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RESEARCH OF THE PROCESS OF MOBILITY OF A MULTICOMPONENT MIXTURE PARTICLE BY A SPIRAL FLOW MIXER

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The article presents the results of the study of the process of moving a particle of a multicomponent mixture in a spiral flow mixer. The kinematics of particle motion in cylindrical coordinates are considered and the influence of design and operating parameters on the trajectory of movement is analyzed. The relevance of the study is due to the need to increase the efficiency of mass transfer processes, ensure uniform distribution of components in heterogeneous systems, and optimize the energy consumption of equipment. A mathematical model of the absolute and relative particle velocity is presented, taking into account rotational and translational motion. Special attention is paid to the influence of the geometry of the working body on the uniformity of mixing and the efficiency of the process. The article analyzes the influence of the geometry of the screw blades (diameter, spiral pitch, width and angle of inclination) on the circulation flows, mixing intensity and uniformity of dispersion of components. The theoretical provisions are confirmed by the data of modern experimental and numerical studies, as well as the results obtained by domestic and foreign scientists. In particular, it is proven that optimization of design parameters allows to significantly reduce the time to achieve homogeneity of the mixture without a significant increase in energy consumption.

The practical significance of the article lies in creating scientific prerequisites for developing methods for designing and modernizing spiral flow mixers, taking into account the specifics of processing various types of multicomponent mixtures. The developed particle motion scheme can be used for mechanical engineering and optimizing spiral mixer designs in the food and processing industries.

The conducted research expands the theoretical understanding of the dynamics of multicomponent mixtures and provides a scientific basis for the rational design of spiral-type mixers with optimized geometric and kinematic parameters. The implementation of the proposed model will allow for more accurate prediction of particle motion trajectories, reduction of dead zones in the working chamber, and enhancement of mixing uniformity.

***Key words**: spiral flow mixer, multicomponent mixture, mixing, particle kinematics, velocity, energy efficiency.*

Eq. 23. Fig. 5. Ref. 11.

1. Problem formulation

The study of the movement of materials in devices with helical-screw and helical working elements (blades) is devoted to the studies of famous scientists G. Delaplace, J.-C. Leuliet, V. Relandeau [1], who investigated the influence of geometric parameters of screw and ribbon impellers on circulation and mixing time. The numerical and experimental analysis of screw ribbon mixers is devoted to the works of Martin Robinson and PW Cleary [2]. Elias Huseby and Gautier Verhille [3] conducted modern studies on the sedimentation and motion of a helical ribbon in a viscous medium and discovered the physical interaction of rotation and displacement.

2. Analysis of recent research and publications

In the studies of O. Mykhaylova [4], optimization of screw mixer designs in small containers was performed with minimizing torque while ensuring maximum mixing uniformity using machine learning algorithms.

I. Gevko [5] investigated screw-conveyor mixers with a rotating casing, the use of which provides more intensive mixing due to the introduction of cyclic shock-oscillating loads; the characteristics of the optimal angular velocity of the casing to ensure the required mixing quality were established.

A comprehensive analysis of modern scientific publications shows that most existing studies focus on improving the efficiency of mixing through empirical optimization of blade geometry and rotational speed, while insufficient attention is paid to the kinematic modeling of particle trajectories in spiral-type mixers. Despite the achievements of researchers in defining the circulation zones and general flow structures, the interaction between rotational and translational particle motion in cylindrical coordinates remains underexplored, particularly for multicomponent, non-Newtonian systems. Moreover, many works emphasize the hydrodynamics of homogeneous fluids, while the heterogeneous nature of organo-mineral mixtures introduces additional complexity due to differences in particle density, shape, and moisture absorption.

3. The purpose of the article

The purpose of this study there are analysis of methods and means of drying of agricultural materials and their classification for the possibility of further implementation in practice of the most efficient, from an energy point of view, drying method.

4. Results and discussion

The process of mixing components of liquid organo-mineral fertilizers in ribbon-screw mixers is complex and depends on a number of factors that can be classified into three main groups: physical and mechanical properties of components of liquid organo-mineral fertilizers; technological and design parameters of mixers and kinematic parameters of the mixer.

