DETERMINATION OF THE PARAMETERS OF TRANSPORTING AND MIXING FEED MIXTURES ALONG THE CURVILINEAR PATHS OF TUBULAR CONVEYORS
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ВИЗНАЧЕННЯ ПАРАМЕТРІВ ПРОЦЕСУ ТРАНСПОРТУВАННЯ ТА ЗМІШУВАННЯ КОРМОВИХ СУМІШЕЙ НА КРИВОЛІНІЙНИХ ТРАСАХ ТРУБЧАТИХ КОНВЕЄРІВ

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ABSTRACT

The results of theoretical and experimental studies of simultaneous transporting and mixing the components of feed mixtures along the curvilinear paths of tubular conveyors are presented in this article. A mathematical model of the dependence of the change of elementary work performed while transporting the bulk material elementary mass along the curvilinear section is developed. Based on experimental researches, the technique of determining the technological parameters, which ensure the reduction of energy consumption while mixing bulk materials with the given quality of feed mixtures, is proposed. When considering the range of changes in the inner holes of the washers $d_h = 14…25$ *mm* and the angles of their position to the horizon $\alpha = 30^\circ…75^\circ$, the intensity of the material components passing-through and their consequent mixing increases with the increase of the value of the parameter d_h and the reduction of the angle α.

РЕЗЮМЕ

У статті представлено результати теоретичних і експериментальних досліджень одночасного транспортування та змішування компонентів кормових сумішей на криволінійних трасах трубчатих конвеєрів. Побудована математична модель, яка характеризує залежність зміни елементарної роботи, що виконується під час переміщення елементарної маси сипкого матеріалу по криволінійній ділянці. Запропонована методика та проведені експериментальні дослідження з визначення параметрів виконання технологічного процесу, які забезпечать зниження енерговитрат при змішуванні сипких тіл та задану якість кормових сумішей. Встановлено, що для діапазону зміни внутрішніх отворів шайб $d_h = 14…25$ *мм і кутів їх розташування до горизонту* $\alpha = 30^\circ…75^\circ$ *інтенсивність пересипання компонентів матеріалів та відповідно їх змішування зростає при збільшенні значення параметр* d_h *і зменшенні величини кута* α.

INTRODUCTION

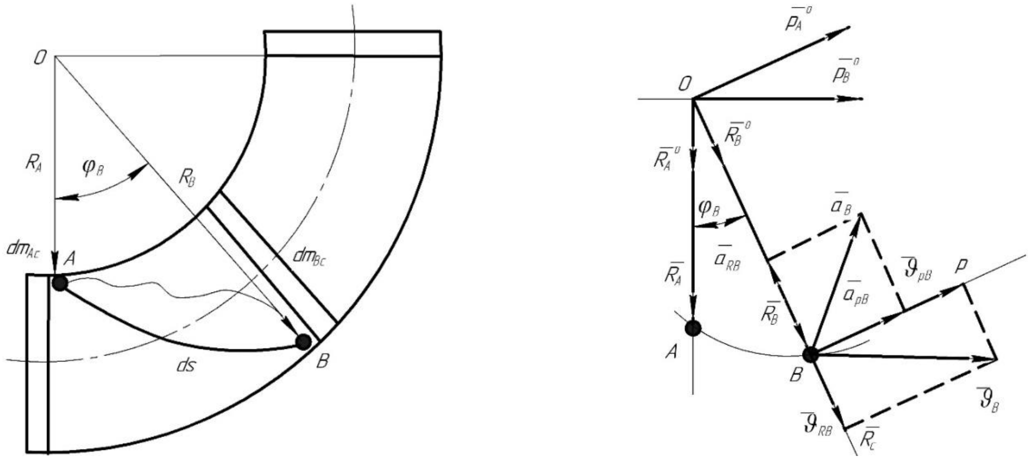
Based on the analysis of literature sources and experimental results of studying the processes of bulk materials transportation in closed jackets *(Loveikin V. et al., 2010; Lyashuk O.L. et al., 2015; Owen Philip J. and Cleary Paul W., 2010; Rogatynska O. et. al., 2015; Rohatynskyi R. M. et al., 2016; Roberts Alan W. and Bulk Solids, 2015)* the vast majority of screw conveyors are found to possess the limited functionality; therefore, they can be used only on short paths of material movement. The challenge is to minimize the degree of damage to agricultural materials by applying the elastic working bodies *(Loveikin V. and Rogatynska L., 2011; Rogatynska L.R., 2010)* or by combining the processes of shredding and transporting lump materials (e.g., root crops) for feed preparation *(Pankiv V.R. and Tokarchuk O.A, 2017)*. Due to such minimization of damages, the functional performance of transporters can be significantly improved. To increase the conveyors' performance, the material flow movement should be intensified by means of pneumatic devices *(Manjula E.V.P.J. et al., 2017; Naveen Tripathi et al., 2015; Baranovsky V.M. et al., 2018; Hevko R.B. et al., 2018)* and screw and tubular conveyors *(Haydl H.M., 1986;* Yao Y.P., et.al., 2014*)*. Many scientists have studied the methods of improving the operational and functional performance of screw and tubular conveyors, and the ways of reliable protecting their drive elements *(Hevko B.M. et al., 2017; Hevko R.B. et al., 2016; Hevko R.B. et al., 2017)* The objective of the present research is to ensure the reduction of energy consumption during simultaneous transporting and mixing bulk components of feed mixtures along the curvilinear paths of tubular conveyors.

