A Model of Rotational Mixing of Loose Environment on the Platform of Cyber-Physical Systems

A. B. Kapranova, D. D. Bahaeva, D. V. Stenko, and I. I. Verloka

Abstract Based on the energy method, a stochastic model of the process of rotational mixing of the loose environment at the first stage of the mixer-compactor with a conveyor belt on the platform of cyber-physical systems is proposed taking into account the physicomechanical properties of the components being mixed. Analytical expressions are obtained for the differential functions of the distribution of the number of particles of loose components according to their scattering angle during the formation of rarefied streams above the conveyor belt during the operation of one row of elastic blades fixed in tangent planes to the surface of a cylindrical drum. The described elements of the cyber-physical system are required to create a theoretical base for the engineering method for calculating the parameters of the mixer-compactor.

Keywords Cyber-Physical system · Mixer-Compactor · Loose materials · Mixture · Elastic shoulder blades · Distribution functions · Parameters

1 Introduction

Current trends in the development of chemical technologies in the field of processing of loose components reflect the need to organize appropriate technological processes in the absence of contradictions between their two main characteristics - energy efficiency and intensity [1]. The growing needs of the food, chemical, pharmaceutical, construction, and other sectors of the national economy for homogeneous loose

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mixtures with specified mechanical properties and regulated requirements for the porosity index confirm the urgency of developing new equipment for these purposes. In this regard, the combination of several technological operations [2] or, as a special case, their execution in sequential mode [3], but in the working volume of one device, becomes a priority in the design of mixing and compactor equipment to obtain a deaerated homogeneous mixture of solid dispersed materials with a given volume ratio of components. There is a need to take into account the influence of many factors that can adversely affect the final product of the production of the loose mixture, including the effect of segregation [4], the properties of aerability and adhesion, the ratio of the particle-size distribution of the components, etc. [5–7]. One of the ways to combat the undesirable effect of segregation during the preparation of granular mixtures may be to organize the process of mixing particles of components in rarefied streams [8, 9]. Providing designers with appropriate dependencies of the main indicators of mixing, as one of the processes within the framework of one technological chain, on the set of its design and operating parameters suggest the development of a theoretical base from the perspective of a cyber-physical system [10]. The aim of the work is to develop a stochastic description of the process of formation of rarefied flows at the stage of rotational mixing during the organization of further combining this operation with compaction of the obtained granular mixture on a conveyor belt on a cyber-physical platform. The latter includes the formation of a set of independent parameters of the specified mixing process.

2 Features of the Construction of Mixing Models During the Operation of the Mixer-Compactor of Loose Materials with a Conveyor Belt

The difficulties of mathematical modeling of the process of mixing particles of granular components are associated, first of all, with the multifactorial nature of the tasks solved in this case [11], which is reflected in the choice of the main approach to the description of this technological operation and attention to the creation of an appropriate cyber-physical platform. Despite the wide range of available mixing models from deterministic descriptions [5–7, 12] to stochastic models [1, 13–15] and their various modifications with combination elements, in this case, it is advisable to use the second one to obtain information on particle distribution according to a given process characteristic. In addition, the probabilistic nature of particle motion in rarefied flows of granular materials determines a specific method of mathematical description for the selected modeling approach, in particular, it is proposed to use the energy method [16], which allows one to take into account the basic physical and mechanical characteristics of loose materials and the features of motion -partition of their constituent particles. Thus, the interest in studying the process of rotational mixing from the standpoint of the cyber-physical system has all the bases. The use of conveyor belts in apparatus for processing solid dispersed environment [17] allows you to successfully combine a number of technological operations within the same working volume [3]. Such an organization allows for continuous operation of the designed equipment, for example, in the production of dry construction mixtures using movable rigid perforated ridges [18], mixing powders on the conveyor with fixed separating plates [19], or even without mixing organs due to vibration effects [20], etc.

