INVESTIGATION OF THE BULK MATERIAL MOVEMENT KINEMATICS IN CONICAL SCREW CONVEYOR
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ДОСЛІДЖЕННЯ КІНЕМАТИКИ РУХУ СИПКОГО МАТЕРІАЛУ У ГВИНТОВОМУ КОНВЕЄРІ КОНІЧНОЇ ФОРМИ

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ABSTRACT
New design of the conic shape screw conveyor is presented in the paper and the results of theoretical investigations of the bulk material kinematic movement in this conveyor were shown. Dependencies for finding kinematic and operating parameters, which provide long-term stability of such mixers were found. Stand equipment for investigation of the transporting efficiency and mixing of the bulk materials have been developed and manufactured. Mechanic screw conveyors' properties at high frequency range of rotation, under smooth and sharp starting, rotation frequency change and reversing in the automatic regime have been studied taking advantage of the ALTIVAR 71 and multipurpose measuring system with accelerometers for finding dynamic loadings by PC. The results of experimental investigations of the efficiency depending on the screw pitch and every next turn, the screw conic surface inclination and the screw rotation frequency are presented. It will make possible to clear the process of the bulk materials transporting and mixing for every possible combination of the initial parameters. Specifically, increasing the increment of the cargo displacement radius per turn from 1 mm to 5 mm results in a velocity increase ranging from 1.28 times to 2.44 times. Moreover, increasing the inclination angle of the forming cone surface from 1 degree to 2 degrees provides a 1.18-fold increase in productivity, and varying the increment of the screw pitch from 0.004 m to 0.01 m per turn results in a 1.07-fold decrease in productivity. Increasing the rotation frequency of the conical screw α from 200 r/min to 500 r/min leads to a doubling of productivity.

РЕЗЮМЕ
У статті представлено нову конструкцію гвинтового конвеєра конічної форми, подано результати теоретичних досліджень кінематику руху сипкого матеріалу у вищезгаданому конвеєрі. Виведені залежності для визначення кінематичних та експлуатаційних параметрів, що забезпечують стабільну роботу таких змішувачів. Розроблено і виготовлено стендове обладнання для дослідження продуктивності транспортування та змішування сипких матеріалів, а також характеристик механічних гвинтових конвеєрів в широкому діапазоні частоти обертання, при плавному та різкому пуску, зміні частоти обертання і реверсуванні в процесі досліджень в автоматизованому режимі за допомогою перетворювача частоти серії ALTIVAR 71 та універсальної вимірювальної системи з акселерометрами для визначення динамічних навантажень з отриманням відповідних даних у ПК. Представлено результати експериментальних досліджень. продуктивності залежно від кроку шнека на кожному послідовному витку, кута нахилу твірної конічної поверхні шнека, частоти обертання шнека, які дозволять краще зрозуміти процес транспортування та змішування сипких матеріалів для кожної відповідної комбінації вхідних параметрів.Зокрема при збільшенні приросту радіуса переміщення вантажу на одному витку від 1 мм до 5 мм призводить до зростання швидкості вантажу від 1,28 рази до 2,44 рази. При цьому збільшення кута нахилу твірної конусної поверхні шнека від 1 град до 2 град забезпечує зростання продуктивності в 1,18 рази, а зміна величини приросту кроку шнека на кожному послідовному витку від 0,004 м до 0,01 м призводить до спадання продуктивності в 1,07 рази. Збільшення частоти обертання конусного шнека від 200 об/хв. до 500 об/хв. призводить до зростання продуктивності в 2 рази.

INTRODUCTION

The development of production and improvement of the transportation machines' efficiency can be achieved due to the creation of new and improvement of available screw conveyors with advanced technological capabilities. The application of such screw conveyors makes it possible to increase the accuracy of bulk material feeding and provide wide range of transportation efficiency.

Screw conveyors with variable geometry of the screw operating body and casing in the direction of material movement are designed to transport, mix and dose bulk materials and are usually installed at the beginning of the screw conveyor transport system *(Pysarenko et al., 1988; Zareiforoush et al., 2010; Loveikin and Rogatynska, 2011; Aulin et al., 2019; Zalutskyi et al., 2018; Trokhaniak et al., 2020)*. Due to the application of such conveyors, the accuracy of the minute feeding of bulk material increases *(Tian et al., 2018; Zaica et al., 2016; Zaica et al., 2020)*.

The use of variable speed drive increases the accuracy of bulk material dosing and ensures the achievement of wide range of transportation productivity. Screw conveyors with variable geometry of screw operating bodies are available in a wide range of cross-sectional dimensions, lengths, configurations and construction materials *(Hevko et al., 2021; Bulgakov et al., 2022; Bulgakov et al., 2023; Hud et al., 2023*). The SC loading area is usually completely filled with material under gravitation and connected to square, rectangular or cylindrical hopper by means of conical or straight neck (*Lyashuk et al., 2019*).