MATERIALS AND METHODS

The material movement along the curvilinear section of the conveyor *(Hevko R.B. et al., 2017*, Fig. c) is considered as a case of the plane motion of the elementary mass dm_c (Fig.1a); the mass is located between the scraper spaces of the working body moving uniformly at the initial average velocity ϑ_c. The movement of the elementary volume dV_m along the curvilinear section of the path is considered in polar coordinates; the path's axis is at point *O* (Fig.1b). The scraper moves along the trajectory of the fourth section of the ring with an average diameter D_c, transporting the average elementary mass of the bulk material dm_c.

The position of the elementary mass centre of the bulk material dm_c in the vector form is determined by the polar coordinates $\vec{R}_c$ (radius-vector of the mass center movement dm_c) and φ_c (polar angle).

The elementary mass center of the material dm_{Ac} (Fig.1b) at the initial moment of motion at the rate ϑ_A (at t = 0) is at point *A*. Its position is determined by the radius-vector $\vec{R}_A$, where $\varphi_A = 0$. In time $t = t_B$, the elementary mass center of the material $dm_{Ac,}$ moves to point B under the action of centrifugal forces. The elementary mass center of the material dm_{Bc} is determined by the radius-vector and the polar angle φ_B.



a) b)

Fig. 1 - Analytical models: a - for determining the movement of the elementary mass center of the material along the curvilinear path; b - for determining the kinematic parameters of the bulk material movement

The motion equations of the elementary mass center of the bulk material dm_c in the polar coordinates for the case of the plane motion of the material body are deduced

$$\vec{R}_c = f_1(t); \quad \varphi_c = f_2(t) \tag{1}$$

For further analysis, the single vectors $\vec{R}_A^0$ and $\vec{R}_B^0$ are introduced (Fig. 1b); the vectors are directed in corresponding radii-vectors of corresponding points that characterize the corresponding elementary mass centres of the bulk material dm_{Ac} and dm_{Bc}, as well as the vectors $\vec{p}_A^0$ and $\vec{p}_B^0$, which are perpendicular to the corresponding radii-vectors $\vec{R}_A$ and $\vec{R}_B$ and directed towards the increase of the polar angle φ_B.

Applying the radial ϑ_{RB} and tangential ϑ_{pB} velocities, the magnitude and direction of the scalar velocity ϑ_B of the elementary mass center of the bulk material dm_{Bc} are determined

$$\vartheta_B = \sqrt{\left(\vartheta_{R_B}\right)^2 + \left(\vartheta_{p_B}\right)^2} = \sqrt{\left(\dot{R}_B\right)^2 + \left(R_B\dot{\varphi}\right)^2} = \sqrt{\left(\frac{dR_B}{dt}\right)^2 + R_B^2\left(\frac{d\varphi_B}{dt}\right)^2} \tag{2}$$

