = 1$ and $i = 2$ and denote the equivalent reactions of the spiral and the casing to the system as $N_1 = N_{11} + N_{12}$, $N_2 = N_{21} + N_{22}$. We assume that $\Delta \to 0$, and the combined system (of the two equations (17) at $i = 1$ and $i = 2$) becomes identical to system (15) with respect to the unknowns N_1, N_2, and $\theta = \theta_C$. Excluding N_1, N_2 from system (15), we obtain the equation of stationary motion of the system of two (or more) particles, given by the parameter of the elevation angle $\beta_2 = \beta_{2C}$ of the trajectory of the centre of their masses, and in which the mass of the system is substituted for the mass of one particle m, and the coordinates of the centre of mass of the system $C(R_C; \theta_C; z_C)$ are taken instead of the coordinates of the particle.

Analysis of (15) and (17) shows that dependence (15) is also valid for the array of many particles, i.e., separated flow (dragging body), where the coordinates of the particle correspond to the coordinates of the centre of gravity of the drag body under transient conditions with the introduction of appropriate correction factor. Accordingly, the results obtained for the material particle can be extended to the binding mixture movement in the screw mixer, where the coordinates of the centre of mass $C(R_C; \theta_C; z_C)$ of the system are used instead of the particle coordinates. Here, R_C, θ_C and z_C are, respectively, radial, angular, and axial parameters of the location of the centre of mass of the drag body with the reduced parameters (Fig. 4) and the corresponding correction factors determined experimentally.

Then the procedure for calculating the kinematic parameters of the screw mixer in the area of continuous movement of the drag body will be as follows.

According to (16), when the angular parameter $\theta = \theta_C$ of the drag body increases to a certain value, the angle approaches to $\beta_{20} \to \pi/2$ (Fig. 2), where the mixture moves along the casing. According to the selected filling factor φ_V of the conveyor-mixer, the expected value of the angular parameter of the location of the centre of the drag body is determined, and according to the graph in Fig. 2, constructed for a specific angular velocity $\theta = \theta_C$ of the casing, we determine the value $\beta_{20} = \pi/2$, as one of the possible values, which we use to determine the refined value as the first iteration. In this case, $\dot{\theta} = \omega_2$ and the value of the angle change $\beta_{20}(\theta)$ as the function of the angle Θ is determined by the dependence, which includes the radius of the centre of mass of the particles of the drag body and the correction factor k_C, which takes into account the differences in the transport of the drag body and the material particle and is determined experimentally

$$\beta_{20}(\theta) = \arccos\left[\frac{\operatorname{tg}\theta \cos(\alpha + \varphi_1)}{\mu_2\left(\dfrac{k_C R_C \omega_2^2}{g \cdot \cos\theta} + 1\right)}\right] - \alpha - \varphi_{\mu 1}. \tag{18}$$

Then the procedure for calculating the kinematic parameters of the screw mixer in the area of continuous movement of bulk material will be as follows.

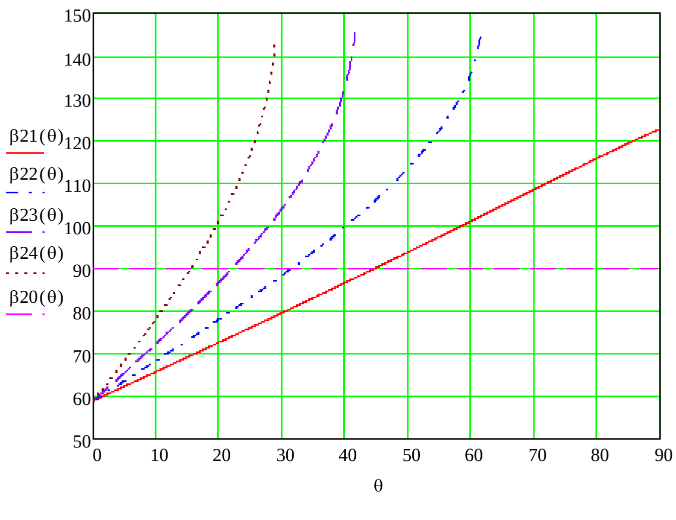

Figure 3. Change in the elevation angular parameter β_2 of the particle trajectory relative to the rotating casing depending on the angle of its placement Θ for: 1 – $\omega_2 = 25{,}0$ s^{-1}; 2 – $\omega_2 = 20{,}0$ s^{-1}; 3 – $\omega_2 = 15{,}0$ s^{-1}; 4 – $\omega_2 = 10{,}0$ s^{-1}

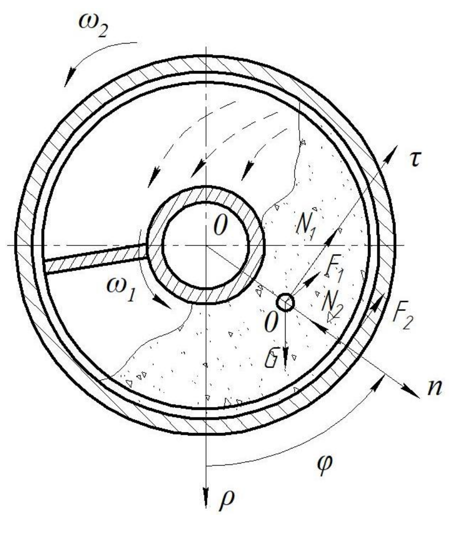

Figure 4. Placement of the drag body of bulk material in the working space of the screw conveyor-mixer