In this case, one of the methods for organizing rarefied flows from layers of loose components on a movable belt is to use rotary drive devices in the form of drums with elastic blades [21], symmetrically mounted above the conveyor at an angle to the direction of movement of the belt. The vertical screen to the horizontal working surface of the conveyor serves as an additional mixing device and the sealing roller with holes for removing air on the other side of the vertical screen functions as a deaerator. The organization of the process of formation of rarefied flows depends on the choice of the configuration of the elastic elements and the method of their fastening on the mixing drum [8–10, 21], for example, there are: a radial arrangement of thin cylindrical bills [1], screw winding of flexible elements [9], meetings arrangement of screw coils for brush elements [8, 10], etc. In this case, the surfaces of rectangular elastic blades are fixed in tangent planes to the cylindrical surfaces of each mixing drum located above the conveyor belt. At the same time, the installation of these elastic blades is carried out in rows with alternating directions of their location along the axis of symmetry of the cylindrical mixing drums. Such fastening of the elastic blades ensures the scattering of particles in different directions of the mixed components fed by a conveyor belt into the gap of these drums in the form of layers. The stochastic description using the energy method [16] of the process of forming rarefied streams of loose components over a conveyor at the stage of rotational mixing using one row of rectangular elastic blades fixed in this way is the main task of this study.

The concept of a mechanical mixer of two loose components with continuous operation proposed in [10] can be adapted to the case of rotational mixing with a set of information variables, set z $(t) = \{x(t), y(t), a, b\}$ total number. The following notation is accepted here.: $a = \left\{a_{j1} = cont\right\}$, $j_1 = \overline{1, u_1}$—design parameters for threads «1» and «2»; b—set of operational parameters; $x(t) = \{x_i(t)\}$, $i = \overline{1, 2}$ and $y(t) = \{x_1(t), x_2(t), V_C\}$—respectively, the sets of input and output parameters of the studied process, where V_C—mixture heterogeneity coefficient. Splitting information variables into two categories (basic z_m—calculated from the proposed model and designed z_p—remaining in this division) suggest the choice of the following two sets from the last category. The first one relates to a set of regulated parameters z_{pr}, the number of which determines the number of degrees of freedom of the mixing process, and the second to optimizing parameters z_{po}. However, the formulation of the multifactor task of optimizing the process of mixing loose solids in some cases can be replaced by a more simplified task of finding effective ranges for changing the desired parameters using the generated analytical base.

For example, an analysis of the modeled differential functions of the distribution of the number of particles of loose components according to the selected process characteristic allows us to identify such effective limits for the change of design and operating parameters so that the condition for achieving the specified quality of the mixture formulated in [8–10] is fulfilled We clarify that for the considered rotational mixing of loose components on a conveyor belt, the following sets of parameters can be distinguished: $x = \{Q_{Vi}, n_{Vi}\}$, $y = \left\{Q_{Vi}, n_{Vi}, V_C^{tech}, \Delta V_C\right\}$, $b = \{\omega, h_0, h_L\}$, where $Q_{Vi}-$ component volumetric consumption $i = 1, 2$; n_{Vi}—their volume fractions, V_C^{tech}—regulatory values of the coefficient of heterogeneity, ΔV_C—absolute parameter errors V_C^{tech}, ω—angular rotation speed of the drum, h_0—clearance height drum-tape, h_L—the height of the layers of loose materials supplied by the conveyor to the specified gap. In this set a determined by the values of the following design parameters: length and width of the conveyor belt; radius r_b and drum width; length l_b and width of elastic blades, number of blades n in one row, and the number of these rows on the cylindrical surface of the mixing drum, etc. In this presentation, we restrict ourselves only to the main set $a = \{r_b, l_b, n,\}$.