Directional cosines are defined by formulas

- between the directions of the vectors $\vec{\vartheta}_B$ and $\vec{R}_B^0$

$$cos\left(\widehat{\vec{\vartheta}_B, \vec{R}_B^0}\right) = \frac{\dfrac{d\vec{R}_B}{dt}}{\vec{\vartheta}_B} = \frac{\dot{R}_B}{\vartheta_B} = \frac{\dot{R}_B}{\sqrt{\left(\dot{R}_B\right)^2 + \left(R_B\dot{\varphi}\right)^2}} \tag{3}$$

- between the directions of the vectors $\vec{\vartheta}_B$ and $\vec{p}_B^{\,0}$

$$\cos\left(\vec{\vartheta}_B \overset{\wedge}{,} \vec{p}_B\right) = \frac{\vec{R}_B \dfrac{d\varphi_B}{dt}}{\vec{\vartheta}_B} = \frac{R_B\dot{\varphi}_B}{\vartheta_B} = \frac{R_B\dot{\varphi}_B}{\sqrt{\left(\dot{R}_B\right)^2 + \left(R_B\dot{\varphi}\right)^2}} \tag{4}$$

Differential equation for determining the vector acceleration $\vec{a}_B$ of point *B*, which specifies the position of the elementary mass center of the bulk material *dm*$_{Bc}$ in time *t* = *t*$_B$, is deduced

$$\begin{aligned} \vec{a}_B &= \frac{d^2R_B}{dt^2}\vec{R}_B^0 + \frac{dR_B}{dt}\frac{d\varphi_B}{dt}\vec{p}_B^0 + \frac{dR_B}{dt}\frac{d\varphi_B}{dt}\vec{p}_B^0 + R_B\frac{d^2\varphi_B}{dt^2}\vec{p}_B^0 - R_B\frac{d\varphi_B}{dt}\frac{d\varphi_B}{dt}\vec{R}_B^0 = \\ &= \ddot{R}_B\vec{R}_B^0 + \dot{R}_B\dot{\varphi}_B\vec{p}_B^0 + \dot{R}_B\dot{\varphi}_B\vec{p}_B^0 + R_B\ddot{\varphi}_B\vec{p}_B^0 - R_B\left(\dot{\varphi}_B\right)^2\vec{R}_B^0 = \\ &= \left[\ddot{R}_B - R_B\left(\dot{\varphi}_B\right)^2\right]\vec{R}_B^0 + \left(R_B\ddot{\varphi}_B + 2\dot{R}_B\dot{\varphi}_B\right)\vec{p}_B^0 \end{aligned} \tag{5}$$

Similar to the velocity vector $\vec{\vartheta}_B$, the acceleration vector $\vec{a}_B$ of point *B* is equal to the geometric sum of two vectors, in particular the first vector, which is located on the radius-vector of point *B* $\vec{R}_B = \overrightarrow{OB}$ and directed along it, and the second vector, which is perpendicular to this radius-vector.

The scalar value of the projection of the acceleration vector $\vec{a}_{R_B}$ directed along the radius-vector $\vec{R}_B$ of point *B*, or the scalar value of the projection of the radial acceleration of point *B* are determined by the formula

$$a_{R_B} = \frac{d^2R_B}{dt^2} - R_B\left(\frac{d\varphi_B}{dt}\right)^2 = \ddot{R}_B - R_B\left(\dot{\varphi}_B\right)^2 \tag{6}$$

and the scalar value of the acceleration vector $\vec{a}_{p_B}$ projection, which is perpendicular to the radius-vector $\vec{R}_B$ of point *B*, or the scalar value of the projection of the tangential acceleration of point *B* are equal to

$$a_{p_B} = R_B\frac{d^2\varphi_B}{dt^2} + 2\frac{dR_B}{dt}\frac{d\varphi_B}{dt} = R_B\ddot{\varphi}_B + 2\dot{R}_B\dot{\varphi}_B \tag{7}$$

Applying the radial a_{R_B} and tangential a_{p_B} accelerations, the magnitude and direction of the scalar acceleration of motion a_B of the elementary mass center of the bulk material *dm*$_{Bc}$ are determined.

$$a_B = \sqrt{\left(a_{R_B}\right)^2 + \left(a_{p_B}\right)^2} = \sqrt{\left(\ddot{R}_B - R_B\dot{\varphi}_B^2\right)^2 + \left(R_B\ddot{\varphi}_B + 2\dot{R}_B\dot{\varphi}_B\right)^2} \tag{8}$$

To operationalize the above provisions, the technological process of moving the elementary mass center *A* of the bulk material *dm*$_c$ is formalized as follows. The uniformly variable motion of the elementary mass center *A* of the bulk material *dm*$_c$ is supposed to be set by parametric equations with consideration of aerodynamic forces of air resistance, which is assumed as a quadratic dependence of the resistance forces on the motion velocity.