In the papers of *Haaker et al.,* (*1993), Zaica et al., (2020*), it was determined that the maximum amount of material supply Q_0 per revolution of the screw operating body is the value equal to or less than $0.75Q_{max}$, where Q_{max} is the material supply being equal to the maximum value of the ratio of the turn pitch to the turn diameter. Beyond this value, the increase of turn pitch does not provide the increase of material movement productivity. Also, based on theoretical analysis, it was found that the minimum ratio of the turn pitch to the turn diameter should be at least 0.25.

In the paper of *Yongqin (1997*), *Lyashuk et al., (2018), Lyashuk et al., (2022*), three main methods of increasing material capture in the feed direction are proposed: the use of screw operating body with variable turn pitch, with conical shaft of the screw operating body, and conical screw operating body.

In the paper of *Fernandez et al., (2009), Moorthi et al., (2022*), six different designs of screw operating bodies are investigated for the determination of their effect on the efficiency of bulk material transportation, uniformity of material capture from the hopper, and power consumption during transportation.

In the paper of *Roberts (1991), Ross and Isaacs (1961*) the interaction of bulk material particles with each other were investigated in two different ways. *Roberts, 1991,* and *Aulin et al., 2018,* studied the vortex motion of grains in the screw conveyor theoretically and experimentally. The measured free vortex motion was correlated quite accurately with the obtained vortex motion of the grains based on theoretical equations. However, during force vortex motion, the grain mass demonstrated behavior similar to that of the solid body, while significant hysteresis effect was obtained in the resulting material vortex profile.

In the paper of *Nilsson (1971*), the theoretical analysis was based on the pressures generated around the screw operating body in the axial plane. For screw conveyors, it is difficult to maintain high efficiency at significant rotation speeds of the screw operating because centrifugal forces prevent bulk material from entering the screw operating body. Such investigations and innovations will make it possible to increase the efficiency of bulk materials transportation by designing and substantiating the screw conveyor parameters.

On the basis of structural synthesis and experimental investigations (*Mondal, 2021; Lyashuk et al., 2023*), it was found that conical screw conveyors, compared to cylindrical ones, make it possible to improve the quality of mixing bulk material during its transportation. Therefore, it is necessary to investigate the kinematics of bulk material movement in conical screw conveyor.

MATERIALS AND METHODS

During the operation of conical screw conveyor, the coordinates of bulk material placement and its movement nature are determined by angular parameters θ_1 and θ (*Hevko et al., 2015; Lyashuk et al., 2019*). In order to determine the nature of load movement, let us consider the movement of the selected material volume in xyz coordinates (Fig. 1).

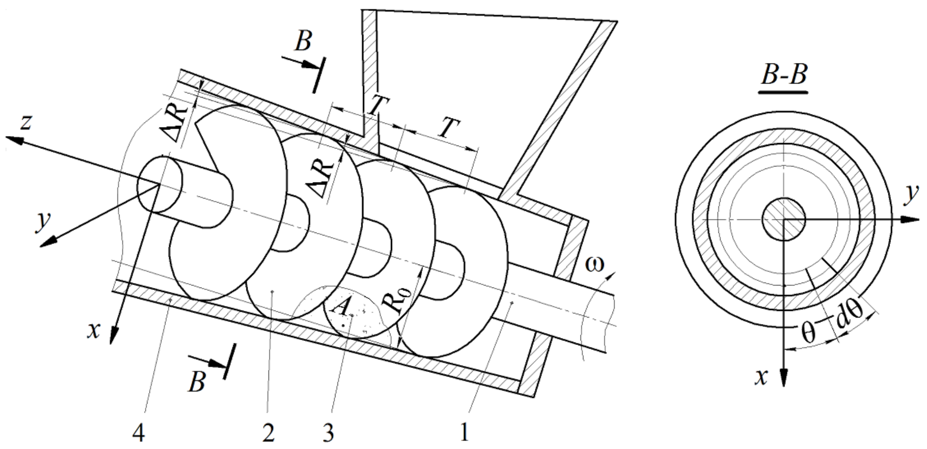

Fig. 1 – Calculation diagram of the movement of a selected load volume in the conical screw conveyor
1 – drive shaft; 2 – conical screw; 3 – selected load volume; 4 – conical casing

The high-speed mode of conveyor operation, where simultaneous transportation and mixing of load take place, is investigated. Under simultaneous contact of the selected material volume A with the surface of the conical screw and the conical surface of the fixed casing, its placement is determined by radial parameter R_0 and angular parameters θ_1 and θ (*Hevko et al., 2015; Rohatynskyi et al., 2015; Yu et al., 2022*).

Let us represent the change of the outer screw radius R and the inner casing radius by linear dependence, where the initial radius of the screw R_0 increases by ΔR for each subsequent turn.