The physical and mechanical properties of fertilizer components include:

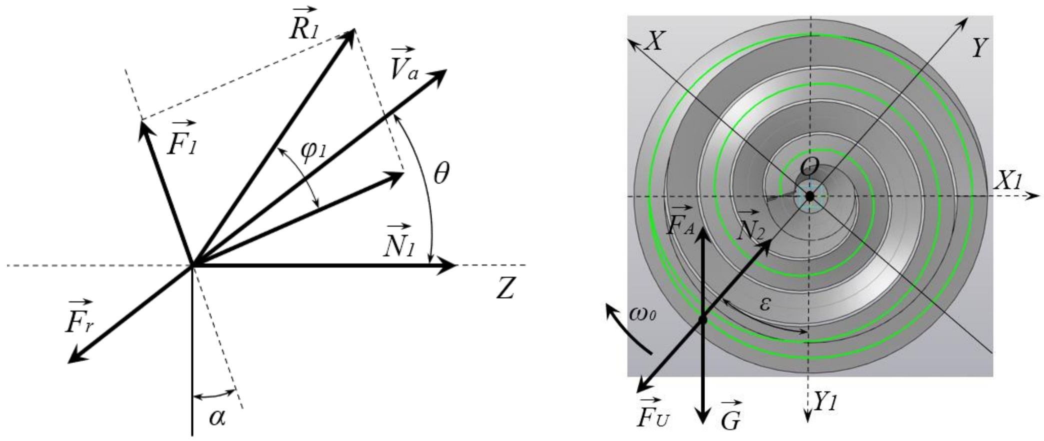
- density of liquid organo-mineral fertilizers (ρ_{lof}, kg/m³) - determines the mass of liquid per unit volume, which affects the flow rate and mixing dynamics;
- kinematic viscosity (ν, m²/s) - characterizes the fluidity of the liquid, affecting the resistance to the movement of filler particles;
- the equivalent particle diameter of the organo-mineral filler (d_{eq}, m) determines the size of the particles, which affects their behavior in the fluid flow.

These parameters affect the hydrodynamic characteristics of the mixture and determine the mixing efficiency.

Technological and design parameters include parameters related to the design of the mixer and the technological process:

- mass flow rate of liquid organo-mineral fertilizers (Q_m, kg/s) - determines the amount of material entering the mixer per unit of time;
- diameter (D_m, m) and mixer length (L_m, m) - affect the volume and geometry of the mixing zone;
- the number of turns of the outer and inner spirals (k_{ou}, k_{in}, pcs.) – determine the intensity of material movement;
- pitch of the outer and inner spirals (s_{ou}, s_{in}, m) - affect the speed of particle transport;
- the diameter of the outer and inner spirals of the mixer (D_{ou}, D_{in}, m) – determine the trajectory of particle movement;
- spiral width (b_s m) – affects the contact area between the spiral and the mixture;
- degree of filling (j) – determines the fraction of the volume occupied by the material;
- mixer volume (V_m, m³) – affects the capacity and mixing time;
- mixing time (t, s) – determines the duration of the process to achieve homogeneity of the mixture.

To build a model of the movement of particles and granules of organo-mineral fertilizers by a ribbon-screw mixer, the movement of a particle of the organo-mineral component of these fertilizers along the mixer with the simultaneous passage of the mixing process with water was considered. The axis Z of the ribbon-screw mixer is located horizontally, and the cross-section of the mixer is described in the coordinates XOY relative to the fixed coordinate system $X_1\ OY_1$. In addition to the gravitational force G, the normal reaction from the surface of the spiral and the mixer body, and the friction force along the spiral, the Coriolis force and the inertia force also act on the particle moved by the outer spiral of the mixer (Fig. 1):



a ***b***

Fig. 1. Diagram of forces acting on a particle moving along a helical ribbon: a – top view; b – cross-section

From the above graphic diagrams of vectors, to explain the direction of forces.

$$F_1 = f_1 N_1, \quad (1)$$

where f_1 – hydraulic coefficient of friction of the particle against the surface of the spiral and the body,

$$F_2 = f_2 \cdot N_2, \quad (2)$$

where f_2 – hydraulic coefficient of friction of the particle against the mixer body.