At the first stage of the research, the force analysis of moving the elementary mass center *A* of the bulk material *dm*$_c$ along the curvilinear trajectory from point *A* to point *B* is considered.

In Fig. 2, an equivalent model of forces arising during the movement of the elementary mass center *A* of the bulk material *dm*$_c$ along the curvilinear trajectory of the plane curve without the rolling friction action is shown. To find the total generalized force *Q*$_c$ acting on the elementary mass center *B* of the bulk material *dm*$_{Bc}$, a differential equation of particle motion is deduced

$$dm_{B_c}\frac{d\vartheta_B}{dt} = Q_c = dm_{B_c}d\vartheta_B = Q_c dt = 0 \tag{9}$$

where *Q*$_c$ is the total generalized force acting on the elementary mass center *B* of the bulk material *dm*$_c$ during its motion along the curvilinear trajectory from the initial position with the coordinates *A{0, 0}* to position *B {x*$_B$*, y*$_B$*}*. Taking into account the components of the forces acting on the elementary mass center *B* of the bulk material *dm*$_{Bc}$, the dependence is developed

$$dm_{B_c}\left\{p\left[\left(\frac{dR_B}{dt}\right)^2 + R_B^2\left(\frac{d\varphi_B}{dt}\right)^2\right] + \left[\frac{f}{R_B}\frac{d\vartheta_B}{dt} + g\left(f\cos\left(arctg\frac{dy}{dx}\right) - \sin\left(arctg\frac{dy}{dx}\right)\right)\right]\right\} = 0 \tag{10}$$

where *f* – friction coefficient; *g* – free fall acceleration.

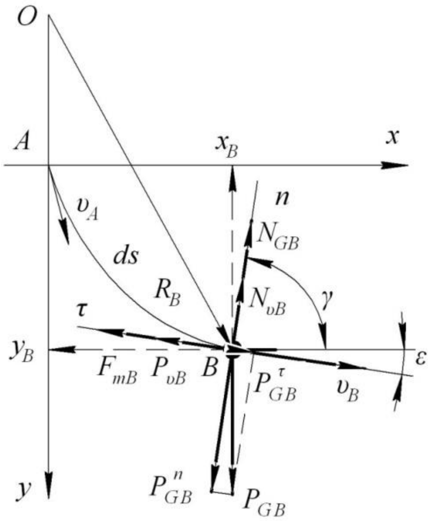


Fig. 2 - Analytical model for determining the dynamic parameters of the bulk cargo movement

The formula of an elementary work δA_{dm_c} that is consumed during the motion of the elementary mass of the bulk material dm_c along the curvilinear trajectory from the initial position with coordinates *A {0, 0}* to position *B {x_B, y_B}* is deduced

$$\delta A_{dm_{B_c}} = dV_{B_c}\psi \int_{o}^{x_B} \begin{matrix} p\left[\left(\frac{dR_B}{dt}\right)^2 + R_B^2\left(\frac{d\varphi_B}{dt}\right)^2\right] + \\ + \left[\begin{matrix} \frac{f}{R_B}\sqrt{\left(\ddot{R}_B - R_B\dot{\varphi}_B^2\right)^2 + \left(R_B\ddot{\varphi}_B + 2\dot{R}_B\dot{\varphi}_B\right)^2} + \\ + g\left[f\,cos\left(arctg\left(\dot{y}_x\right)\right) - sin\left(arctg\left(\dot{y}_x\right)\right)\right] \end{matrix}\right] \end{matrix} \frac{dx}{\sqrt{1+\dot{y}_x}} \tag{11}$$

where dV_{Bc} - elementary volume of the material at point *B*, м^3; ψ - specific mass of the bulk material, kg/m^3.

The deduced equation (11) is a deterministic mathematical model of the dependence of the change of the elementary work *δAdm$_c$* performed during the motion of the elementary mass of the bulk material *dm$_c$* along the *dc* arc in time *t$_B$* on the structural and kinematic parameters of the working body path, or the parameters of material movement with consideration of air resistance forces.

