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IMPROVING THE EFFICIENCY OF THE PROCESS OF CONTINUOUS FLOW MIXING OF BULK COMPONENTS

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Modern industrial and agricultural processing almost always implies mixing loose material on a variety of equipment. At present, there are known mixers of various designs, principles, and techniques to implement the technological process. One of the existing mixing techniques is a continuous flow method that has significant advantages – reducing energy intensity while improving the quality of the process of the mixture continuous preparation and distribution. However, the continuous-flow technique of mixing loose materials has been paid little attention to. This prevents the application of well-known analytical models of the process of moving loose components to substantiate the structural and technological parameters for the working bodies of a continuous flow mixer.

The result of the analytical study of the continuous-flow mixing technique is the constructed system of differential equations of the movement of a bulk material's components in the airflow under the influence of the working bodies' surfaces of the designed mixer. The reported system of differential equations underlies the physical-mathematical apparatus for the numerical modeling of the specified process employing the software package StarCCM+ (USA).

The result of the numerical modeling is the established dependences of the dynamics of change in the concentration of components in the mixture and the homogeneity of the mixture in the zones of a continuous flow mixer depending on the study factors (the frequency of rotations, the angle of attack of the blade mixer, the performance of feeding the first and second components).

The optimal structural and technological parameters for a continuous flow mixer involved in the process of mixing a two-component feed mixture (stem and concentrated feed) have been determined, at which the uniformity of the resulting forage mixture is maximal

Keywords: loose material, continuous flow mixing, numerical modeling, working body, structural and technological parameters

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1. Introduction

In industrial and agricultural engineering, the mixing process involves a set of operations that include the manipulation of a heterogeneous physical system in order to make it more homogeneous [1]. Modern industrial and agricultural processing almost always implies the implementation of a mixing process using a variety of equipment. The type of operations and equipment applied during mixing depends on the condition of mixed materials (gas, liquid, bulk material, or their combinations).

The loose material is a conglomerate of discrete solids, macroscopic particles, characterized by loss of energy during interaction [2]. The components that make up the loose material should be large enough that they are not subjected to thermal fluctuations.

Since the flow of bulk material is characterized by local dissipation, there is still no satisfactory theory. Most theories are associated with local equilibrium and modeling, making use of assumptions about the continuum [3–6]. However, in this case, the contact interaction between the particles is not taken into consideration, which leads to a mathematical notation of the mixing processes in the first approximation.

Therefore, it is a relevant task to build an analytical model of the process of mixing the flows of loose components based on numerical modeling, taking into consideration the contact interaction between the particles and the surface of the working bodies of mixers.

2. Literature review and problem statement

At present, there are known mixers of various designs, principles, and techniques to implement the technological process. As stated in work [7], basically all mixers can be divided into two large groups: the cyclic and continuous action. Paper [8] reports the results of studying continuous action mixers, which are more effective during the preparation of large volumes of the mixture and simultaneous transportation and unloading during the next technological operation. The kinetics of forming the multicomponent mixtures of various bulk materials are described in study [9]. However, the resulting models are intended only to assess the structure of the components in the mixture.

The design of most mixing equipment is basically a container that hosts a rotating working body (for example, a screw, spiral blades, etc.) [10]. Drum-type designs are also used in which a container itself rotates [11]. As noted in [12, 13], both types of mixer designs are quite energy-intensive when achieving the required quality because the mixing of bulk components typically implies large volumes.

An alternative to the specified mixing techniques is a continuous-flow method, which has significant advantages – reducing energy intensity while improving the quality of the process of continuous preparation and distribution of the mixture. Existing technical means designed for this purpose [14] are based on a portion mixing of two oncoming flows of the loose material, which allows the even redistribution of the material's components in a small volume.

As revealed by the analysis of the scientific literature [15, 16], the process of the movement of loose components under the influence of airflow has been addressed in many theories and procedures for calculating the coordinate positions of particles. Underlying these studies is the physical-mathematical apparatus of moving a material point under the influence of various forces that does not take into consideration the interaction of particles with each other, which have a random initial position. As stated in [16], the problem of interaction between the flow of bulk components and an airflow refers to the classic problem of the gas-dynamics of two-phase flows.