3 Analysis of the Peculiarities of the Movement of the Elastic Blades of the Mixing Drum When Scattering Particles of Loose Materials

Consider the movement of elastic blades long—l_b, making up the one-row bill, which is fixed in the manner described above on a rotating with an angular velocity ω in mixing drum. Let the radius of the drum be r_b, the distance between the drum and horizontal conveyor belt—h_0, the number of deformed bills within a quarter of the angle of rotation of the drum—n_b. To describe the movement of the endpoints of the elastic blades M_j, $j = \overline{1, n_b}$ after leaving the gap between the drum and the conveyor, we introduce two Cartesian coordinate systems with parallel axes Oxy, $O_1x_1y_1$ in the transverse plane of the cross-section of the drum. The first center O lies on the axis of rotation of the mixing device, the coordinates of the second center $O_1\left(x_{O_1}; y_{O_1}\right)$ in system Oxy respectively equal $x_{O_1} = r_b \sin\alpha_0$, $y_{O_1} = r_b \cos\alpha_0$ in direction axes Ox, O_1x_1 vertically down and perpendicular to the tape, where $\alpha_0 = 2\pi/n$—the angle between attachment points K_s, K_{s+1}, $j = 1, \ldots, s, s+1, \ldots, n_b$ adjacent elastic blades on the surface of the drum, n—total number of blades of one row.

We connect the polar coordinate system (r, θ) with axe O_1x_1 when counting counterclockwise the polar angle θ. We introduce the equation of motion of the endpoints of the elastic blades M_j, $j = \overline{1, n_b}$ in polar coordinates in the form of a spiral of Archimedes $r_a(\theta)$, assuming that for the initial position of the blade deformed in the gap, the number $j = 1$ the coordinates of the points are respectively equal: $K_1(r_b; 0)$ in system Oxy and $M_1\left(x_{1M_1}; y_{1M_1}\right) = M_1(h_0 + r_b(1 - \cos\alpha_0); 0)$ in system $O_1x_1y_1$. Moreover, it is assumed that the position of the point M_δ, $j = 1, \ldots, n_b, \delta, \ldots, n$ for the reconstructed blade is the endpoint of the specified spiral, in particular, let $M_\delta\left(x_{M_\delta}; y_{M_\delta}\right) = M_\delta(-r_b; -l_b)$. Then the equation of the spiral of Archimedes is given by the expression

$$r_a(\theta) = A + B\theta \tag{1}$$

where are the notation $A = h_0 + r_b(1 - \cos\alpha_0)$, $B = (\{(r_b + l_b)^2 + \left[r_b(1 + \cos\alpha_0)\right]^2\}^{1/2} - A\big)/\theta_\delta$, $\theta_\delta = \pi + \mathrm{arctg}\{(r_b + l_b)/[r_b(1 + \cos\alpha_0)]\}$. Point position M_j, $j = \overline{1, n_b}$ in the polar system is determined by the following equation for an arbitrary point M on the spiral of Archimedes (1)

$$\begin{aligned} r_{M_j}(\theta) &= r_M(\theta) = r_a(\theta)\cos[3\beta(\theta)/2] \\ &+ (\{2r_a(\theta)\cos[3\beta(\theta)/2]\}^2 - 4\{[r_a(\theta)]^2 - r_b^2\})^{1/2}/2, \end{aligned} \tag{2}$$

where angle $\beta(\theta) = \mathrm{arctg}[B/r_a(\theta)]$ is the angle between the polar normal to the tangent spiral at the point $M = M_j$ and radius vector $\overrightarrow{O_1M_j} = \vec{r}_a\big(\theta_{M_j}\big)$. Note that the approximation is accepted for the connection between the angles $\beta(\theta) \approx 2\beta'(\theta)$, where β' - the angle between the same polar normal and radius vector $\overrightarrow{OM_j} = \vec{r}_{M_j}$. In view of the Eqs. (1), (2) analyzed the movement of particles of two loose components ($i = 1, 2$), which are scattered by deformable elastic blades from layers stacked on top of each other $h_L = \sum_{\nu=1}^{2} h_{L\nu}$ on a movable tape that fills the gap between the mixing drum and the specified conveyor. Let the average diameter of spherical particles with a density ρ_{Ti} taking into account the number of fractions n_ν defined by the expression $d_{Ti} = \sum_{\nu=1}^{n_\nu} d_{Ti\nu}n_\nu$. Particle speed $V_{r\theta i}$ for each loose component ($i = 1, 2$) with the described movement at the moment of separation from the end of the deformed elastic blade in the polar coordinate system is given by

$$V_{r\theta i}(r_M(\theta), \theta) = \omega r_M(\theta)/\cos\{\mathrm{arctg}[B/r_a(\theta)]\}. \tag{3}$$