To minimize the elementary work performance during the motion of the bulk material along the curvilinear section of the working body path, the trajectory of the bulk material motion should be determined and optimized by integrating the above analyzed mathematical model (11). Furthermore, the minimum time of moving the bulk material along the curvilinear section of the working body path can be substantiated.

For experimental research, the working body of the scraper conveyor-mixer is design in the form of separate hinged sections (Fig.3). The design consists of a guiding jacket *1*. In the jacket, there are hinged scraper sections arranged in the form of a ring *2*, and hooks *3* and *7*. The ring part of the sections is covered by a disc *4* with a central inner opening *5*. The working body is driven by a gear wheel, which contacts with the conical surface of the disc. The components of the bulk material *6* are captured by disks and partially passed through the central openings; then, they are mixed into a solid mixture, which is transported to the unloading zone.

To determine the degree of passing the bulk agricultural materials through the washer holes at their various angular positions along the curvilinear sections of the conveyor-mixer, an experimental stand with a working body is developed in the form of washer scrapers with different inner holes of various diameters (Fig. 4). The stand was located vertically; its overall dimensions were horizontally - 500mm; vertically - 650 mm. Radius of knee position - 400 mm; its inner radius - 46 mm; the washer outer diameter – 45 mm.

The method for determining the time of the bulk material passing through the washer scrapers is as follows. In the curved knee, which consists of five sections, the bulk cargo weighing from 100 to 150 g was delivered; the coefficient of the space between scrapers is ψ = 0.6 ... 0.9. After opening the damper valve, the pressure of the cargo flow pushed the lever pedal, activating an electric timing device. When the flow stopped moving, the electric timing device was disconnected. The amount of cargo was weighed on electronic weighting machines.

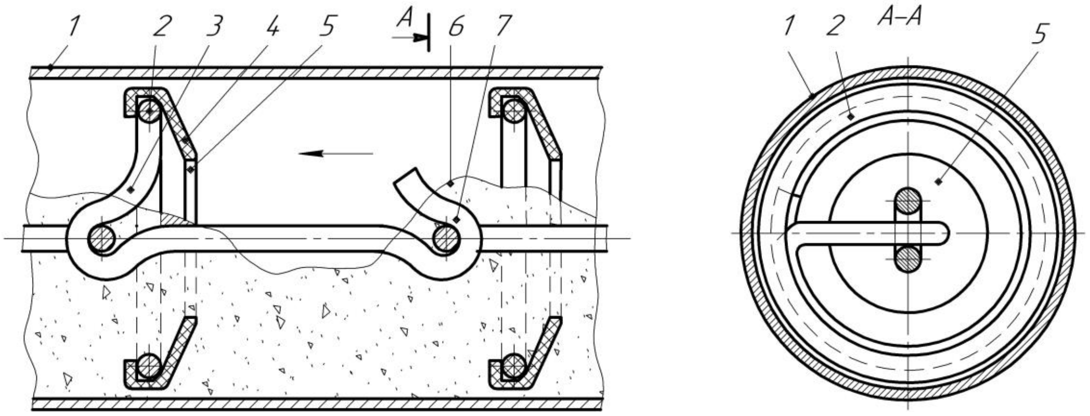
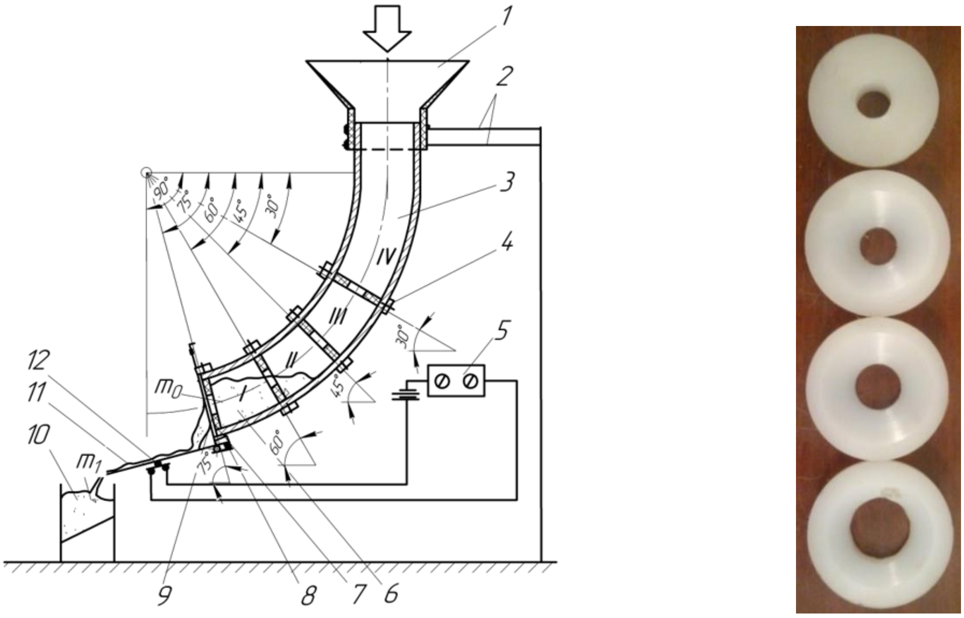