Also widespread is the diffusion model of the process of mixing loose components [7], which is described by the differential equation of change in the concentration of a key component in the mixture. The disadvantage of this model is that it can be used only for two-component mixtures when mixing large volumes. That is, it is not suitable for a continuous flow mixing technique.

Our analysis indicates that the continuous-flow mixing technique of loose components has been paid little attention to by researchers. This makes it impossible to use known analytical models of the process of moving loose components to justify the structural and technological parameters for the working bodies of a continuous flow mixer. The above allows us to argue that it is appropriate to conduct research aimed at building a physical-mathematical model of the process of a continuous flow mixing of loose components.

3. The aim and objectives of the study

The aim of this study is to improve the efficiency of the process of mixing loose components by using a continuous flow mixer with the substantiated mode-technological parameters.

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

– to propose an equivalent scheme of a continuous flow mixer for loose components;

– to build an analytical model of the process of moving loose components under the influence of airflow and the surfaces of the working bodies of a continuous flow mixer;

– to perform numerical modeling of the operational process of a continuous flow mixer and define its rational mode-technological parameters.

4. The research materials and methods

Substantiating the equivalent scheme of a continuous flow mixer for loose components implied taking into consideration our analysis of the scientific literature on the variety of designs, principles, and techniques of implementing the mixing process, in line with the generally accepted procedures of patent and information research and DSNU 3575-97 «Patent research. Main provisions and procedure of conducting».

Underlying the development of an analytical model of the process of moving loose components is the theoretical research aimed at building a system of differential equations of particle movement in airflow under the influence of the surfaces of the working bodies of the designed mixer. This system of equations was derived using the basic provisions of the theories of classical mechanics, gas-dynamics, the theory of elasticity, and the mechanics of contact interaction.

Numerical modeling of the operational process of a continuous flow mixer employed the software packages STAR-CCM+ (USA) and Mathematica (USA). The STAR-CCM+ (USA) software suite applies methods of numerical modeling to solve the set task, which are based on the models of k–ε turbulence of the divided current, the field of gravity, the real Van der Waals gas, discrete elements, multiphase interaction. In turn, the software package Mathematica (USA) uses the mathematical method of planning a numerical experiment employing a correlation-regression analysis, the methods of differential and cumulative calculus to determine the rational mode-technological parameters of the designed mixer.

5. The research results

5. 1. The structural-technological scheme of a continuous flow mixer

Based on the results of our analysis of literary data and our previous research, it has been found that the continuous flow mixing technique for loose components has a less energy intensity at the high quality of the process of continuous preparation and simultaneous distribution of the mixture. Therefore, the continuous flow technique for mixing oncoming flows of bulk components (Fig. 1) makes it possible to simultaneously mix and dispense the mixture by applying a single working body. The flow of the first loose component is created by gravitational forces, and the oncoming flow of the second loose component – by using the rotational movement of the blade mixer. Setting the motion of the flows of loose components in oncoming directions makes it possible to obtain a high homogeneity of the mixing. In turn, the simultaneous discharge with mixing leads to a decrease in the energy intensity of the process due to that the work is executed with relatively small volumes of the material.

In addition, the proposed design of the mixer executes an oncoming multistep mixing because, when moving in the direction of unloading, the already formed mixture would be directed towards the flows of other components that enter the mixer.

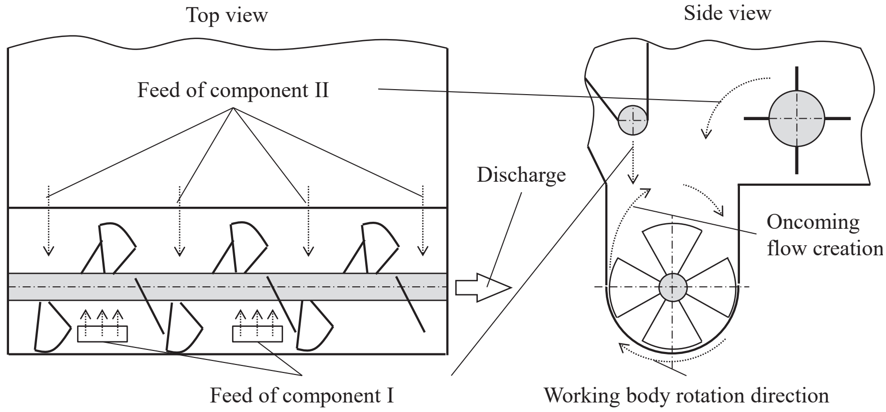

Fig. 1. Equivalent scheme of the technological continuous flow mixing process

5. 2. An analytical model of the process of the continuous flow mixing of loose components

Being aware of all the difficulties of the set task, it is necessary to investigate the process of moving bulk components under the influence of an airflow («fan effect») and the surfaces of the working bodies of the designed mixer.