One screw turn corresponds to the angular parameter $\theta_1=2\pi$, then the function of changing the screw radius and load movement radius can be written as follows:

$$R(\theta_1) = R_0 + \frac{\Delta R \theta_1}{2\pi}. \quad (1)$$

The increase in the screw radius and the load movement radius on one turn is:

$$\Delta R = \frac{R_{max} - R_0}{i}, \quad (2)$$

where R_{max} - maximum screw radius in the bulk material unloading area, m; i - is the number of turns involved in the movement of bulk cargo along helical trajectory.

The number of turns involved in the movement of bulk cargo along helical trajectory is determined by the following dependence:

$$i = \frac{\omega_v t}{2\pi}, \quad (3)$$

where ω_v - angular velocity of bulk material movement, rad/s; t - time of cargo movement from the loading area to the unloading area, s.

The time of cargo movement from the loading area to the unloading area is determined by the following formula:

$$t = \frac{2L\pi}{(\omega - \omega_v)T}, \quad (4)$$

where L - the length of the screw operating part, m; ω - the angular speed of the screw rotation, rad/s; T - the screw turn pitch, m.

Having substituted Eq. 4 into Eq. 3, is obtained:

$$i = \frac{\omega_v L}{(\omega - \omega_v)T}. \quad (5)$$

Then the increase in the screw radius and the load movement radius on one turn is:

$$\Delta R = \frac{T(R_{max} - R_0)(\omega - \omega_v)}{\omega_v L}. \quad (6)$$

In the parametric form, with sufficient approximation, the coordinates of the selected material volume A are determined by the following dependencies:

$$\begin{cases} x_A = \left(R_0 + \dfrac{\Delta R \theta_1}{2\pi}\right)\cos\theta; \\ y_A = \left(R_0 + \dfrac{\Delta R \theta_1}{2\pi}\right)\sin\theta; \\ z_A = \dfrac{T\left(\omega_1 t - \theta\right)}{2\pi}, \end{cases} \tag{7}$$

where: x_A, y_A, z_A – are material coordinates, m.

The equations of conical screw with constant pitch $T=2\pi C$ rotating with angular velocity ω in parametric form are as follows:

$$\begin{aligned} x_s &= \left(R_0 + \frac{\Delta R \theta_1}{2\pi}\right)\cos(\theta_1 + \omega t); \\ y_s &= \left(R_0 + \frac{\Delta R \theta_1}{2\pi}\right)\sin(\theta_1 + \omega t); \\ z_s &= c\theta_1 = (T/2\pi)\theta_1. \end{aligned} \tag{8}$$

The equation of the conical operating surface of the stationary screw conveyor casing looks like:

$$\begin{aligned} x_k &= \left(R_0 + \frac{\Delta R \theta_2}{2\pi}\right)\cos\theta_2 \\ y_k &= \left(R_0 + \frac{\Delta R \theta_2}{2\pi}\right)\sin\theta_2; \\ z_k &= u_2, \end{aligned} \tag{9}$$

where θ_2– angular parameter of the point of the screw casing surface, rad; u_2 – radial parameter of the point of the screw casing surface, m.

The projections of material movement velocity are found by differentiating the equations in Eq. 7:

$$\begin{cases} \dot{x}_A = \dfrac{\Delta R}{2\pi}\dfrac{d\theta_1}{dt}\cos\theta - \left(R_0 + \dfrac{\Delta R \theta_1}{2\pi}\right)\sin\theta\dfrac{d\theta}{dt}; \\ \dot{y}_A = \dfrac{\Delta R}{2\pi}\dfrac{d\theta_1}{dt}\sin\theta + \left(R_0 + \dfrac{\Delta R \theta_1}{2\pi}\right)\cos\theta\dfrac{d\theta}{dt}; \\ \dot{z}_A = \dfrac{T}{2\pi}\left(\omega - \dfrac{d\theta}{dt}\right). \end{cases} \tag{10}$$

The screw velocity is determined by the following dependencies:

$$\begin{cases} \dot{x}_{1s} = -\left(R_0 + \dfrac{\Delta R \theta_1}{2\pi}\right)\omega\sin\theta; \\ \dot{y}_{1s} = \left(R_0 + \dfrac{\Delta R \theta_1}{2\pi}\right)\omega\cos\theta; \\ \dot{z}_{1s} = 0. \end{cases} \tag{11}$$