The Archimedean (buoyant) force and the hydrodynamic force of fluid resistance also act . Its direction is opposite to the gravitational force G:

$$F_A = \rho\ g\ V_h, \quad (3)$$

where ρ is the density of the mixture, kg/m ^{3}; g – acceleration of free fall, m/s^2; V_p – volume of the displaced particle, m^3 .

The hydrodynamic drag force F_{th} equal to:

$$F_{th} = \lambda \cdot S_{ca} \cdot \frac{\rho \cdot V_p^2}{2}, \quad (4)$$

where λ is the Darcy coefficient (hydrodynamic resistance); S_{ca} – average cross-sectional area of the particle, m^2; V_p – absolute velocity of the particle, m/s.

The coordinates of the vectors will depend on the local angle of inclination of the ribbon and the position of the particle on the spiral.

The coefficient of hydrodynamic resistance is chosen as a function of the Reynolds number (*Re*) according to the following:

$$\xi = f\,(Re). \quad (5)$$

We assume that the particle of the organo-mineral filler has a spherical shape, then the volume of the particle will be determined by the formula:

$$V_p = \frac{4}{3} \cdot \pi \cdot R_p^3, \quad (6)$$

where R_p^3 – radius of the organo-mineral filler particle, m.

The mass of the particle is:

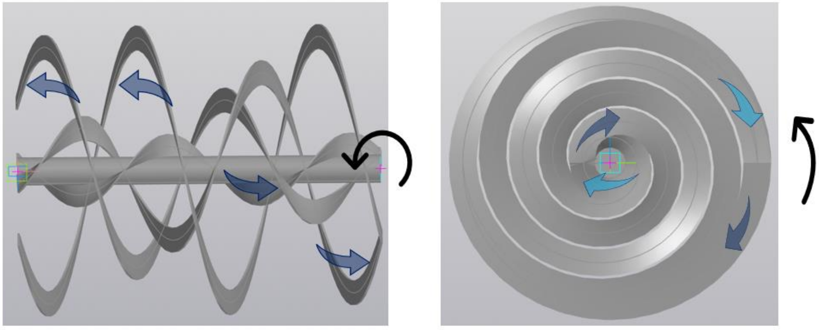
$$m = V_p \cdot \rho_p = \frac{4}{3} \cdot \pi \cdot R_p^3 \cdot \rho_p. \quad (7)$$

Instead of the centrifugal forces of the translational and relative motions and the Coriolis force - the centrifugal force F_{cf} the absolute motion of the particle:

$$F_{cf} = m\ R_{or}\ \omega_a{}^2, \quad (8)$$

where R_{or} – outer radius of the outer spiral, m; ω – angular velocity of absolute particle motion, rad/s.

In accordance with the recommendations [4, 5], the resulting force R_1 between the normal reaction from the screw surface N_1 and the friction force of the particle on the screw surface F_1 (Figure 2) was introduced and the dependence of the pressure drop along the length of the squeezing screw nozzle was taken into account [6].



a ***b***

Fig. 2. Directions of movement of liquid organo-mineral fertilizers during mixing by a multi-way belt during operation: a – top view; b – cross-section

The Z axis is directed along the axis of the multi-threaded spiral of the ribbon-screw mixer, and the cross-section of the mixer is in the coordinates of the XOY (Fig. 1). The system of differential equations of motion of a particle in a steady flow of a liquid, which moves taking into account all forces and assumptions at $\ddot{x} = 0$, $\ddot{y} = 0$ and $\ddot{z} = 0$ has the following form:

$$\begin{cases} N_2 - G \cdot cos\varepsilon + F_A \cdot cos\varepsilon - F_c = 0 \\ - G \cdot sin\varepsilon - F_2 \cdot sin\theta + F_A \cdot sin\varepsilon + R_1 \cdot sin\,(\alpha + \varphi_1) - F_r \cdot sin\theta = 0. \\ - F_2 \cdot cos\theta + R_1 \cdot cos\,(\alpha + \varphi_1) - F_r \cdot cos\theta = 0 \end{cases} \quad (9)$$