Fig. 3 - Working body of the scraper conveyor-mixer



a) b)

Fig. 4 - General view of the experimental stand (a) and washer scrapers with different inner holes (b)

1 - neck; 2 - stand; 3 - knee; 4 - a clamp; 5 - electric timing device; 6 - bulk material;
7 - scraper; 8 - spring of a lever; 9 - damper valve, 10 - capacity; 11 - lever pedal; 12 - contacts

In the knee sections, the washer scrapers were arranged at the angles: $\alpha_1 = 75°$; $\alpha_1 = 60°$; $\alpha_1 = 45°$; $\alpha_1 = 30°$. The inner holes in the washers varied within the range from 14 to 25 mm.

To provide the process of agricultural product transporting, a passing of the bulk material through the washer scrapers per second was calculated at their various angles of inclination to the horizon: $Q = m / t$, where m – cargo weight; t - time of passing.

RESULTS

The research results are presented on the graphic dependences shown in Figs. 5-6.

Experimental studies were conducted to define the maximum possible loading coefficient between the scraper spaces $\psi = 0.95$.

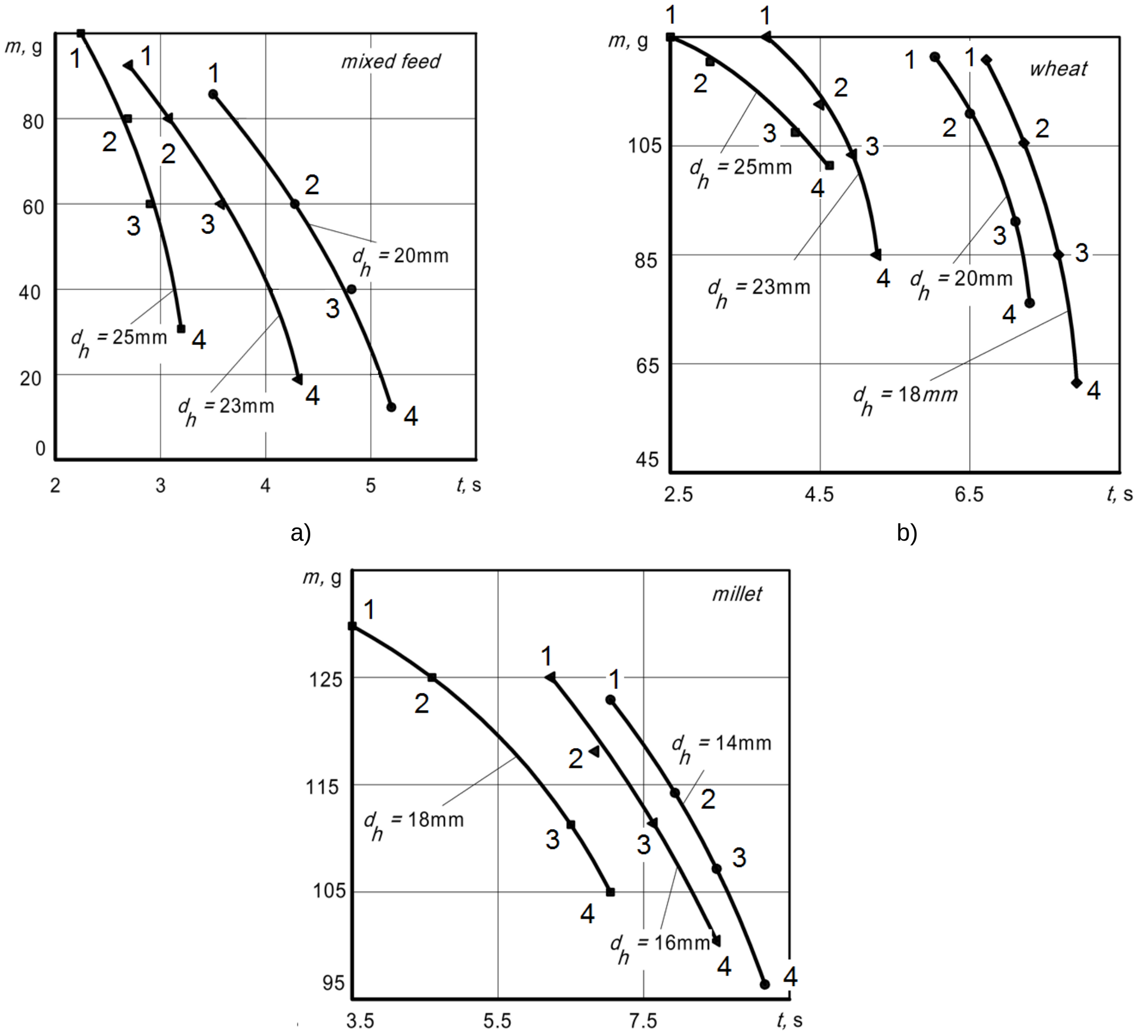
The graphic dependences of the mass m of the combined feed passed through the washer holes with diameters d_h = 20...25 mm on the moment of time t are shown in Fig. 5 a. The change in the hole diameter from 20 to 25 mm is found to cut time for the combined feed