Taking into account dependencies in Eq. 10 and Eq. 11, velocities of material movement relatively to the screw in the direction of axes x, y, z are found:

$$\begin{cases} \dot{x}_1 = \dfrac{\Delta R}{2\pi}\dfrac{d\theta_1}{dt}\cos\theta + \left(R_0 + \dfrac{\Delta R \theta_1}{2\pi}\right)\sin\theta\left(\omega - \dfrac{d\theta}{dt}\right); \\ \dot{y}_1 = \dfrac{\Delta R}{2\pi}\dfrac{d\theta_1}{dt}\sin\theta - \left(R_0 + \dfrac{\Delta R \theta_1}{2\pi}\right)\cos\theta\left(\omega - \dfrac{d\theta}{dt}\right); \\ \dot{z}_1 = \dfrac{T}{2\pi}\left(\omega - \dfrac{d\theta}{dt}\right). \end{cases} \tag{12}$$

The modulus of material velocity relatively to the screw and conical casing is determined by the corresponding formulas (*Rohatynskyi et al., 2015*):

$$\left|\dot{s}_1\right| = \sqrt{\dot{x}_1^2 + \dot{y}_1^2 + \dot{z}_1^2}; \quad (13)$$

$$\left|\dot{s}_2\right| = \sqrt{\dot{x}_2^2 + \dot{y}_2^2 + \dot{z}_2^2}. \quad 14)$$

Having substituted Eq. 12 into Eq. 13 and Eq. 10 into Eq. 14, taking into account that the material is in constant contact with the casing, after reductions, is obtained:

$$\left|\dot{s}_1\right| = \sqrt{\left(\left(R_0 + \frac{\Delta R \theta_1}{2\pi}\right)^2 + \frac{T^2}{4\cdot\pi^2}\right)\cdot\left(\omega - \frac{d\theta}{dt}\right)^2 + \frac{1}{4\pi^2}\Delta R^2\left(\frac{d\theta_1}{dt}\right)^2}; \quad (15)$$

$$\left|\dot{s}_2\right| = \sqrt{\left(R_0 + \frac{\Delta R \theta_1}{2\pi}\right)^2\left(\frac{d\theta}{dt}\right)^2 + \frac{T^2}{4\cdot\pi^2}\left(\omega - \frac{d\theta}{dt}\right)^2 + \frac{1}{4\pi^2}\Delta R^2\left(\frac{d\theta_1}{dt}\right)^2}. \quad (16)$$

The acceleration of the material is found by differentiating equations in Eq. 10:

$$\begin{cases} \ddot{x}_A = \frac{\Delta R}{2\pi}\frac{d^2\theta_1}{dt^2}\cos\theta - \frac{\Delta R}{\pi}\frac{d\theta_1}{dt}\sin\theta\frac{d\theta}{dt} - \left(R_0 + \frac{\Delta R\theta_1}{2\pi}\right)\cos\theta\left(\frac{d\theta}{dt}\right)^2 - \left(R_0 + \frac{\Delta R\theta_1}{2\pi}\right)\sin\theta\frac{d^2\theta}{dt^2}; \\ \ddot{y}_A = \frac{\Delta R}{2\pi}\frac{d^2\theta_1}{dt^2}\sin\theta + \frac{\Delta R}{\pi}\frac{d\theta_1}{dt}\cos\theta\frac{d\theta}{dt} - \left(R_0 + \frac{\Delta R\theta_1}{2\pi}\right)\sin\theta\left(\frac{d\theta}{dt}\right)^2 + \left(R_0 + \frac{\Delta R\theta_1}{2\pi}\right)\cos\theta\frac{d^2\theta}{dt^2}; \\ \ddot{z}_A = -\frac{T}{2\pi}\frac{d^2\theta}{dt^2}. \end{cases} \quad (17)$$

Let us consider the stable mode of cargo movement in high-speed conical screw conveyor-mixer, where the material moves along helical trajectory (Fig. 2) and for which the following conditions are provided at the steady-state mode:

$$\frac{d\theta}{dt} = \text{const} = \omega_v; \quad \frac{d^2\theta}{dt^2} = 0; \quad \frac{d\theta_1}{dt} = \text{const} = \omega_v; \quad \frac{d^2\theta_1}{dt^2} = 0.$$

For the provided conditions from Eq. 12, the projections of the material movement velocity relative to the conical screw on the axis of coordinate system xyz are found:

$$\begin{cases} \dot{x}_1 = \frac{\Delta R\omega_v}{2\pi}\cos(\omega_v t) + \left(R_0 + \frac{\Delta R\omega_v t}{2\pi}\right)\sin(\omega_v t)(\omega - \omega_v); \\ \dot{y}_1 = \frac{\Delta R\omega_v}{2\pi}\sin(\omega_v t) - \left(R_0 + \frac{\Delta R\omega_v t}{2\pi}\right)\cos(\omega_v t)(\omega - \omega_v); \\ \dot{z}_1 = \frac{T}{2\pi}(\omega - \omega_v). \end{cases} \quad (18)$$