Then the two components of kinetic energy (E_{1i} for translational movement of a particle with mass together with its center of mass in a projection onto the transverse plane of the mixing drum and E_{2i} for the rotational motion of a particle relative to this center, taking into account the values of the random component of the angular momentum L_i and axial moment of inertia I_i calculated by the Formulas

$$\begin{aligned} E_{1i} &= m_i[V_{r\theta i}(r_M(\theta), \theta)]^2/2 \\ &= (\pi/12)\rho_{Ti}\omega^2 d_{Ti}^3(r_M(\theta)/\cos\{\mathrm{arctg}[B/r_a(\theta)]\})^{2,} \end{aligned} \tag{4}$$

$$E_{2i} = L_i^2/(2I_i) = (5\pi/6)\rho_{Ti}\omega^2 d_{Ti}[r_M(\theta)]^4. \tag{5}$$

Note that the energy of the elastic interaction of each particle with a flexible blade when scattering loose materials is determined by the work of the elastic forces of the corresponding beat with an empirical angular coefficient of its stiffness k_u

$$E_{3i} = k_u\theta_i^2/2 \approx k_u\theta^2/2. \tag{6}$$

So, the energy of each particle $E_i = \sum_{\nu=1}^{3} \mathrm{E}_{\nu \mathrm{i}}$ in the described movement when scattering from an elastic blade equal to the sum of its three components according to the expressions (4)–(6)

$$E_i = a_i d_{Ti}\omega^2 \left\{ d_{Ti}^2 + 10p_{30} \frac{(c_0 + c_1\theta)^4}{c_0^2\left[(p_0 + p_1\theta)^2 + p_{20}^2\right]} \right\} \frac{(c_0 + c_1\theta)^4}{c_0^2\left[(p_0 + p_1\theta)^2 + p_{20}^2\right]} + \frac{k_u\theta^2}{2} \quad (7)$$

where

$$\begin{aligned}
&a_i = \pi\rho_{Ti}/12, c_0 = k_0 + k_1,\\
&c_1 = \left\{3k_2/\left(2A^3\right) + k_0k_4B/A + A^3B\left[2k_4\left(k_0^2 - A^2\right) + k_3\right]/(8k_1)\right\}/k_4,\\
&p_0 = \cos\{(1/2)\mathrm{arctg}[B/A]\},\ p_1 = \left(B^2/2k_4\right)\sin\{(1/2)\mathrm{arctg}[B/A]\},\\
&p_{20} = [p_0(1 - p_0)]^{1/2},\ p_{30} = (p_0^2 + p_{20}^2)^2, k_0 = A\cos\{(3/2)\mathrm{arctg}[B/A]\},\\
&k_2 = B^2\sin\{(3/2)\mathrm{arctg}[B/A]\},\ k_3 = (3/2)AB\sin\{3\mathrm{arctg}[B/A]\},\\
&k_4 = A^2 + B^2.
\end{aligned}$$

4 Description of the Use of the Energy Method in Stochastic Modeling of Rotational Mixing from the Perspective of a Cyber-Physical System

To further simulate the process of formation of rarefied flows of two loose materials mixed by a rotary device, it is proposed to use the energy method [16], which allows one to take into account the energy form of the stochastic particle motion in the form (7) within the framework of the stochastic approach. Considering the indicated technological operation as a random process of a homogeneous, continuous, stationary, Gaussian type, we apply the formalism of the Markov process for the states of the macrosystem of particles of each component without an influx of energy from outside. Then, in the absence of macro-fluctuations of these macrosystems associated with particle collisions, we consider that in the resulting flows there is insignificant cross-motion of one flow in another, and the particle displacements of both formed flows are co-directed. In this approximation, the Ornstein–Uhlenbeck formalism [16] is valid with the solution of the Fokker–Planck equation in the energy representation for the stationary case with respect to the distribution function of the number of particles in the following form

