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MANUFACTURING ENGINEERING AND AUTOMATED PROCESSES

МАШИНОБУДУВАННЯ, АВТОМАТИЗАЦІЯ ВИРОБНИЦТВА ТА ПРОЦЕСИ МЕХАНІЧНОЇ ОБРОБКИ

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MATHEMATICAL MODELING OF MIXING-GRINDING OF FEED BY VERTICAL CONICAL SCREW

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Summary. *The modeling of a technical system is one of the first stages of cognition of its properties with the aim of further improvement and proper use. Mixing of solid components with their simultaneous grinding by a vertical conical screw working body is a complex workflow, which the authors analytically described through the main parameters of the working body and the modes of the process. The obtained generalized factors, due to which the number of factors from seven decreased to four. This makes it possible to reduce the amount of experimental work by eight times and provide effective results that evaluate the actual action of the factors acting on the selected performance criterion, the coefficient of unevenness in a complex, rather than separately. The resulting model allows you to make a qualitative and quantitative assessment of the process of operation of the feeder-mixer-grinder, to optimize its parameters of the working bodies and modes of operation.*
Key words: *mixer-shredder, model, dimensionless complex, dimensional analysis, vertical screw of variable diameter, similarity criteria.*

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Problem statement. Mixing is the process of uniformly redistributing components throughout the volume of materials to be mixed to a state of uniform mixture. Uniformity of mixture depends on physical and mechanical properties of components, design solutions and operating modes of mixers.

Insufficient study and complexity of the process and its wide prevalence [1] require additional research and formalization of the obtained empirical knowledge about the mixing process, in particular mixing and grinding of loose solid components of fodder mixtures for animals by feed dispensers-mixers with vertical screw working tools, and is equipped with knives.

Scientific research and practice has proved that feeding fodders in the form of a balanced mixture for all components is 15...30% more efficient than feeding of the same components separately [4, 5, 7, 8, 11, 12].

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Analysis of recent research and publications. Mixing accompanies work processes while meeting virtually all the needs of society.That is why mixing is investigated at both empirical and theoretical levels [1...4].

The research is based on physical and mathematical modeling [1...12]. When modeling the mixing of loose materials, the laws of Fick and the mathematical model of Navier-Stokes are used [1...12]. For each individual case of bulk material flow based on positions [21] researchers select typical mathematical models [1]: ideal displacement, ideal mixing, diffusion, collar or combination models. Each of these models has certain positive properties and sufficiently ensures its adequacy in the process of mixing loose materials. In general, the use of models makes it possible to describe mixing phenomena as a three-stage process system. At the first stage, the components are macropereterized, so-called convective separation in the internal volume of the mixer. At the same time, there is a high rate of reduction of the nonuniformity coefficient of the mixture. At the end of the stage in the working volume of the mixer there are macroblocks consisting of particles of one component. Convective mixing depends on the mixer design and its operating modes, which determine the nature of the flow of components in the mixer. The «macroperimetre» step takes place in conjunction with the «micro-displacement» or diffusion step, where the components penetrate through the boundaries of the macroblocks, reducing the heterogeneity coefficient of the mixture.

Increase of diffusion is defined by physicomechanical properties of components of mix. In parallel with convection and increasing-rate diffusion, a third mixing step takes place, the segregation step [9, 10], which degrades the non-uniformity coefficient of the distribution of the components of the mixture, that is, affects back the mixing process. As well as diffusion, segregation depends on the physical and mechanical properties of the components, and also depends on the design and operating modes of the mixer.

It should be noted that the results of the studies [1...12] mixing of loose non-uniform materials together with grinding with vertical screw conical working tools is very limited. A feature of the working tool design is that the screw rotates in the space limited by the walls of the loose mass [11]. Thus, the working member provides axial upward movement of components due to interaction of the components with the continuously forming limiting wall of the loose mass. Modern feed dispenser-mixer is equipped with perfect working tools with high resistance of cutting tools and their minimum power consumption [17, 18].

Purpose, objectives and methodology of research. The purpose of this work is to investigate the force and kinematic effects of component flux particles during mixing using mathematical and physical modelling.

The object of the study is a technological feed mixing system, in which the production means is a vertical mixer-grinder with a variable diameter of a screw with reinforced knives, and the object of the study is components of a balanced mixture with different physical and mechanical properties.