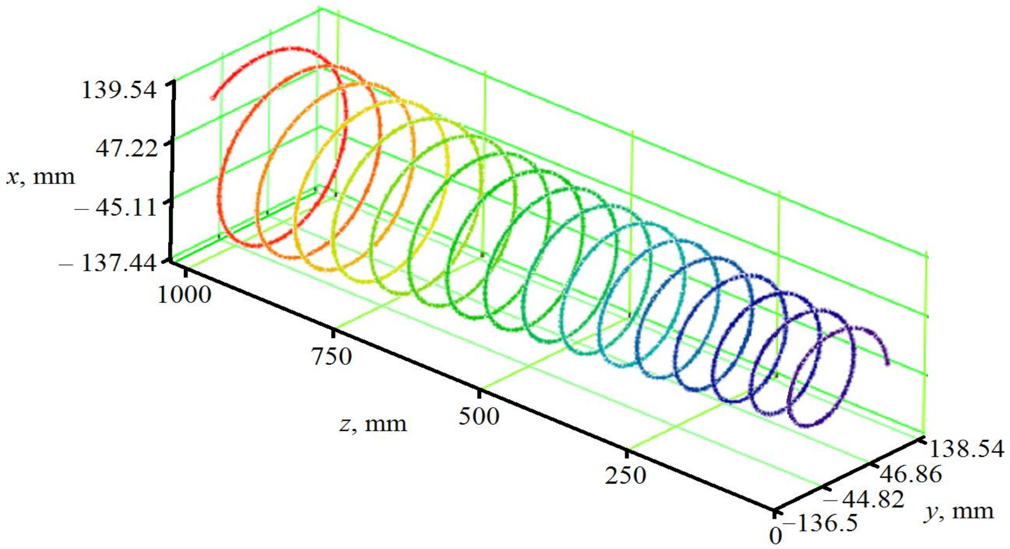

Fig. 2 – Chart of the bulk cargo trajectory in high-speed conveyor with the screw and conical casing:
R_0 = 75 mm; R_{max} = 140 mm, L = 1000 mm, ΔR = 3,97 mm, i = 16

Projections of the material velocity relatively to the conical casing on the axes of coordinate system xyz:

$$\begin{cases} \dot{x}_2 = \dfrac{\Delta R\omega_v}{2\pi}\cos(\omega_v t) - \left(R_0 + \dfrac{\Delta R\omega_v t}{2\pi}\right)\sin(\omega_v t)\omega_v; \\ \dot{y}_2 = \dfrac{\Delta R\omega_v}{2\pi}\sin(\omega_v t) + \left(R_0 + \dfrac{\Delta R\omega_v t}{2\pi}\right)\cos(\omega_v t)\omega_v; \\ \dot{z}_2 = \dfrac{T}{2\pi}(\omega - \omega_v). \end{cases} \tag{19}$$

The modules of the material velocity from Eq.15 and Eq.16 are determined by the following formulas:

$$|\dot{s}_1| = \sqrt{\left(\left(R_0 + \frac{\Delta R\omega_v t}{2\pi}\right)^2 + \frac{T^2}{4\cdot\pi^2}\right)\cdot(\omega-\omega_v)^2 + \frac{1}{4\pi^2}\Delta R^2\omega_v^2}; \tag{20}$$

$$|\dot{s}_2| = \sqrt{\left(\left(R_0 + \frac{\Delta R\omega_v t}{2\pi}\right)^2 + \frac{1}{4\pi^2}\Delta R^2\right)\omega_v^2 + \frac{T^2}{4\cdot\pi^2}(\omega-\omega_v)^2}. \tag{21}$$

The material acceleration is determined by Eq.17:

$$\begin{cases} \ddot{x}_A = -\dfrac{\Delta R\omega_v^2}{\pi}\sin(\omega_v t) - \left(R_0 + \dfrac{\Delta R\omega_v t}{2\pi}\right)\omega_v^2\cos(\omega_v t); \\ \ddot{y}_A = \dfrac{\Delta R\omega_v^2}{\pi}\cos(\omega_v t) - \left(R_0 + \dfrac{\Delta R\omega_v t}{2\pi}\right)\omega_v^2\sin(\omega_v t); \\ \ddot{z}_A = 0. \end{cases} \tag{22}$$

Based on Eq. 20, the graphs of changes in the velocity of the movement of material selected volume relatively to the screw in conical screw conveyor were constructed (Fig. 3, Fig. 4).

Based on the graphs in Fig. 3 and Fig. 4, it was found that the increase in ΔR of the cargo movement radius on one turn of the conical screw conveyor significantly affects the increase in the cargo speed, which contributes to the intensification of the mixing process. That is, the increase in the growth ΔR of the cargo movement radius on one turn from 1 mm to 5 mm results in the increase in the cargo speed from 1.28 times to 2.44 times.