$$\phi_i = A_i exp(-E_i/E_{0i}) \quad (8)$$

where is the normalization constant A_i is found from the condition $\int\limits_{\Psi_i} \phi_i d\Psi_i = 1$ with the introduction of the phase volume element $d\Psi_i = dv_{xi} dv_{yi} \equiv dv_x dv_y$ or $d\Psi = dv_x dv_y = -\omega^2 r dr d\theta$ in the approximation of the simultaneous interaction of an elastic element with particles of each component. Here, the choice of phase variables is explained by the application of the expression for the stochastic energy of a single particle of the component $(i = 1, 2)$ in the form (7). Due to (8), the decrease in the number of particles dN_i component $i = 1, 2$ in elementary volume $d\Psi$ is given by the formula [16]

$$dN_i = A_i \exp(-E_i/E_{0i}) d\Psi. \tag{9}$$

Expressions (8), (9) contain the energy parameter E_{0i}, whose physical meaning is determined by the energy of the stochastic motion of particles at the moment of the beginning of stochastization of the states of the macrosystem $(i = 1, 2)$. Expressions (8), (9) make it possible to determine the desired expression for the differential distribution function of the number of particles of the component i $= 1, 2$ by the distinguished feature of the process under study, for example, by the scattering angle, which in this case coincides with the polar angular coordinate θ

$$f_i(\theta) = (1/N_i) dN_i/d\theta. \tag{10}$$

Then, taking into account expressions (7)–(9) for the energy of stochastic motion of particles of each loose material E_i and exponential law for the number of these particles dN_i in elementary volume $d\Psi$ we obtain the desired dependence

$$\begin{aligned} f_i(\theta) = {} & Q_i\left\{[H_1(\theta)]^2 + p_{20}^2\right\}^{1/2}\left\{\exp\left[-k_u\theta^2/E_{0i}\right]\right\} \\ & \times\left[\operatorname{erf}\left({}_{2i}[H_2(\theta)]^2\left\{[H_1(\theta)]^2 + p_{20}^2\right\}^{-1/2}\right) - \operatorname{erf}\left({}_{2i}\left\{[H_1(\theta)]^2 + p_{20}^2\right\}^{-1/2}\right)\right] \\ & /\left\{\exp\left[-10\left({}_{1i} + k_u\theta^2/E_{0i}\right)\right] - \exp\left(-{}_{1i}\right)\right\} \end{aligned} \tag{11}$$

where $Q_i = [c_0/(16c_1)][\pi k_u/(E_{0i} g_{1i} g_{1i})]^{1/2}$, $H_1(\theta) = p_0 + p_1\theta$, $H_2(\theta) = c_0 + c_1\theta$, $\lambda_{2i} = \left(3/2c_0^2\right)[k_u g_{1i} g_{2i}/(E_{0i})]^{1/2}$, $\lambda_{1i} = k_u g_{1i} g_{2i}/\left[E_{0i}\left(2p_0^2 + p_{20}^2\right)\right]$.

The value of the energy parameter E_{0i} determined from the balance equation for the total particle energies of each macrosystem $(i = 1, 2)$: when capturing particles of a component $i = 1, 2$ the ends of the flexible elements from the gap of the drum-tape (E_{Ci}) and when disseminating these particles with specified bills (E_{Di}) in the field of changes in the polar angular coordinate $\theta \in [\theta_{0i}; \theta_{1i}]$. Then, taking into account the effect of mixing the components, we have

$$\sum_{i=1}^{2} E_{Ci} = \sum_{i=1}^{2} E_{Di}. \tag{12}$$

When taking into account the different thicknesses of the layers of loose materials on the conveyor belt ($h_{Li} = h_L/2$), as well as the nature of the movement of the endpoints of the elastic blades M_j, $j = \overline{1, n_b}$ in polar coordinates (1), (2) and when averaging the particle velocity $V_{r\theta i}$ mass m_i for each loose component ($i = 1, 2$) by the polar angular coordinate in the region $\theta \in [0; \alpha_0]$ the Eq. (12) relatively E_{0i} takes the form

$$\begin{aligned}&\sum_{i=1}^{2} N_i m_i \left\{ h_0^2/2 + \alpha_0^{-1} \int_0^{\alpha_0} [r_M(\theta)]^4 / \{[H_1(\theta)]^2 + p_{20}^2\} d\theta \right\} \\ &+ \sum_{i=1}^{2} A_i \int_{\theta_{0i}}^{\theta_{1i}} d\theta \int_{r_{Li}}^{r_M(\theta)} E_i \exp(-E_i/E_{0i}) r dr = 0 r_{Li}\end{aligned} \quad (13)$$

where $r_{L1} = h_0 + r_b(1 - \cos\alpha_0)$, $r_{L2} = r_{L1} - h_L/2$ at appropriate values θ_{1i}.