passing-through from 3.5 s to 2.25 s, providing the washer location angle to the horizon is $\alpha = 30°$. At the same time, respectively 84.6% and 96.1% of the combined feed are passed through in the space between the scrapers.

Providing the washer location angle α = 75 °,

The time of passing-through the combined feed is t = 4.9 s, provided d_h = 20 mm and α = 75 °. The time of passing-through the combined feed is t = 5.2 s, provided d_h = 25 mm α = 75°. At the same time, respectively, only 17.3% and 30.8% of the combined feed is passed through.

Thus, the angle of the washers' arrangement dominantly influences the process of the combined feed passing-through. Therefore, with the approach to the vertical section, the process of passing-through and consequent mixing the feed components significantly intensifies.

The wheat grain is passed through the washer hole of the diameter d_h = 18 mm (Fig. 5 b).



a)

b)

c)

Fig. 5 - Graphic dependences of the mass *m* of the mixed feed (a), wheat (b), and millet (c) passed through washer holes with different diameters d_h and their location angles to the horizon on the moment (1 – α=30°, 2 – α=45°, 3 – α=60°, 4 – α=75°) of time *t*

Thus, providing d_h = 18 mm, α = 30 °, and t = 6.8 s, 96% of wheat is passed-through. Providing d_h = 20 mm, α = 30 °, and 96% of passed-through wheat, the process takes 6 s.