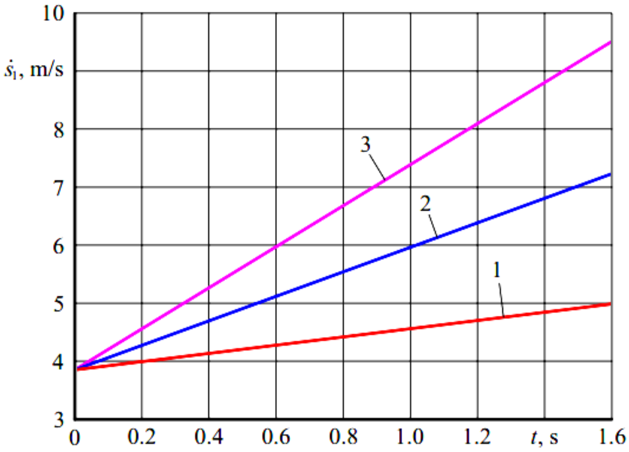

Fig. 3 – Chart of changes in the velocity of the movement of material selected volume relatively to the screw in conical screw conveyor over time R_0=75 mm:
1 – ΔR = 1 mm; 2 – ΔR = 3 mm; 3 – ΔR = 5 mm

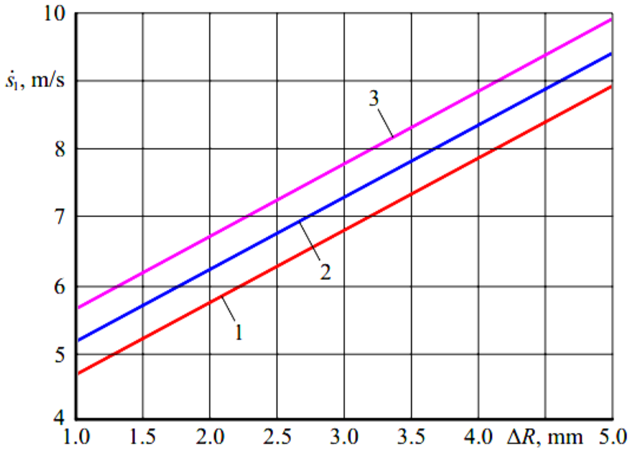

Fig. 4 – Chart of changes in the velocity of the movement of material selected volume relatively to the screw in conical screw conveyor from the increase in the cargo movement radius on one turn:
1 – R_0 =70 mm; 2 – R_0 = 80 mm; 3 – R_0 = 90 mm

RESULTS

In order to carry out experimental investigations, a special laboratory installation was designed and manufactured. It includes: multifunctional screw conveyor, replaceable conical-shaped casings, screws with variable turn pitch, screws with corrugated surface and variable pitch for mixing materials during transportation. The installation is shown in Fig. 5.

The installation structure features include the use of conical screw conveyor-mixer equipped with the casing with adjustable hole sizes designed to spill the material during transportation. It makes possible to increase the transportation efficiency by mixing bulk materials with simultaneous stirring.