To investigate the process of moving a loose material under the influence of airflow, it is necessary to define the appropriate mathematical apparatus. It will make it possible to derive the trajectories, force diagrams, as well as slip magnitudes of the particles moving in airflow at a speed gradient.

We record the system of differential equations of the movement of one particle within the assigned region of airflow speeds:

$$\begin{cases} \Omega_p \cdot \rho_p \dfrac{d_p \overline{V_p}}{dt} = \overline{F}, \\ \dfrac{d_p \overline{S_p}}{dt} = \overline{V_p}, \\ \dfrac{d_p}{dt} = \dfrac{\partial}{\partial t} + \overline{V_p} \cdot \overline{\nabla}, \end{cases} \quad (1)$$

where Ω_p is the particle volume, m^3; ρ_p is the particle density, kg/m^3; $\overline{V_p}$ is the vector of particle movement speed, m/s; $\overline{S_p}$ is the vector of particle movement, m; $\overline{F}$ is the vector of the resulting force acting on particles, N.

The process of solving the system of equations (1) by analytical techniques is quite complicated:

a) the total number of forces acting on a particle in airflow is uncertain since the processes that determine the behavior of the particle in the flow are not fully described;

b) the analytical expressions for some forces in the right-hand side of equation (1) are unknown (for example, an expression for the hydrodynamic air strength).

The forces acting on a particle when it is moving in a turbulent airflow can be divided into the following groups based on the causes for their occurrence [18]:

1. Gravity force:

$$\overline{F_g} = \Omega_p \rho_p \overline{g}, \quad (2)$$

where $\overline{F_g}$ is the gravity force vector, N.

2. The force of Archimedes:

$$\overline{F} = \Omega_p \rho_a \overline{g}, \quad (3)$$

where $\overline{F}$ is the vector of the force of Archimedes, N; ρ_a is the air density, kg/m^3.

3. The effort caused by a change in the pressure towards the movement of the carrier flow due to its acceleration [19]:

$$\overline{F_{ac}} = \Omega_p \rho_a \frac{d_a \overline{V_a}}{dt}, \quad \frac{d_a}{dt} = \frac{\partial}{\partial t} + \overline{V_a} \cdot \overline{\nabla}, \quad (4)$$

where $\overline{F_{ac}}$ is the effort caused by a change in pressure, N; $\overline{V_a}$ is the vector of air movement speed, m/s.

4. A viscous resistance effort arising from particle movement at some relative speed in an airflow [20]:

$$\overline{F_D} = \frac{1}{2} \pi D_p^2 \rho_a f_M(\mathrm{Re}) \left(\overline{V_a} - \overline{V_p}\right) \left|\overline{V_a} - \overline{V_p}\right|, \quad (5)$$

where $\overline{F_D}$ is the viscous resistance effort, N; $f_M(\mathrm{Re})$ is the viscous resistance coefficient.

5. The force equivalent to the influence of the attached mass is represented as follows:

$$\overline{F_m} = \frac{1}{2} \Omega_p \rho_a \frac{d}{dt} \left(\overline{V_a} - \overline{V_p}\right) \quad (6)$$

and expresses the growing inertia of the particle during its non-stationary movement [21]. A moderate increase in the particle mass comes from the inertia of the elements of the environment, to which the particle should add additional acceleration during its movement. This additional movement of the medium is equivalent to the movement of some fictitious mass (attached mass), which moves at the same relative speed as the particles.