After transformations, the equation of motion of a particle in a ribbon-screw mixer was obtained:

$$\frac{m \cdot g \cdot sin\varepsilon - \rho \cdot g \cdot V\text{p} \cdot sin\varepsilon}{f2\left(m \cdot g \cdot cos\varepsilon - \rho \cdot g \cdot V\text{p} \cdot cos\varepsilon + m \cdot r \cdot \omega_a^2\right) + \xi \cdot \pi \cdot (R_a^2 \cdot \rho \cdot v_a^2)/2} = cos\theta \cdot tg\,(\alpha + \varphi_1) - sin\theta\,. \quad (10)$$

Denoting the left side of the equation by the variable N, we obtain the expression:

$$cos\theta \cdot tan\,(\alpha + \varphi_1) - sin\theta = N,$$

and we get:

$$sin\,(\alpha + \varphi_1 - \theta) = N \cdot cos\,(\alpha + \varphi_1).$$

According to the recommendations of T. Lercher [7, 8] on modeling the influence of design parameters on speed characteristics and productivity, and research by Grigoriev A.M. [9], the absolute angular velocity of the fraction of fertilizer components in a ribbon-screw mixer is determined from the expression:

$$\omega_a = \omega + \omega_{rel}. \quad (11)$$

The absolute velocity of a particle of fertilizer components is described by adding velocities in a moving (rotating) coordinate system:

$$v_a = \omega\, r + v_{rel}. \quad (12)$$

In cylindrical coordinates this takes the form:

$$v_a = (v_r) \cdot e_r + (\omega\, r + v_\varphi) \cdot e_\varphi + (v_z)\, e_z, \quad (13)$$

where ω – the angular speed of rotation of the working element of the mixer, rad/s; r – the radius of the particle's location relative to the axis of rotation; v_r, v_φ, v_z – projections of the relative velocity of the fraction of fertilizer components in the radial, tangential and axial directions, respectively.

Having performed the projection in the Cartesian axes $X\ Y\ Z$ under the condition $\omega = (0,\ 0,\ \omega)$, $r = (x, y, z)$, we have:

$$\omega\, r = (-\,\omega\, y,\ \omega\, x,\ 0). \quad (14)$$

We have the relative velocity in the cylindrical components (v_r, v_φ, v_z) (radial, tangential, axial). Moving to X, Y, Z we have the projections of the absolute velocity:

$$v_{a,x} = -\omega \cdot y + v_r \cdot cos\varphi - v_\varphi \cdot sin\varphi,$$
$$v_{a,y} = \omega \cdot x + v_r \cdot sin\varphi + v\varphi \cdot cos\varphi,$$
$$v_{a,z} = v_z.$$

The system of differential equations of motion of a particle moving along an internal spiral without touching the mixer body, taking into account all forces, will have the form:

$$\begin{cases} m\ddot{x} = - G \cdot sin\varepsilon + F_A \cdot sin\varepsilon + R_1 \cdot sin\,(\alpha + \varphi_1) - F_r \cdot sin\theta \\ m\ddot{y} = - G \cdot cos\varepsilon + F_A \cdot cos\varepsilon - F_c. \\ m\ddot{z} = R_1 \cdot cos\,(\alpha + \varphi_1) - F_r \cdot cos\theta \end{cases} \quad (15)$$

Further solution of the system of equations was carried out in a steady state mode, after transformations we obtained an expression that determines the angle:

$$\theta = \alpha + \varphi_1 - \arcsin\left[\cos(\alpha + \varphi_1)\cdot \frac{m\cdot g\cdot \sin\varepsilon - \rho\cdot g\cdot Vp\cdot \sin\varepsilon}{\xi\cdot \pi\cdot (R_a^2\cdot \rho\cdot v_a^2)/2}\right]. \tag{16}$$

In cylindrical coordinates *(r, φ, z)* the translational component is equal to:

$$V_{tr} = \omega\, r\, e_{\varphi}. \tag{17}$$

If a particle moves along a helical tangent with an elevation angle of

$$\beta = \arctan\left(\frac{p}{2\,\pi\cdot r}\right), \tag{18}$$

where p − spiral pitch.

Relative velocity along the tangent v_t:

$$v_a \approx e_r\cdot 0 + e_{\varphi}\,(\omega\cdot r + v_t\cdot \cos\beta) + e_z\cdot(v\,t\cdot \sin\beta) \tag{19}$$

The obtained expressions allow us to determine the values of absolute particle velocities and absolute particle angular velocities in a ribbon-screw mixer in a stationary mode.