To achieve the goal of the research, we use a simulation method that will make it possible to establish the regularity of the process between the determining and defining criteria. This problem refers to physical ones, in which there is no fundamental physical law regulating the process, in this case mixing with grinding solid materials with different physical and mechanical properties (task of the second kind) [14] We choose independent factors and function – coefficient of non-uniformity of distribution of components We define initial conditions and express all factors through mixing time, function and its derivative [13]. Make the differential equation behind the system operation process We find a solution of general and separate parts and analyze the obtained result Thus we examine the mixing process and necessary kinematic parameters of the mixer-grinder.

In order to simplify and solve the obtained dependencies, we give differential equations in the criterion form according to the rule of integral analogues [6, 15].

This reduces the number of variables, reduces complexity, and increases the overall description of the physical mixing process.

The technique of the integral analog rule is that we remove the communication symbols between the members of the equation (symbols differentiation, integration and non-uniform functions); Replace all members of the equation with their integral counterparts; Divide all members of the equation (except for the removed non-uniform functions) into one of them and obtain n-1 similarity criteria; Complement the obtained system of similarity criteria with additional criteria in the form of arguments of non-uniform functions included in the equation, and convert the obtained similarity criteria into another more convenient form of recording by multiplying, dividing, increasing to a degree or multiplying by a constant coefficient, etc. [6, 15, 16].

In order to evaluate the influence of mixer parameters (geometric and kinematic) and physical and mechanical properties of fodder components on the mixing process, we make a model by analysis of dimensions [6, 16, 19]. Such a model describes in detail the internal mechanism of the mixing process [6, 15, 16] and optimizes the parameters and modes of the mixing process with a feed shredder, a mixer.

Thus the rule of integral analogues is used in the known formalized physical process described. In the absence of a description of the process, it is advisable to use the method of dimension analysis [6, 15, 16, 19]. The method of using the method of analysis of dimensions [6, 21] involves selection of independent variables affecting the object under study. For our subject of study this is as following:

$$\frac{d\nu}{dt} = \mathfrak{f}(V, \rho, \omega, l, \tau, \vartheta, S), \qquad (1)$$

where $\frac{d\nu}{dt}$ – is the leveling rate of the control component in the mixture, kg/s;
ν – mean square deviation of the number of reference component;
t – time of mixing, c;
V – volume of the hopper, m^3;
ρ – volume weight of the component of mixture, $\frac{\mathrm{kg}}{\mathrm{m}^3}$;
ω – screw speed, s^{-1};
l – screw step, m;
τ – tangential shear force of feed particles, Pa;
ϑ – the speed of movement of the components of the mixture, $\mathrm{m/s}$;
S – the area of the lateral surface of the screw coil, m^2.

When evaluating independent variables we take into account dimensional coefficients and physical constants.

Select a system of basic dimensions through which you can express all selected variables using the MLT system of basic dimensions.

After that, we note dimensions of independent most significant (strong) uncorrelated variables: $V, \rho, \omega, l, \tau, \vartheta, S$ and make up dimensionless combinations. For the main ones we select values V, ρ, τ.

We check the correctness of the compiled combinations, which are also called generalized parameters [6]. Bearing in mind that each combination is dimensionless, the number of combinations must be n-k, i.e. equal to the difference between the independent variables (n) and the selected number of basic values (k). Each variable has to occur in combinations at least once.

Research results. Process of mixing of loose components happens to crushing by the vertical screw of variable diameter with the knives placed on a tangent to its outer edges due to action gravitational (G = mg) and centrifugal ($F = \frac{mv^2}{R}$) forces and movement of components of mix along an axis ($S = vt$) up and their circulation in the horizontal plane of the bunker mixer.

Physical nature of the process of mixing loose materials based on the performed studies [1, ...12] and modern mathematical modeling techniques [13, 14, 23] allow to describe this process with a first-order differential equation with separating variables:

$$\frac{dv}{dt} = -kv(t) \qquad (2)$$

describing a whole class of such natural processes. Solving equation (2) expresses the function:

$$v = Ce^{-kt}, \qquad (3)$$

and taking into account initial and boundary conditions, the process function of this process system will be as follows:

$$v = 0{,}998e^{-0{,}5t} \qquad (4)$$

at probability $R^2 = 1.00$.

Equation (2) adequately describes the process of operation of the ideal mixing model examined herein by evaluating the mixing quality by the non-uniformity factor at the convective and diffusion mixing steps and at the beginning of the segregation step. The coefficient gradually and smoothly decreases and by t = 10 min is $v = 0{,}07$ (Fig. 1).