6. The total power of the particle's contact interaction between it and the wall, which is based on the spring-damper contact model by Hertz-Mindlin [22]:

$$\overline{F_{contact}} = \overline{F_n} + \overline{F_t}, \quad (7)$$

where $F_{contact}$ is the effort of interaction between the particle and the surface of the working body, N; $\overline{F_n}$ is the normal component of an effort, N; $\overline{F_t}$ is the tangential component of an effort, N.

The normal component of a force is determined from the following equation:

$$\overline{F_n} = -K_n \overline{d_n} - N_n \overline{V_n}; \quad (8)$$

where K_n is the normal stiffness factor of the elastic component, kg/f^2;

$$K_n=\frac{4}{3}E_{eq}\sqrt{d_nR_{eq}}; \quad (9)$$

N_n is the normal coefficient of damping of the damping component, kg/f;

$$N_n=\sqrt{(5K_nM_{eq})}N_{n\ damp}. \quad (10)$$

According to study [22], the tangential component of a force is determined as follows:

$$\overline{F_t}=-K_t\overline{d_t}-N_t\overline{V_t}, \quad (11)$$

if $\left|K_t\overline{d_t}\right|<\left|N_t\overline{V_t}\right|C_{fs}$, where C_{fs} is the statistical coefficient of friction of the particles, or a wall. Otherwise, the tangential component of the force is determined from the following equation:

$$\overline{F_t}=\frac{\left|K_n\overline{d_n}\right|C_{fs}\overline{d_t}}{\left|\overline{d_t}\right|}; \quad (12)$$

where K_t is the tangential stiffness coefficient of an elastic component, kg/f^2;

$$K_t=8G_{eq}\sqrt{d_tR_{eq}}; \quad (13)$$

N_t is the tangential coefficient of damping of the damping component, kg/f;

$$N_t=\sqrt{(5K_tM_{eq})}N_{t\ damp}; \quad (14)$$

N_{damp} is the damping coefficient:

$$N_{damp}=\frac{-\ln(C_{n\ rest})}{\sqrt{\pi^2+\ln(C_{n\ rest})^2}}; \quad (15)$$

R_{eq} is the equivalent radius of two particles A and B, m;

$$R_{eq}=\frac{1}{\frac{2}{D_A}+\frac{2}{D_B}}; \quad (16)$$

M_{eq} is the equivalent mass of two particles A and B, kg;

$$M_{eq}=\frac{1}{\frac{1}{M_A}+\frac{1}{M_B}}; \quad (17)$$

E_{eq} is Young's equivalent module of two particles A and B, Pa;

$$E_{eq}=\frac{1}{\frac{1-\nu_A^2}{E_A}+\frac{1-\nu_B^2}{E_B}}; \quad (18)$$

G_{eq} is the equivalent shear module of two particles A and B, Pa;

$$G_{eq}=\frac{1}{\frac{2(2-\nu_A)(1+\nu_A)}{E_A}+\frac{2(2-\nu_B)(1+\nu_B)}{E_B}}; \quad (19)$$

M_A, M_B are the particles' weights, A and B, kg; d_n, d_t, is the virtual overlap of particles A and B in the normal and tangential directions, m; D_A, D_B are the effective particle diameters, A and B, m; E_A, E_B are the Youngs' modules of particles A and B, Pa; ν_A, ν_B are the Poisson coefficients of particles A and B; $\overline{V_n},\overline{V_t}$ are the normal and tangential components of the relative particle surface speed at the point of contact, m/s.

Dependences (16) to (19) are adequate for the process of interaction of particles with the surface of the working body, but, for the surface of the working body, we accept the radius $D_{wall}=\infty$ and the mass of the surface of the working body $M_{wall}=\infty$. As a result, expressions (16) and (17) are transformed to (20):

$$R_{eq}=D_p/2,\ M_{eq}=M_p. \quad (20)$$

For further research of the kinematic and dynamic characteristics of particles when they move in an airflow, we accept the following assumptions:

1. Particles are the rigid ellipsoids with a defined effective diameter, which are indistinguishable from each other.
2. There is no heat exchange between the particles and the environment.
3. The carrying flow is understood as an airflow that moves stationary in the specified region under isothermal conditions.