When viscous fluids are moved in machines with helical-screw working elements, internal friction forces arise, which obey Newton's law:

$$\tau = \mu\, \partial_u / \partial_y, \tag{20}$$

where τ – tangential stress, Pa; μ – dynamic viscosity, Pa·s; ∂_u / ∂_y – velocity gradient in the direction normal to the shear plane.

The volumetric flow rate of the mixer can be determined through the mass flow rate:

$$Q_v = Q_m / \rho_{lic}. \tag{21}$$

where Q_m – mass flow rate of liquid organo-mineral fertilizers, kg/s; ρ_{lic} – density of the liquid, kg/m³.

To ensure a given weight flow rate of liquid organo-mineral fertilizers Q_m, kg/s at a known application rate and unit speed Q_{ar} (t/ha) and v (m/s) it is necessary to calculate the volume of the mixer of the components of liquid organo-mineral fertilizers is determined by the formula:

$$Q_m = Q_{ar}\, b\cdot z\cdot v, \tag{22}$$

where b – the width of the furrow for the liquid component of fertilizers, m; z – workers organs, pcs.

The volume of the mixer is determined by the formula:

$$V_{mix} = Q_m\, t\, j, \tag{23}$$

where t – mixing time, s; j – is the mixer filling factor, j = 0.75.

Calculations performed in the Mathcad 15 program allowed us to obtain the dependence graphs presented in the figures.

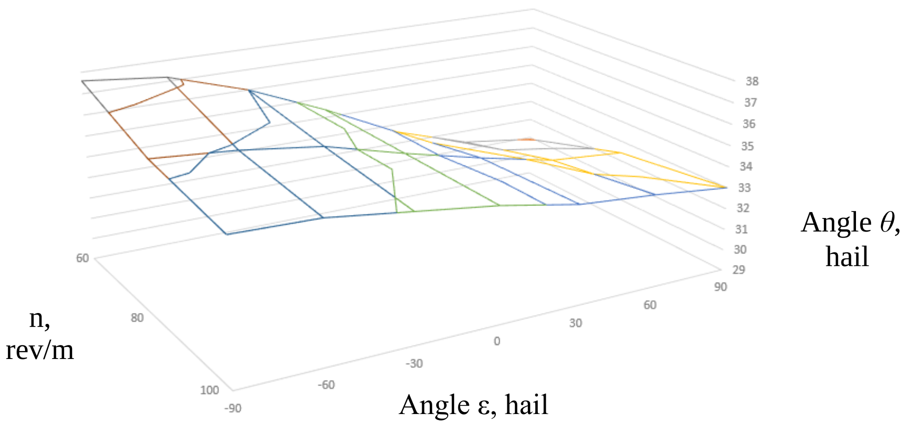


Fig. 3. Dependence of the angle θ on the position of the particle, determined by the angle ε

According to Figures 3 and 4, when the angle of rotation of the screws changes within 180˚, the particle moves along the cylindrical part of the mixer body at an angle in the range from 30,9˚ to 37,5˚. That is, the tangential component of the absolute velocity, which characterizes the peripheral velocity of the particle, has a rather large value for the considered parameters of the mixer, which is important for ensuring high-quality mixing of the components.