Taking into account (10), the refined angular velocity of the centre of gravity will be as follows

$$\dot{\theta}_C = \frac{\omega_2 + \omega_1 \operatorname{ctg}\beta_{20} \operatorname{tg}\alpha}{1 + \operatorname{ctg}\beta_{20} \operatorname{tg}\alpha} \tag{19}$$

Substituting this value instead ω_2 from dependence (18), we obtain the value of the next iteration. In the case when $\beta_{21} > \pi/2$, it is recommended to increase the angular speed of rotation of the casing and repeat the calculations for the new value ω_2 (Fig. 2). Based on the known angular velocities ω_1 and ω_2 the elevation angle of the trajectory of the centre of the drag body $\beta_2 = \beta_{21}$, we determine all the kinematic parameters of the process (Fig. 3). Thus, the relative velocity of the drag body with the centre coordinates $C(R_C;\theta_C;z_C)$ according to (19) is determined by the following dependence

$$v_p(\theta_C) = \frac{R_C(\omega_1 - \omega_2)\sin\alpha}{\sin[\alpha + \beta_2(\theta_C)]}. \tag{20}$$

The circular component of the relative velocity is

$$v_{p\varphi}(\theta_C) = \frac{R_C(\omega_1 - \omega_2)\sin\alpha\cos[\beta_2(\theta_C)]}{\sin[\alpha + \beta_{20}(\theta_C)]}. \tag{21}$$

Accordingly, the circular component of the absolute velocity of the drag body, on which the mixing efficiency depends, will be the function of the angular parameter θ_C of the centre of mass O_C

$$v_\varphi(\theta_C) = R_C\omega_2 + v_{p\varphi}(\theta_C) = R_C\omega_2 + \frac{R_C(\omega_1 - \omega_2)\sin\alpha\cos[\beta_2(\theta_C)]}{\sin[\alpha + \beta_2(\theta_C)]}. \tag{22}$$

Axial component of the velocity of the drag body (relative, also known as absolute)

$$v_z(\theta_C) = \frac{R_C(\omega_1 - \omega_2)\sin\alpha\sin[\beta_2(\theta_C)]}{\sin[\alpha + \beta_2(\theta_C)]}. \tag{23}$$

The value of the elevation angle β_0 of the helical trajectory of the mixture (in case of contact with the casing) in the fixed coordinate system will be as follows

$$\beta_0 = \beta_0(\dot{\theta}) = \mathrm{arctg}[(\omega_1/\dot{\theta} - 1)\,\mathrm{tg}\,\alpha]. \tag{24}$$

Such adjustment is made taking into account that the drag body occupies about the third of the mixer's working space, depending on the filling factor of the screw conveyor–mixer (Fig. 4). Since the body of the mixture dragging occupies a certain volume, its upper points are offset from the axis On which passes through the centre of mass O_C by an angle $\Delta\theta_2$. Accordingly, in the system $O\rho\theta z$ this point will have an angular coordinate. Considering that the entire mass of the mixture makes a circular motion, then the angular velocity of each particle will be practically the same $\dot{\theta}_i = \dot{\theta}_C$. The condition for the separation of such mass Δm_2 particle from the casing is the predominance of the component of the particle gravitational force over the component of centrifugal forces $N_2 \le \Delta m_2 g$ and after simplifications is $R\dot{\theta}_2^2/g \le 1$. Taking into account (19)

$$\left(\frac{R_C\omega_2^2}{g}\right)\left[1 + \frac{(\omega_1/\omega_2 - 1)\sin\alpha\cos[\beta_2(\theta_C)]}{\sin[\alpha + \beta_2(\theta_C)]}\right]^2 = \frac{k_\omega R_C\omega_2^2}{g} \le 1. \tag{25}$$

where k_ω is the coefficient that takes into account the recommended inclination of the mixture route along the rotating casing, which is set by the angle $\beta_2(\theta_C)$. The angular velocity ω_2 of the casing is determined from dependence (25). In order to ensure the separation of the part of the drag body in the given proportion of the mixture that is thrown over the shaft and the mixture that remains in the previous cell, the angular range of overlap of the drag body, where $N_2 < 0$ is calculated according to dependence (25), provided that up to 50% of the mixture should be thrown over the shaft. Based on the condition of ensuring uniformity of mixing, the number of shoveling cycles n_c is set and the time of the mixture passing through the mixer $\mathrm{t_L} = 2\pi n_c / \omega_2$ is determined. Based on the known length L of the mixer and the time t_L of the mixture passage, the maximum linear speed of the mixture passage is determined

$$\mathrm{v_{max}} = L_0\omega_2 / (2\pi n_c)\,. \tag{26}$$

According to (23), the angular velocity of the operating body $\omega_1 = \omega_2 + 2\pi v_{max} / T$ is determined. The flow rate of the current screw mixer, similar to (5), will be

$$\mathrm{Q} = 0{,}125\varphi_V \psi T(\omega_1 - \omega_2)(D^2 - d^2)\,. \tag{27}$$