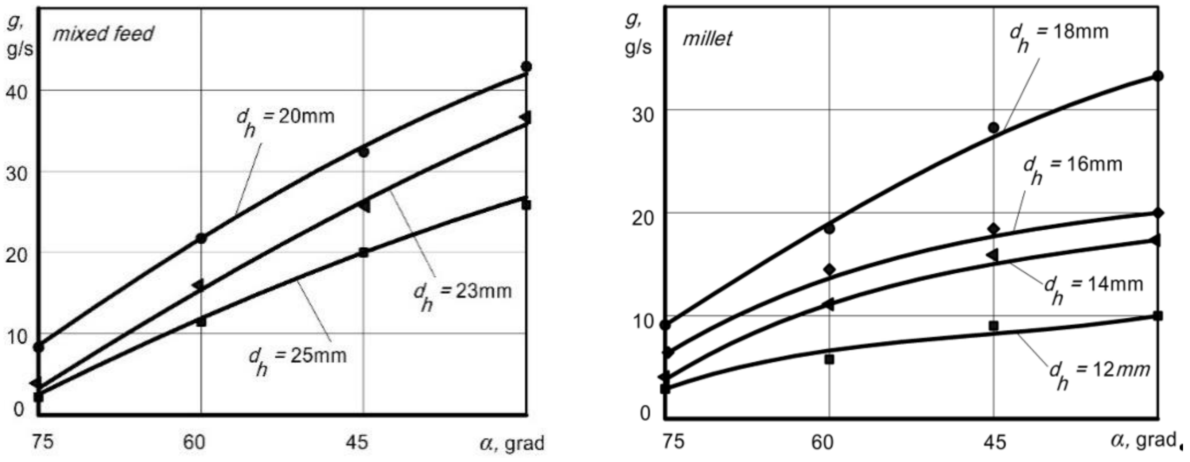
The diameter of the washer hole d_h increases from 23 to 25 mm, the time of wheat passing-through sharply decreases (if α = 30 °), respectively, from 3.7 s to 2.5 s. In both cases, the percentage of passed-through wheat is 98.4%.

At the same time, providing α = 75 ° and d_h = 18 mm, 47% of wheat is passed-through in time t = 8 s; and, respectively, providing α = 75 ° and d_h = 25 mm, 80% of wheat is passed-through in time t = 4.6 s.

Based on the analysis of the graphic dependencies shown in Fig. 5c, the scrapers with the diameter of the inner openings d_h = 14 and 18 mm are found more effective for transporting the millet and its further mixing with the appropriate concentrated additives. Such diameter values are proved to ensure the implementation of the technological process with the corresponding indicators, similar to the above considered cases.

The dependence of passing the combined feed and millet through different holes of scraper washers per second *g* (g/s) on their location angle to the horizon was experimentally developed.

The research results are presented in the form of graphical dependencies shown in Fig. 6.



a) b)

Fig. 6 - Graphical dependencies of passing *g* the combined feed (a) and millet (b) on the inclination angle α of the washer scrapers to the horizon per second

Based on the developed dependencies, the necessary structural parameters of the working bodies of the washer conveyor-mixer can be defined. To provide a certain degree of mixing feed mixtures, their main components should be considered.

CONCLUSIONS

Based on the known research results, a new technological model of simultaneous transporting and mixing the components of bulk cargo along curvilinear paths is proposed.

The process of moving the bulk material by scraper and washer working bodies along the curvilinear section of the technological path is simulated; the dynamic parameters of the bulk cargo movement are determined. The developed equation is a deterministic mathematical model of the dependence of the change of elementary work performed during the movement of the bulk material elementary mass. The model allows determining the minimum time of moving the bulk material along the curvilinear section of the working body path.

The dependences of the mass *m* of the combined feed passed through the holes of diameter d_h = 20 ... 25 mm on time *t* were analyzed. The change in the washer hole' diameter was found to cut time for passing the combined feed in time from 3.5 s to 2.25 s, providing the angle of washer location is $\alpha = 30^\circ$. Correspondently, the amount of passed combined feed in the space between scrapers is 84.6% and 96.1% of its total mass. In the range of changing in the holes and angles parameters, the washer location angle is considered to influence dominantly the process of the combined feed passing-through. Therefore, with the approach to the vertical section, the process of passing and mixing the components of feeds significantly intensifies.

The washer hole diameter d_h = 18 mm is found more applicable for transporting the wheat grain. Thus, providing d_h = 18 mm, $\alpha = 30^\circ$, and *t* = 6.8 s, 96% of wheat is passed-through; providing d_h = 20 mm, $\alpha = 30^\circ$, and 96% of passed-through wheat, the process takes 6 s. Then, providing $\alpha = 75^\circ$, d_h = 18 and 25 mm, the percentages of the passed wheat are, respectively, 47% at *t* = 8 s and 80% at *t* = 4.6 s.

The scrapers with the diameter of the inner holes d_h = 14 and 18 mm are found more applicable for transporting the millet and its further mixing with the appropriate concentrated additives. Such diameter values are proved to ensure the implementation of the technological process with the corresponding indicators, similar to the above considered cases.

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