5 Results of Modeling

Let us consider an illustration of the proposed stochastic model of the process of forming rarefied flows of loose components at the stage of rotational mixing using one row of rectangular elastic blades fixed in tangent planes to the cylindrical surface of the mixing drum located above the conveyor belt. Let the technological operation of mixing natural sand be carried out State Standard (GOST) 8736–93 at i = 1 ($\rho_{T1} = 1.525 \times 10^3$ kg/m3; $d_{T1} = 1.5 \times 10^{-4}$ m) and semolina GOST 7022–97 at i = 2 ($\rho_{T2} = 1.440 \times 10^3$ kg/m3; $d_{T2} = 4.0 \times 10^{-4}$ m). The choice of these loose materials is associated with the need to replace some toxic compounds with model mixtures with similar physical and mechanical properties, in particular, provided that the densities of the constituent substances are comparable. We give the main values of the parameters of the formed cyber-physical platform of the process under study: a) $r_b = 3.0 \times 10^{-2}$ m; $l_b = 4.5 \times 10^{-2}$ m; $n = 8$ for the design of the mixer at the preliminary stage of operation of the apparatus of the mixer-compactor loose environment with a conveyor belt; б) $h_0 = 3.0 \times 10^{-2}$ m; $h_L = 3.0 \times 10^{-2}$ m; $\omega =$ (41 – 53) s-1 for operating modes of the designed equipment.

According to the stochastic modeling of the rotational mixing process under study using expression (11), families of curves are constructed for the dependences of the differential distribution function of the number of particles of each component $f_1(\theta)$ and $f_2(\theta)$ by polar angular coordinate θ respectively in Fig. 1a and b.

The values of the energy parameters calculated according to (13) E_{0i} presented in Table 1.

An analysis of the results shows that at the initial angles of rotation of the elastic blades, the loose discharge of loose materials occurs (see the characteristic first bursts in charts 1–3, Fig. 1a, b), in particular, more than half of component 1, when the flexible elements are maximally deformed after the drum-tape leaves the gap.At the same time, for both components there remains a tendency to further remove the

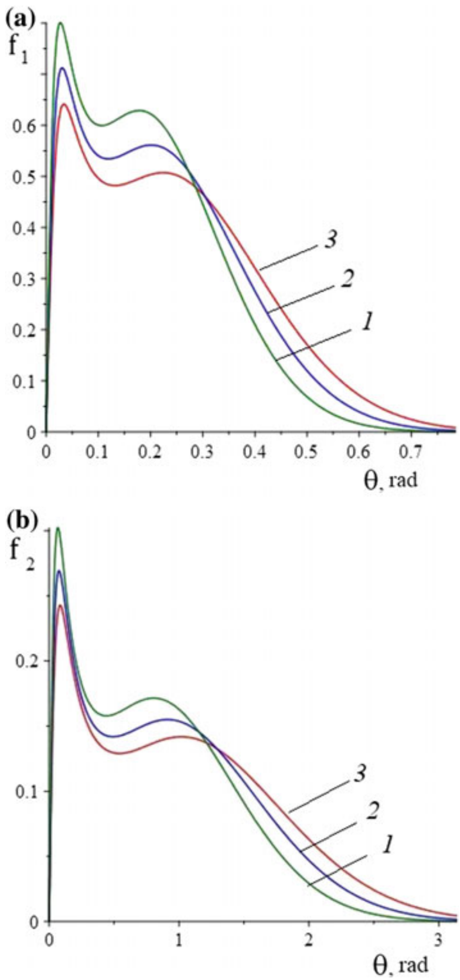

Fig. 1 Dependence $f_i(\theta)$: **a**—natural sand GOST 8736-93 ($i = 1$); **b**—semolina GOST 7022-97 ($i = 2$); $\omega = 41.9\ s^{-1}$ (*1*); $\omega = 47.1\ s^{-1}$ (*2*); $\omega = 52.4\ s^{-1}$ (*3*)