According to (10), the unevenness of mixing depending on the number of shoveling cycles $n_ц$ can be approximated by exponential dependence, the components (coefficients and model parameters) of which are determined experimentally

$$\xi = A(\varphi_0, \psi)e^{-kn_c} + \zeta \tag{28}$$

where $A(\varphi_0,\psi)$ is component that depends on the mixer filling and the degree of the mixture overfilling; k is coefficient that takes into account the rheological properties of the components of the mixture, their cohesion; ζ is component that takes into account the partial separation of the mixture components (separation) under the influence of gravity and other factors.

4. CONCLUSIONS

The carried out investigations showed that the application of direct-flow screw conveyors-mixers with rotating casings makes it possible to improve significantly the main characteristics of the mixing process and expand the scope of their use, particularly, in automated systems. This is substantiated by the fact that the specified conveyors-mixers are able to provide and regulate all the main parameters of the mixing process on one equipment for mixtures of different component composition with different rheological properties.

It has been determined that the efficiency of mixing the mixture in direct-flow screw conveyors-mixers is determined by the number of mixture shoveling and the ratio of the part of the mixture that fell over the shaft to the part that moved along the screw. It is shown that the stability of the process of screw movement of the mixture with subsequent disruption of the flow and shoveling is ensured by the rotation of the casing, which prevents the transition of the flow to horizontal transportation. In particular, the adjustment of the angular speed of rotation of the casing makes it possible to ensure the optimal detachment of the mixture from the surface of the casing in its given area and its effective shoveling, depending on the filling factor of the conveyor and the rheology of the bulk mixture.

The selection of the mode of movement (ahead or lag) of the mixture in relation to the rotating casing is regulated by the selection of the spiral pitch and angular speed of the casing, depending on the rheological properties of the mixture.

The quality of mixing and the stability of its composition over time is ensured by the number of shovelling operations and the time spent in the conveyor's working area, which is regulated by the difference in the angular velocity of the screw and the casing.

Regulation of the speed mode and the time of the mixture presence in the working area ensures effective mixing of the mixture in the mode of flow transportation, makes it possible to reduce the length of the direct-flow screw conveyors-mixers and, accordingly, their material capacity, as well as their energy consumption, due to the reduction of energy costs for pouring the mixture and reducing the working area of the mixer.

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ДОСЛІДЖЕННЯ ГОРИЗОНТАЛЬНИХ ГВИНТОВИХ КОНВЕЄРІВ-ЗМІШУВАЧІВ З ОБЕРТОВИМ КОЖУХОМ

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Резюме. *Розглянуто модель переміщення сумішей у горизонтальних гвинтових конвеєрах-змішувачах з обертовим кожухом, напрям обертання якого співпадає з напрямом обертання гвинтового робочого органу. При малих швидкостях гвинта та кожуха суміш зсувається по гвинту й реалізується тихохідний режим транспортування, аналогічний тихохідним гвинтовим конвеєрам, із незначним ефектом перемішування суміші. Показано, що процес перемішування суміші проходить інтенсивніше при перехідному режимі роботи конвеєра, при якому вантаж обертовим кожухом піднімається до верхньої частини робочого простору конвеєра, звідки частина зсувається по спіралі вниз, а частина пересипається через вал і потрапляє в іншу комірку, утворену сусідніми витками гвинтового робочого органу. При цьому проходить як перелопачування суміші, так і її розосередження по довжині, що забезпечує високу згладжувальну здатність конвеєра-змішувача. Для встановлення кінематичних параметрів конвеєра-змішувача в циліндричній системі координат розглянуто рівняння рівноваги окремих елементів суміші, на яке діють сили реакції від обертових кожуха та гвинтового робочого органу. Показано, що переміщення тіла волочіння у гвинтовому конвеєрі-змішувачі можна описати рівняннями, аналогічними переміщенню частинки з приведеними параметрами. Встановлено діапазони значень кутових швидкостей обертання кожуха, за яких відбувається стаціонарний рух сипкого вантажу від зони його гвинтового транспортування до зони розриву в'язей із обертовим кожухом і спадання вниз та пересипанням через вал. Показано, що осьова швидкість гвинтового конвеєра-змішувача визначається різницею кутових швидкостей гвинта та кожуха і кроком гвинта. Виведено залежності для визначення кінематичних параметрів змішувача, які забезпечують режими роботи змішувача із умови заданої якості змішування.*

Ключові слова: *гвинтовий конвеєр-змішувач; прямоточний гвинтовий змішувач; обертовий кожух; сипка суміш; кінематика потоку сипких вантажів; рівняння руху; тіло волочіння сипкого матеріалу.*

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