By fitting (2) to (7) to (1), we obtain a system of differential equations of particle movement in airflow under the influence of the surfaces of the working bodies of the designed mixer:

$$\begin{cases}\frac{d_p\overline{V_p}}{dt}=\overline{g}+\frac{\rho_a}{\rho_p}\overline{g}+\frac{\rho_a}{\rho_p}\frac{d_a\overline{V_a}}{dt}+\frac{\rho_a}{2\rho_p}\frac{d}{dt}(\overline{V_a}-\overline{V_p})+\\ +\frac{\pi D_p^2\rho_a f_M(\mathrm{Re})}{2\Omega_p\cdot\rho_p}(\overline{V_a}-\overline{V_p})\left|\overline{V_a}-\overline{V_p}\right|+\frac{\overline{F_{contact}}}{\Omega_p\cdot\rho_p},\\ \frac{d_p\overline{S_p}}{dt}=\overline{V_p},\\ \frac{d_p}{dt}=\frac{\partial}{\partial t}+\overline{V_p}\cdot\overline{\nabla},\\ \overline{F_{contact}}=\begin{cases}\overline{F_n}+\overline{F_t}, & \overline{S_{pA}}=\overline{S_{pB}},\\ 0, & \overline{S_{pA}}\neq\overline{S_{pB}}.\end{cases}\end{cases} \quad (21)$$

The solution to the system of differential equations (21) is the trajectory of the flight, the vector of speed and acceleration of particles, which make it possible to determine the location of the particles at any time.

The above system of differential equations underlies the physical-mathematical apparatus of the numerical modeling of the specified process.

5. 3. Numerical modeling of the operational process of a continuous flow mixer

The system of differential equations of the process of the movement of particles of loose material in an airflow (1) is not solved by analytical methods in a general case. Studies [23–25] suggest solving such systems by a finite-element method, which is implemented via simulation in the CAD/CAM/CAE systems. The simulation process itself can be executed using different approaches [26] but the most widespread in recent times are the models of perfect displacement and perfect mixing [27, 28].

The strategy of the comprehensive system analysis of a physical-mechanical system implies a qualitative analysis at the initial stage. In this case, two levels of the hierarchy of the physical-mechanical effects and phenomena are distinguished for the mixing process:

– the set of physical-mechanical phenomena in the elementary volume (micro-level);

– the set of physical-mechanical phenomena in the volume of the entire apparatus (macro-level).

Among the modern methods of computer simulation of the physical and technological processes, of particular interest are the methods based on the concept of the discrete representation of a substance – the method of particle dynamics and the method of discrete elements.

A discrete-element method can be considered as a generalization of the finite-element method. When modeling the process using a finite-element method, the initial positions, the speeds of particles and airflow are set. Then, based on these initial data, as well as the assigned physical laws of contact interaction, one calculates the efforts acting on each particle at each time interval. The resulting force is calculated for each individual element, and a Cauchy problem is solved for the selected period, the result of which is the initial data for the next step. The following models were chosen as the physical models for numerical modeling: a k–ε model of the turbulence of the separated current, a field of gravity, a model of real gas by Van der Waals, a model of discrete elements, a model of multiphase interaction [29–32]. The discrete-element method is based on the laws of pulse preservation and the moment of pulse for the Lagrange models of the multiphase environment. However, to build a physical-mathematical model, it is necessary to accept the assumption that the particles are represented in the form of identical ellipsoids with a predefined density and effective diameter.

We shall construct a physical-mathematical model of the process of continuous flow mixing of loose materials using the software package Star-CCM+ (Fig. 2, 3). The resulting physical-mathematical model of the process of continuous flow mixing of bulk materials makes it possible to determine the structural and technological parameters for a continuous flow mixer depending on the physical and mechanical properties of components at the optimal qualitative, quantitative, and energy indicators of the mixing process.