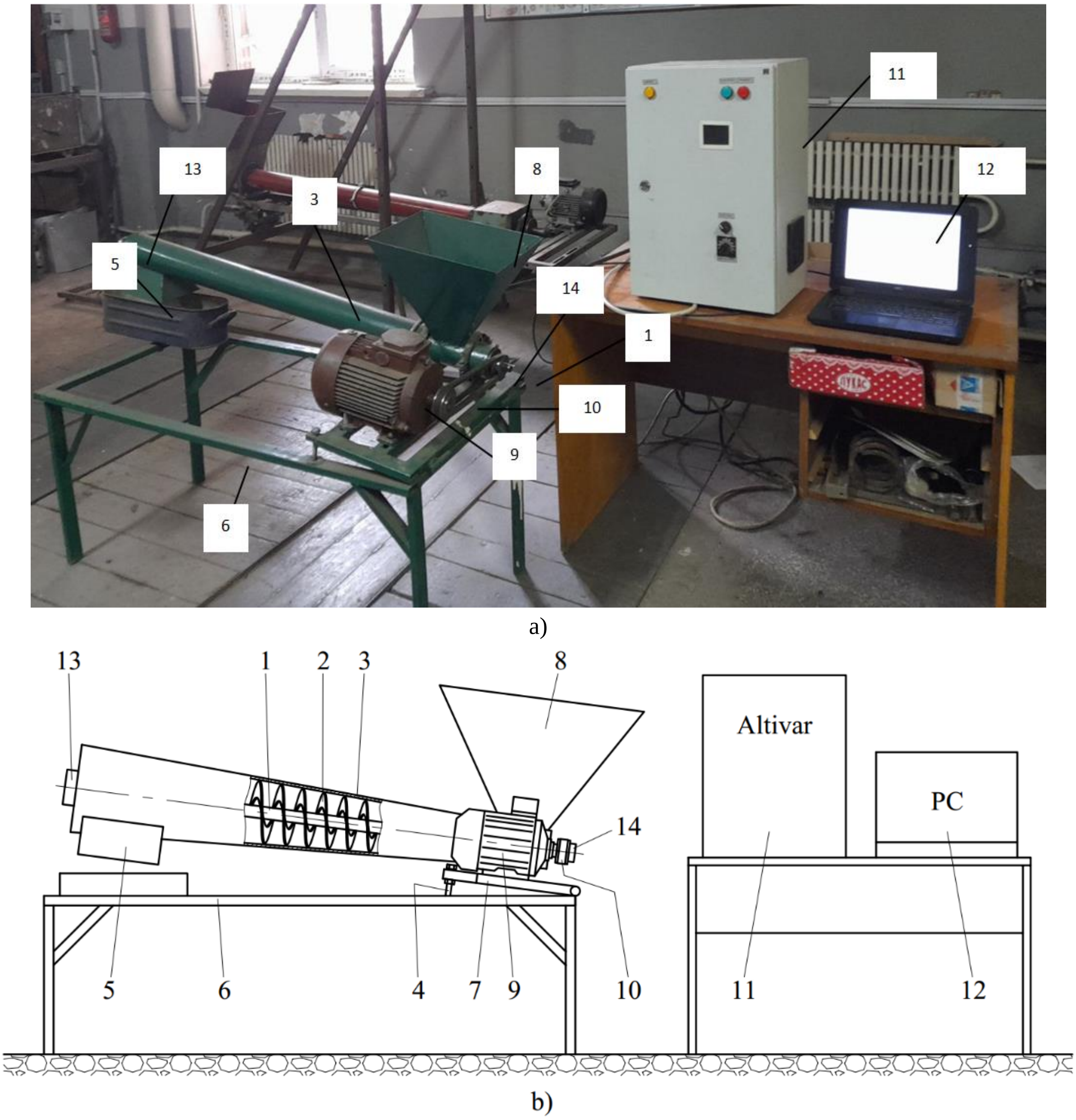

Fig. 5 – Experimental installation for the investigation of conical screw conveyor-mixer characteristics:
a – general view of the installation; b – schematic diagram of the installation; 1 – screw shaft; 2 – screw surface with the increasing gap between the shaft and the screw; 3 – conical casing; 4 – mechanism for adjusting the overload height; 5 – unloading nozzle; 6 – frame; 7 – movable table; 8 – hopper; 9 – electric drive; 10 – belt drive; 11 – drive rotation frequency converter; 12 – personal computer; 13 – accelerometer DN-3-M1; 14 – accelerometer DN-4-M1

After calculations, design and manufacture of the screw conveyors, the following limits of variation of input factors were determined:

- the amount of the screw pitch increase on each subsequent ΔT = 0.004-0.01 m;
- the inclination angle of the screw conical surface α = 1-2 deg;
- the speed of conical screw rotation n = 200-500 r/min;
- height of the protrusions (corrugations) on the outer diameter of the screw surface A = 0.004-0.012 m;
- rotational speed of the corrugated screw n_1 = 70-270 r/min.

The main design parameters of the conical screw are determined:

- for the lower level of variation of the experimental factors: maximum pitch of the conical screw on the last turn T_{max} = 0.129 m, maximum diameter of the conical screw D_{max} = 0.151 m, the number of turns i = 13;
- for zero level of variation of the experimental factors: maximum pitch of the conical screw on the last turn T_{max} = 0.156 m, maximum diameter of the conical screw D_{max} = 0.175 m, number of turns i = 11.86;
- for the upper level of variation of the experimental factors: maximum pitch of the conical screw on the last turn T_{max} = 0.178 m, maximum diameter of the conical screw D_{max} = 0.2 m, number of turns i = 10.84.

For the research, 18 different types of conical screws were manufactured. Experimental investigations of the designed and manufactured laboratory model of the multifunctional screw conveyor with replaceable casings and conical screws with variable pitch and with special corrugated conical screws with variable pitch for materials mixing during transportation were carried out. During these investigations the regularities of changes in the productivity of screw conveyors with ordinary conical screws from changes in three main factors were established: the value of the increase in the screw pitch ΔT at each step, the angle of inclination of the conical screw surface *α*, the screw rotation frequency *n* during the transportation of wheat and pea grains, and the efficiency of screw conveyors with common conical screw depending on changes in three main factors: the increase in the pitch of corrugated screw on each subsequent turn ΔT, the height of the corrugations on the outer diameter of the screw surface A, and the corrugated screw rotation frequency n_1.