Not all known mathematical models have an analytical solution, which means that it is possible to investigate the process and optimize its optimal flow mode and determine the parameters of the technical system that implements the process. This is particularly the case with models [1, 5, 7] that describe a complex process. Therefore, for this case, it will be useful to convert differential equation [15] to criterion equation. For this purpose we use the rule of integral analogues. This rule makes it possible to approximate the error of the equation to the error of the original data, and if it is difficult or impossible to determine the physical value that is included in the criterion equation, to perform it by multiplication, division, power and the like. Get the equation derived from the first.

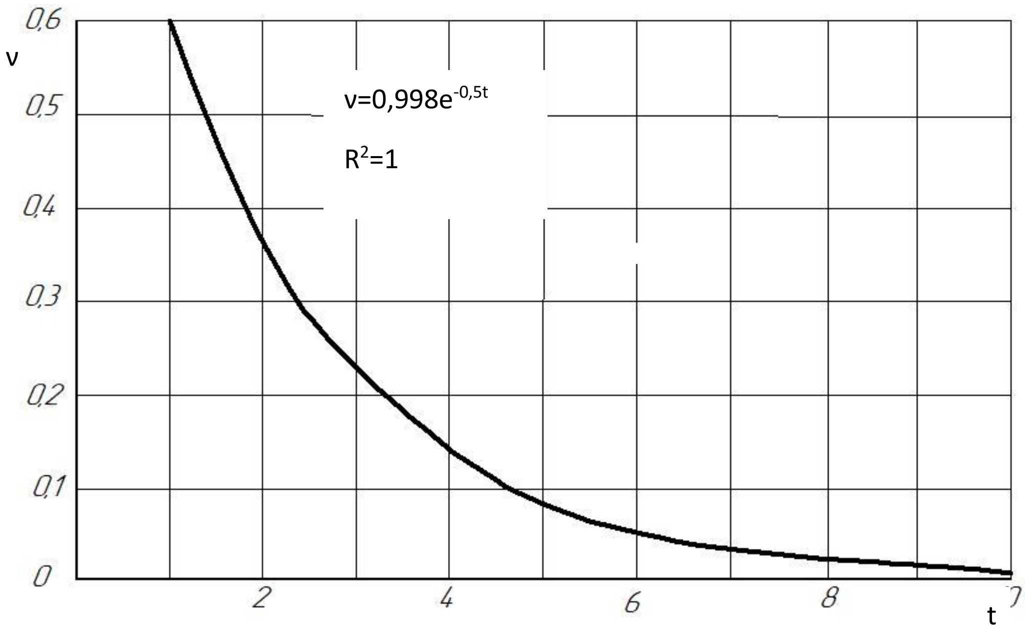

Figure 1. The dependence of the heterogeneity coefficient of the mixture in time

Such a mathematical model of ideal displacement [1, 5] is close to convective mixing:

$$\frac{dc}{dt} = -\nu \frac{dc}{dx}, \tag{5}$$

where c – where c is the concentration of the key component, %;
t – duration, c;
υ – linear speed of the mixture, m/s;
x – coordinate, m.

Having written down $\frac{dc}{dt} + \upsilon \frac{dc}{dx} = 0$ and having accepted [15] $\varphi_1 = \frac{dc}{dt}$ a $\varphi_2 = \frac{dc}{dx}$ and $\varphi_1' = \frac{c}{t}$ a $\varphi_2' = \frac{c}{l}$ and having divided the first member into the second, we will get $\pi = \frac{\upsilon t}{l}$, and rising to degree $a = -1$, will get $\pi' = \frac{l}{\upsilon t}$ – a criterion characterizing the rate of change of the concentration of the control component of the mixture.

Diffuse model corresponds to flow of mixture with piston motion:

$$\frac{dc}{dt} = -\nu \frac{dc}{dx} + D_L \frac{d^2c}{dt^2}, \tag{6}$$

where D_L – is the longitudinal mixing factor.

Write equation (6) as:

$$\frac{dc}{dt} + \upsilon \frac{dy}{dx} - D_L \frac{d^2c}{dt^2} = 0.$$

We accept $\varphi_1 = \frac{dc}{dt}$; $\varphi_2 = \upsilon \frac{dc}{dx}$; $\varphi_3 = D_L \frac{d^2c}{dt^2}$ and according to a technique [15] $\varphi_1' = \frac{c}{t}$; $\varphi_2' = \upsilon \frac{l}{t}$; $\varphi_3' = D_L \frac{t}{l}$. We will get $\pi_1 = \frac{\upsilon t}{l}$ i $\pi_2 = \frac{D_L t}{l^2}$.