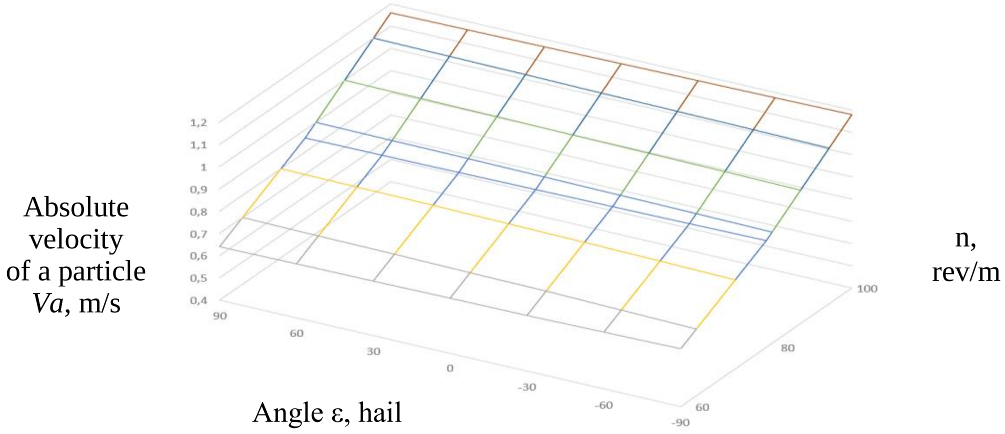


Fig. 4. Dependence of the absolute velocity of a particle v_a on the angle ε

According to the presented dependencies, graphs of the relation Q_m = ($Q_{\text{appl. rate}}$) and Q_m = (V) at the recommended application rate with the speed of movement of the unit v = 6.5 km/h when performing the technological operation of inter-row cultivation – $Q_{\text{appl. rate}}$ = 0.5 t/ha [10, 11] Figures 5,a and 5,b.

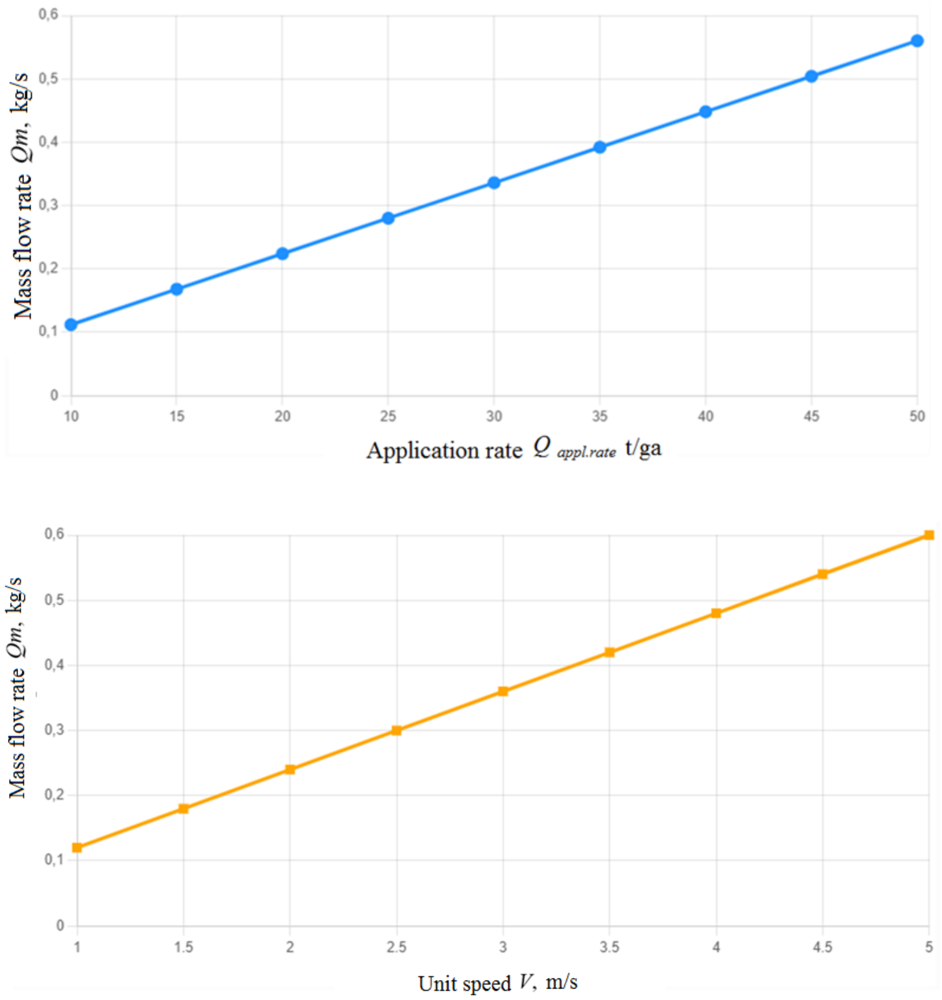


Fig. 5. Graphs of the dependence of the mass flow rate of liquid fertilizers on the speed of the tool: a) - $Q_m = f(Q_{nv})$; b) - $Q_m = f(v)$

The graphs examined show the dependence of the growth of Q_m with increasing application rate and movement speed.