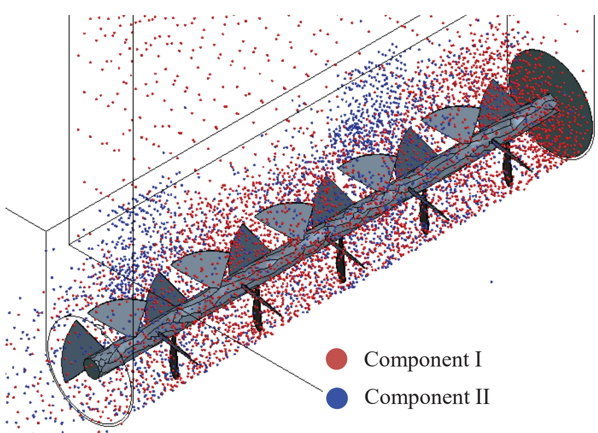

Fig. 2. 3D modeling of the process of continuous flow mixing of loose components using a continuous flow mixer

We shall consider the example of the process of mixing the components of a forage mixture whose physical-mechanical properties are as follows [33–35]:

– for component I (stem feed): Poisson coefficient, 0.26; Young's module, 0.8 MPa; density, 700 kg/m^3; rest friction coefficient, 0.9; normal recovery coefficient, 0.5; the tangent recovery coefficient, 0.5; roll resistance coefficient, 0.3; the effective diameter of a stem feed particle, 25 mm;

– for component II (concentrated feed): Poisson coefficient, 0,25; Young's module, 0.2 MPa; density, 400 kg/m^3; rest friction coefficient, 0,7; normal recovery coefficient, 0,6; the tangent recovery coefficient, 0.6; roll resistance coefficient, 0.5; the effective diameter of a concentrated feed particle, 2 mm.

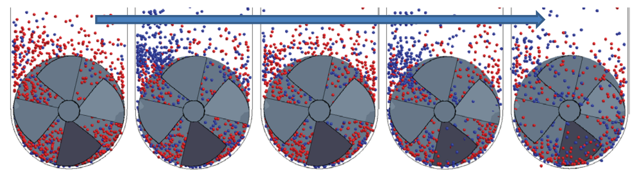

Fig. 3. Transverse cross-sections of the continuous flow blade mixer

The medium's properties that meet normal conditions [29, 32, 33] were as follows: the medium, air; dynamic viscosity, $1.85508 \cdot 10^{-5}$ Pa·s; the turbulent Prandtl number, 0.9; the acceleration of free fall, 9.8 m/s^2; temperature, 293 K; pressure, 101,325 Pa. The size of the simulation grid cell was 0.001 m.

For the theoretical modeling of the process of continuous-flow mixing, the following structural parameters of the continuous flow mixer were adopted (Fig. 4):

– the number of unloading windows of component II – 2 pcs.;
– the length of unloading windows – 250 mm;
– the width of unloading windows – 60 mm;
– the length of the blade mixer – 2,000 mm;
– the diameter of the blade mixer – 400 mm.

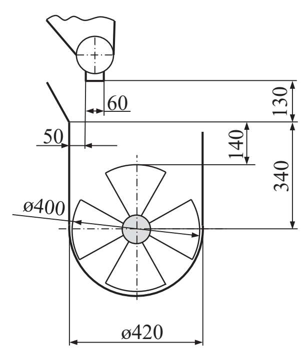

Fig. 4. Structural parameters of a continuous flow mixer

The simulation was carried out in accordance with the adopted full-factor experiment plan (81 experiments), which makes it possible to determine a regression equation of the second order [30–32]. The following factors were accepted: the rotation frequency of the mixer (n), the angle of attack of the mixer's blades (α), the feed performance of component I (Q_1), the feed performance of component II (Q_2). The levels and significance of the theoretical research factors are given in Table 1.

The adopted criteria for optimization are the homogeneity of the mixture θ and the concentration of component I in the mixture C_1.

It should be noted that the mixer was divided into 10 zones (Fig. 5), in each of which we determined the above optimization criteria. This allowed us to observe the dynamics of the process of mixing components.

Table 1

Factors of theoretical research

Factor variance level	Factor			
	Mixer rotation frequency n, rpm	Mixer blade angle of attack α, °	Feed performance of component I Q_1, t/h	Feed performance of component II Q_2, t/h
Upper level (+)	250	65	24	4.8
Basic level (0)	175	45	18	4.2
Lower level (–)	100	25	12	3.6
Variance interval	75	20	6	0.6