Table 1 Model features

Loose material name, brand	Drum rotational speed ω, s^{-1}	Energy parameter E_{0i}, × 10^{-5} J
Natural sand GOST 8736-93	41.9	3.312
	47.1	4.193
	52.4	5.176
Semolina GOST 7022-97	41.9	59.320
	47.1	75.080
	52.4	92.690

remaining particles during the restoration of the shape of the elastic scapula (see the second bursts in the graphs indicated above). In addition, the dispersion for component 2 is more pronounced than for component 1, for example, the dispersion range for semolina is about 1.5 times longer than for sand. This fact indicates that, for given structural and operational parameters, the particles of component 2 scatter at a faster rate than component 1, which is explained by the physicomechanical features of the loose materials under consideration. Smaller particles of natural sand ($d_{T2}/d_{T1} = 2.7$), but heavier ($\rho_{T2}/\rho_{T1} = 0.94$) than semolina particles, due to which they bounce at a smaller angle from the surfaces of elastic blades. However, a simple change in the angular velocity of rotation of the mixing drum in the selected range (41–45) s−1 does not change this picture, which confirms the conclusions made in [8–10] about the need for additional research of other factors that significantly affect the process of formation of rarefied flows in a rotational way. For example, as was shown in [8–10], these factors include the degree of deformation of flexible elements in the gaps with the drum, which is characterized by the ratio of the beat length to the height of the gap. In addition, the result of the work of only one row of elastic blades is considered.

6 Conclusion

The above remarks on the obtained simulation results lead to the need to expand the set of studied design parameters when forming a cyber-physical platform to develop an engineering method for calculating the designed mixer-compactor.

The revealed characteristic tendency to scatter the main number of particles at small rotation angles of the mixing drum for both components is the basis for obtaining the conditions for the effective mixing of loose components. This requires such adjustment of the ranges of the set of process parameters that affect the formation of the cyber-physical system in order to ensure the convergence of extreme angular values for the polar coordinate θ of the mixed components. For example, this indicated approach is actually observed ($\theta < 0.19$ rad) when comparing the first bursts in graph 3 (Fig. 1a) and graph 3 (Fig. 1b), plotted with the same maximum value of the angular velocity of the drum from the selected parameter variation range ω.

Thus, the stochastic modeling of the process of forming rarefied flows of loose components at the stage of rotational mixing using one row of rectangular elastic blades fixed in tangent planes to the cylindrical surface of the mixing drum located above the conveyor belt showed the possibility of applying the energy method.

The resulting analytical dependences for the differential distribution functions of the number of particles of each component along the polar angular coordinate allow:

- identify the main factors of analysis necessary for the analysis of the efficiency of the mixing process;

- expand the parameters of the process under study involved in the formation of the platform of its cyber-physical system;
- to predict the behavior of loose components during their rotational mixing in order to create conditions for effective mixing when analyzing the attainability of the criterion for the convergence of extreme angular values of the polar coordinate for mixed loose components;
- taking into account the above facts, confirm the feasibility of using a mixing device in the form of a drum with elastic blades fixed on the conveyor belt using this method by evaluating the quality criterion of the obtained loose mixture, for example, by calculating its heterogeneity coefficient.