To determine the mixing time, it is necessary to take into account the time of saturation of the mineral filler with moisture. To do this, we take into account the swelling coefficient, which depends on the hygroscopic moisture content of the fertilizer components, which determines the time required for high-quality mixing of all components of the multi-component mixture and determines the mixing efficiency.

The proposed approach to studying particle kinematics in a spiral flow mixer, taking into account the specified parameters, allows not only to improve the quality of mixing of multicomponent mixtures, but also provides a basis for the development of energy-efficient designs, which will contribute to reducing operating costs in industrial conditions.

5. Conclusion

The study of the process of moving a particle of a multicomponent mixture in a spiral flow mixer made it possible to establish the dependence of the kinematic characteristics of the movement on the design parameters of the working body and the modes of its operation. It was determined that the geometry of the screw blades, in particular the diameter, spiral pitch and angle of inclination, significantly affect the formation of circulation flows and the trajectory of particle movement, which in turn determines the intensity of the mixing process and the uniformity of the distribution of components. The proposed scheme with velocity projections in cylindrical coordinates made it possible to clearly display the relationship between the rotational and translational motion of the particle and created the prerequisites for further mathematical modeling of processes in the mixer.

The results obtained confirm the effectiveness of using spiral flow mixers for working with multicomponent systems and can be used to optimize their design and improve technological processes in mechanical engineering, agro-industrial, food and chemical industries.

An important practical result of the research is that the developed approach not only contributes to improving the quality of mixing, but also forms the basis for creating energy-efficient mixing devices that reduce operating costs in industrial conditions.

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ДОСЛІДЖЕННЯ ПРОЦЕСУ ПЕРЕМІЩЕННЯ ЧАСТКИ БАГАТОКОМПОНЕНТНОЇ СУМІШІ СПІРАЛЬНИМ ПОТОКОВИМ ЗМІШУВАЧЕМ

У статті представлено результати дослідження процесу переміщення частки багатокомпонентної суміші у спіральному поточному змішувачі. Розглянуто кінематику руху частки у циліндричних координатах та проведено аналіз впливу конструктивних і режимних параметрів на траєкторію переміщення. Актуальність дослідження зумовлена необхідністю підвищення ефективності масообмінних процесів, забезпечення рівномірності розподілу компонентів у неоднорідних системах, а також оптимізації енергетичних витрат обладнання. Наведено математичну модель абсолютної та відносної швидкості частки з урахуванням обертального та поступального руху. Особливу увагу приділено впливу геометрії робочого органу на рівномірність змішування та ефективність процесу. У статті проаналізовано вплив геометрії гвинтових лопатей (діаметр, крок спіралі, ширина та кут нахилу) на циркуляційні потоки, інтенсивність перемішування та рівномірність диспергування компонентів. Теоретичні положення підтверджуються даними сучасних експериментальних і чисельних досліджень, а також результатами, отриманими вітчизняними та закордонними науковцями. Зокрема, доведено, що оптимізація конструктивних параметрів дозволяє суттєво знизити час досягнення однорідності суміші без істотного збільшення енергетичних витрат.

Практична значимість статті полягає у створенні наукових передумов для розробки методик проектування та модернізації спіральних поточних змішувачів з урахуванням специфіки переробки різних видів багатокомпонентних сумішей. Розроблена схема руху часток може бути використана для машинобудування та оптимізації конструкцій спіральних змішувачів у харчовій та переробній промисловості.

Проведене дослідження розширює теоретичне розуміння динаміки багатокомпонентних сумішей та забезпечує наукову основу для раціонального проектування спіральних змішувачів з оптимізованими геометричними та кінематичними параметрами. Реалізація запропонованої моделі дозволить точніше прогнозувати траєкторії руху частинок, зменшити мертві зони в робочій камері та підвищити рівномірність змішування.

Ключові слова: *спіральний поточний змішувач, багатокомпонентна суміш, перемішування, кінематика частки, швидкість руху, енергоефективність.*

Ф. 23. Рис. 5. Літ. 11.

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