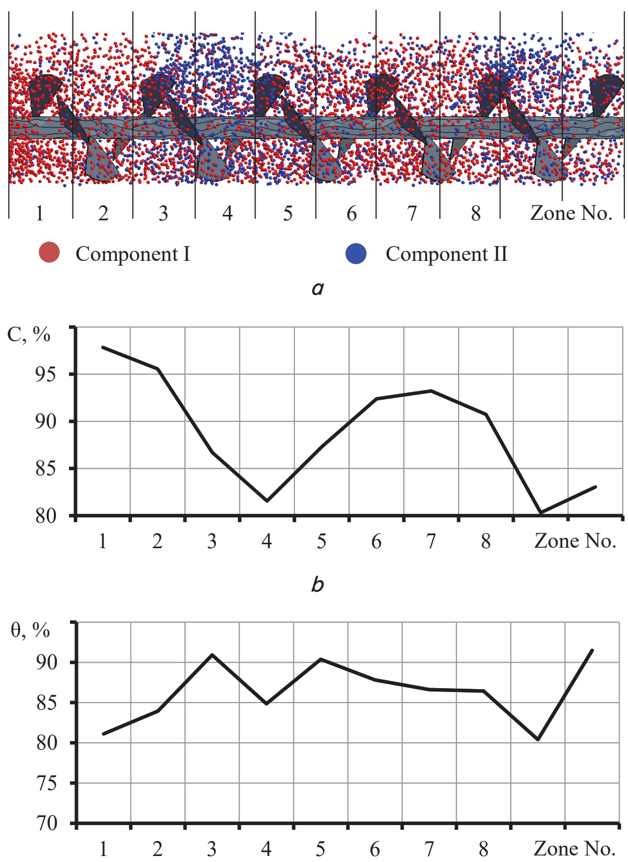

Fig. 5. Results of numerical modeling for each zone of the continuous flow mixer at $n = 175$ rpm, $\alpha = 45°$, $Q_1 = 18$ t/h, $Q_2 = 4.2$ t/h: *a* – graphical visualization of the process of mixing loose components; *b* – the dependence of mixture homogeneity θ; *c* – concentration of component I in the mixture C_i

The mixture homogeneity θ is determined from the following formula:

$$\theta = 1 - \frac{100}{C_0}\sqrt{\frac{\sum_{i=1}^{n}(C_i - C_0)^2}{n-1}}, \%, \quad (22)$$

where C_0 is the specified concentration of component I in the mixture, %:

$$C_0 = 100\frac{Q_1}{Q_1 + Q_2}, \quad (23)$$

C_i is the concentration of component I in the i-th zone of the mixer, %; n is the number of mixer zones.

For each experiment, according to the plan of the numerical experiment, we derived the dependences of the mixture homogeneity θ and the concentration of component I in the mixture C_i for each mixer zone. The results of experiments for the basic levels of factor variance are shown in Fig. 5.

Based on the results of modeling and subsequent processing of data employing the Mathematica software package (USA) using the feature «NonlinearModelFit», we derived a regression model of the process of the continuous flow mixing of feed components by a feed-dispensing mixer, which takes the following form:

$$\theta = -8.62329 + 0.14057n - 0.0003746n^2 + \\ + 1.34766Q_1 - 0.0311957Q_1^2 + 29.9269Q_2 - \\ - 3.4718Q_2^2 + 0.414694\alpha - 0.00400284\alpha^2. \quad (24)$$

According to the calculated correlation coefficient values ($R = 0.97$) and the Student criterion $t_{0.05}(81) = 1.99$, insignificant at the level of confidence probability above 95 % are the coefficients of the pairwise interaction of factors. The effect of the investigated factors on the homogeneity of mixing loose components is shown in Fig. 6, 7.

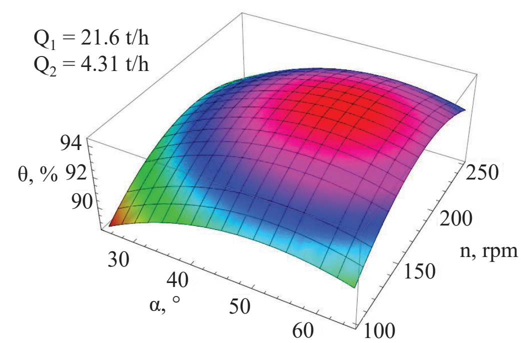

Fig. 6. Dependence of the mixture homogeneity θ on the rotation frequency n and the angle of attack α of the blade mixer