References

1. Kafarov, V.V., Dorokhov, I.N, Arutyunov, S.Yu.: In: System Analysis of Processes of Chemical Engineering. pp. 440. Science, Moscow (1985)
2. Kapranova, A.B.: Stochastic model of parallel or sequential processes of deaeration and mixing of granular media using the operation of a centrifugal device as an example. Theoretical Foundations Chem. Eng. **53**(2), 292–304 (2018)
3. Kapranova, A.B., Zaitzev, A.I., Kuz'min I.O.: Studying the porosity of powders under pressure compaction in deaeretion mixers. Theor. Found. Chem. Eng. **49**(4), 436–446 (2015)
4. Bauman, I., Curic, D., Boban, M.: Mixing of solids in different mixing devices. Sadhana **33**(6), 721–731 (2008). https://doi.org/10.1007/s12046-008-0030-5
5. Makarov, Yu. I.: In: Devices for Mixing Loose Materials, pp. 216. Mechanical Engineering, Moscow (1973)
6. Kim, V.S., Skachkov, V.V.: In: Dispersion and Mixing in Production Processes and Processing of Plastics. pp. 240. Chemistry, Moscow (1988)
7. Satomo, I.: Solids mixing. Puranto Kogaku. **10**(5), 63–69 (1972)
8. Kapranova, A.B., Verloka, I.I.: Stochastic description of the formation of flows of particulate components in apparatuses with brush elements. Theor. Found. Chem. Eng. **52**(6), 1004–1018 (2018). https://doi.org/10.1134/S0040579518050330
9. Kapranova, A.B., Bakin, M.N., Verloka, I.I.: Simulation of the quality criterion of a mixture in a drum-belt apparatus. Chem. Petrol. Eng. **54**(5), 287–297 (2018). https://doi.org/10.1007/s10556-018-0477-0
10. Kapranova, A.B., Verloka, I.I., Bahaeva, D.D.: About preparation of the analytical platform for creation of a cyber-physical sys-tem of industrial mixture of loose components. In: Cyber-Physical Systems: Advances in Design and Modelling. Studies in Systems, Decision and Control. **259**, 81–91 (2020). https://doi.org/10.1007/978-3-030-32579-4_7
11. Shaul, S., Rabinovich, E., Kalman, H.: Generalized flow regime diagram of fluidized beds based on the height to bed diameter ratio. Powder Technol. **228**, 264–271 (2012)
12. Lai, F.S.: The convective mixing process and striated mixture. J. Powder Loose Solids Technol. 38 (1978)
13. Leonchik, B.I., Mayakin, V.P.: Measurements in dispersed flows. pp. 248. Energy, Moscow (1985)
14. Dehling, H.G., Gottschalk, T., Hoffmann, A.C.: In: Stochastic Modeling in Process Technology. pp. 279. Elsevier Science, London (2007)
15. Almendros-Ibanez, J.A., Sobrino, C., de Vega, M., Santana, D.: A new model for ejected particle velocity from erupting bubbles in 2-D fluidized beds. Chem. Eng. Sci. **61**, 5981–5990 (2016)

16. Klimontovich, Y. L.: In: Turbulent Motion and the Structure of Chaos: A New Approach to the Statistical Theory of Open Systems, pp. 328. LENAND, Moscow (2014)
17. Kaye, B.H.: Mixing of Powders. In: Fayed, M.E., Otten, L. (eds.) Handbook of Powder Science and Technology. Boston (1997). https://doi.org/10.1007/978-1-4615-6373-0_11
18. Trofimov, V.I., Lebedev V.E.: Utility Model Patent 2325993 Russian Federation, IPC B 28 Cp 5/36. A device for preparing a dry building mixture. Publ. 07.20.10, Bull. No. 20 (2010)
19. Garthus, D.R.: Utility Model Patent 4591275 USA, IPC B 28 C 5/36. Apparatus for mixing pulverulent mate-rial on a conveyor belt. Publ. 05.27.1986 (1986)
20. Pershin, V.F., Baryshnikova, S.V., Kalyapin D.K., Osipov A.A.: Utility Model Patent: 2242273 Russian Federation, IPC B 01 F 3/18. A method of preparing multicomponent mixtures and a device for its implementation. Publ. 12.20.04 (2004)
21. Lebedev, A.E., Vatagin, A.A., Borisovsky, M.E., Romanova, M.N., Badaeva, N.V., Sheronina, I.S.: Utility Model Patent: 2624698 Russian Federation, B01F3/ 18. Unit for mixing and compaction of loose materials. Publ. 07.05.2017 (2017)