Similarly in a two-parameter diffusion model:

$$\frac{dc}{dt} = -\upsilon \frac{dc}{dx} + D_L \frac{d^2c}{dt^2} + \frac{D_R}{R} \cdot \frac{d}{dR}\left(R \frac{dc}{dR}\right), \quad (7)$$

where D_R – is the cross-mixing coefficient;
R i x – are radial and axial coordinates of mixture, m.

After analytical transformations we get $\pi_1 = \frac{\upsilon t}{l}$; $\pi_2 = \frac{D_L t}{l^2}$; $\pi_3 = \frac{D_K t}{l^2}$.

Based on the objectives of the study and properties of the similarity criteria [6, 16] we evaluate the determining (field of flow rates of the mixture) and determining criteria and record the equation as a degree of monomial.

$$\pi_1 = \mathrm{A} \cdot \pi_2^{a} \cdot \pi_3^{в}, \quad (8)$$

where A – is the ratio of degrees;
a i в – degree indicators.

A, a i в we estimate by the results of the implementation of the plan of the complete factor experiment of type 2^2 [19].

The mechanism of operation that ensures the mixer operation process depends on its design [1]. Most of the dependencies currently known [1, 5] do not take into account the design parameters and modes of operation of the mixers, including with a vertical conical screw equipped with knives, which operates in a space limited by the walls of the loose mass. To draw up relations between parameters and modes of operation of this technological system and use the method of analysis of dimensions.

Conclusions and prospects for further research. For the first time, simulation of mixing-grinding process with different physical and mechanical properties of solid fodder components is performed by vertical conical screw with knives attached tangentially to its outer edges. Method of analysis of dimensions is used to obtain model describing internal mechanism of grinding and mixing process, which allows to optimize parameters and modes of working process of mixer-grinder feed dispenser. In order to obtain a model of general description of the process of mixing components, it is advisable to describe the process with differential equations, which will allow to assess adequacy of the obtained model, comparing it with existing models [1, 2, 3, 5, 7].

In addition, it is desirable to assess the technical and economic level of feed dispensers of mixer-grinders of world brands in order to determine a promising technical solution.

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МОДЕЛЮВАННЯ ДИФЕРЕНЦІАЛЬНИМИ РІВНЯННЯМИ РОБОТИ КОРМОРОЗДАВАЧА-ЗМІШУВАЧА-ПОДРІБНЮВАЧА

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Резюме. *Моделювання технічної системи є одним із перших етапів пізнання її властивостей з метою подальшого удосконалення та грамотного використання. Змішування твердих компонентів з одночасним їх подрібненням вертикальним конічним шнековим робочим органом є складним робочим процесом, який автори аналітично дослідили через основні параметри робочого органу та режими функціонування системи.*

Встановлено, що на даний час відсутній фундаментальний фізичний закон, який описує подрібнення та змішування твердих частинок з різними фізико-механічними властивостями. Вибрані кінематичні показники частинок – прискорення, швидкість та шлях в якості функцій. Незалежними факторами є нормальні зусилля на шнек та стінку, яка формується при роботі шнека, коефіцієнт тертя частинок суміші по витку шнека та по стінці суміші, кут підйому витка шнека та кут між вектором абсолютної швидкості частинки сипкої маси і віссю шнека, маса частинки. За постійну взято прискорення вільного падіння. Виразили змінні величини через незмінні фактори та отримали диференційне рівняння другого порядку. Дане рівняння розв'язували методом зниження порядку за допомогою введення допоміжної функції.

Модель дає можливість зробити якісне та кількісне оцінювання процесу роботи кормороздавача-змішувача-подрібнювача, оптимізувати параметри його робочих органів та режими процесу роботи на ЕОМ із використанням програми Mathcad.

Отримано в загальному вигляді проекції шляху, швидкостей та визначено нормальні сили від дії частинок на шнек та на сформовану стінку каналу шнека.

Ключові слова: *кормороздавач-змішувач-подрібнювач, модель, безрозмірний комплекс, аналіз розмірностей, вертикальний шнек змінного діаметра, критерії подібності.*

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