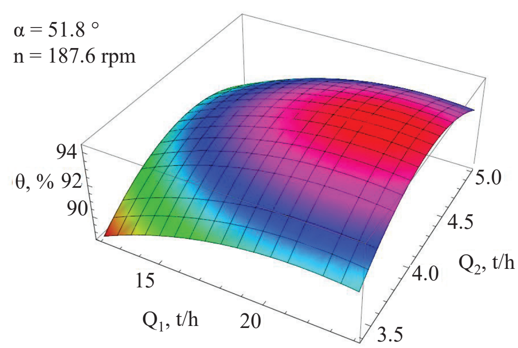

Fig. 7. Dependence of the mixture homogeneity θ on the feed performance of components I and II, Q_1 and Q_2

Accordingly, for the maximum value of the mixture homogeneity, which was 94.35 %, we obtained the optimal parameters of the investigated factors, namely: the frequency of mixer rotation, 187.6 rpm; the angle of attack of the mixer blades, 51.8°; the feed performance of component I, 21.6 t/h; the feed performance of component II, 4.31 t/h.

5. Discussion of results of the numerical modeling of the operational process of a continuous flow mixer

Because a loose material is represented as a system of particles of small sizes, it is necessary to determine their location at any time. The movement of these particles occurs due to the airflow created by the bladed working body, the force of gravity, and their direct contact interaction with the surface of the working body and between themselves. The built equations (1) to (21) make it possible to determine the trajectories of particle motion, speed, and acceleration. They underlie the physical-mathematical apparatus of the numerical modeling of the specified process.

During the numerical modeling of the process of continuous flow mixing using a finite-element method, the initial positions, the speed of the particles and airflow are set. In addition, the boundary conditions for the designed mixer are defined. Then, based on these initial data, the assigned physical laws of contact interaction, one calculates the efforts acting on each seed at each time interval. For each particle, the resulting force is calculated, and the Cauchy problem is also solved for the selected period, the result of which is the initial data for the next step. This procedure underlies the Star-CCM+ software package.

The result of numerical modeling is the established dependences of the dynamics of change in the concentration of mixture components and the mixture homogeneity in the zones of a continuous flow mixer depending on the examined factors (the rotation frequency n, the angle of attack α of the blade mixer, the feed performance of components I and II, Q_1 and Q_2). Fig. 5 shows that each examined factor accepts an optimal value. This is due to that at an excessive increase in the values of the examined factors there is a phenomenon of segregation of the mixture, which leads to the deterioration of its homogeneity.

The reported methodical aspects and research results could be used to determine the rational structural and technological parameters of a continuous flow mixer for any bulk components whose particles' effective diameter does not exceed 30 mm. In this case, the criterion for evaluating the process is the homogeneity of the mixture at the defined performance indicators.

A possible area to further advance our study is the development of the software that would automatically simulate the process of the continuous-flow mixing of loose components of different types. This could greatly expand the application scope of the proposed models.

7. Conclusions

1. Based on the analysis of techniques and technical means for mixing loose components, we have proposed a structural-technological scheme of the continuous flow mixer, which makes it possible to simultaneously mix and dispense the mixture by using a single bladed working body.

2. The result of the analytical study of a continuous flow mixing process is the constructed system of differential equations of the movement of particles of the components of bulk material in airflow under the influence of the surfaces of the working bodies of the designed mixer, which makes it possible to determine the location of particles at any time. The reported system of differential equations underlies the physical-mathematical apparatus of numerical modeling of the specified process employing the software package Star-CCM+.

3. The result of numerical modeling is the established dependences of the dynamics of change in the concentration of components in the mixture and the mixture homogeneity in the zones of the continuous flow mixer depending on the rotation frequency n, the angle of attack α of the blade mixer, and the feed performance of components I and II, Q_1 and Q_2. For the process of mixing a two-component feed mixture (stem and concentrated feed), we determined the optimal structural-technological parameters for a continuous flow mixer at which the homogeneity of the forage mixture is maximal (94.35 %), namely: the mixer rotation frequency, 187.6 rpm; the angle of attack of the mixer blades, 51.8°; the feed performance of the stem feed, 21.6 t/h; the feed performance of the concentrated feed, 4.31 t/h.

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