The general view of the regression equations for the efficiency of screw conveyors with common conical screws from changes in three main factors: the value of the increase in the screw pitch on each subsequent turn ΔT, the angle of inclination of the conical screw surface α, the screw rotation frequency n, i.e., $Q_1 = f(\Delta T, \alpha, n)$ based on the results of full factorial experiments 3^3 and the regression equation for determining the efficiency is derived:

- for wheat transportation:

$$Q_{1w(\Delta T,\alpha,n)} = 0.499 - 49.66\Delta T + 0.393\alpha + 0.0164n - 10\Delta T\alpha - \\ -0.0889\Delta Tn + 0.00233\alpha n + 2555.55\Delta T^2 - 0.0268\alpha^2 - 7.42\cdot 10^{-6} n^2; \quad (23)$$

- for peas transportation:

$$Q_{1p(\Delta T,\alpha,n)} = 0.605 - 67.722\Delta T + 0.345\alpha + 0.01387n - 8.66\Delta T\alpha - \\ -0.0777\Delta Tn + 0.00204\alpha n + 2222.22\Delta T^2 - 0.0235\alpha^2 - 6.49\cdot 10^{-6} n^2. \quad (24)$$

Based on the obtained results of experimental investigations and the derived regression Eq. 23 and Eq. 24, the response surfaces of the dependence of the efficiency of moving bulk material by screw conveyor with common conical screw with variable pitch of turns were constructed using software, as shown in Fig. 6.

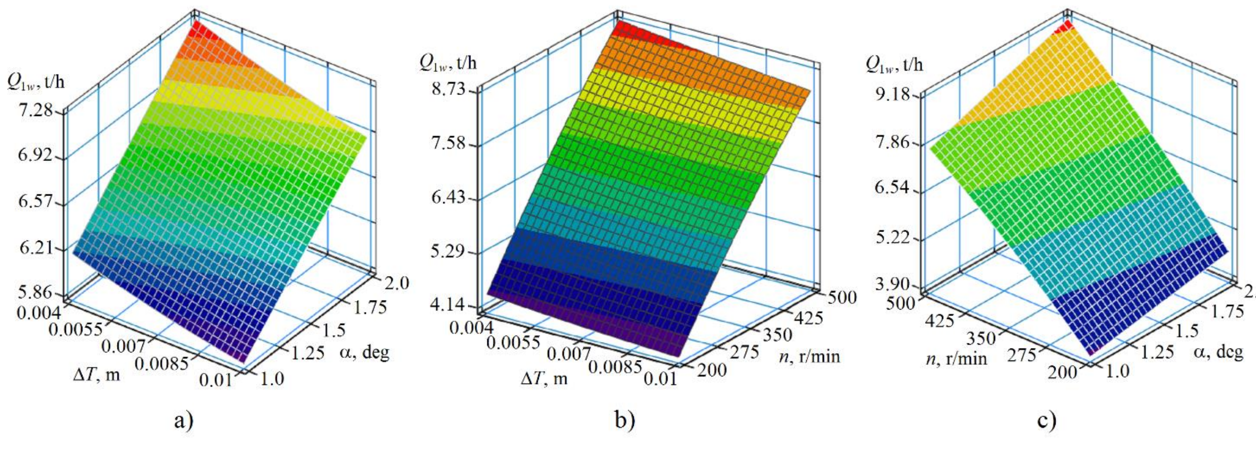

Fig. 6 – Response surfaces of the dependence of efficiency *Q* on the conveyor drive:
a – Q = f(ΔT, α) at n = 350 r/min; b – Q = f(ΔT, n) at α = 1.5 deg.; c – Q = f(n, α) at ΔT = 0.004 m

From Figures 6 and regression equations Eq. 23 and Eq. 24, it can be concluded that with the increase in the angle of inclination of the generative conical surface of the corrugated screw, the screw rotation frequency, and the decrease in the value of the incremental screw pitch at each subsequent turn, the efficiency of transporting bulk material increases. Maximum efficiency during wheat transportation was 9.44 t/h, and the minimum was 3.8 t/h. Maximum efficiency during the transportation of peas was 8.26 t/h, and the minimum was 3.32 t/h.

The increasing in the speed of conical screw n from 200 r/min to 500 r/min resulted in 2-fold increase in transportation efficiency. At the same time, the increase in the angle of inclination of the screw conical surface α from 1 degree to 2 degrees resulted in the increase of efficiency by 1.18 times, and change in the value of the increase in the screw pitch on each subsequent turn ΔT from 0.004 m to 0.01 m resulted in the decrease of efficiency by 1.07 times.

In order to implement the procedure for processing experimental data according to the method described in (https://www.hbmprenscia.com, https://www.ncode.com), the operation project containing the following structural elements (glyphs): Excel Input, Multi Column to Time Series, Butterworth Filter, Meta Data Display, Time Series to Multi Column Output, Frequency Spectrum and XY Display was constructed. The general view of the interface of the operation project for processing experimental data in nCode GlyphWorks environment is shown in Fig. 7.

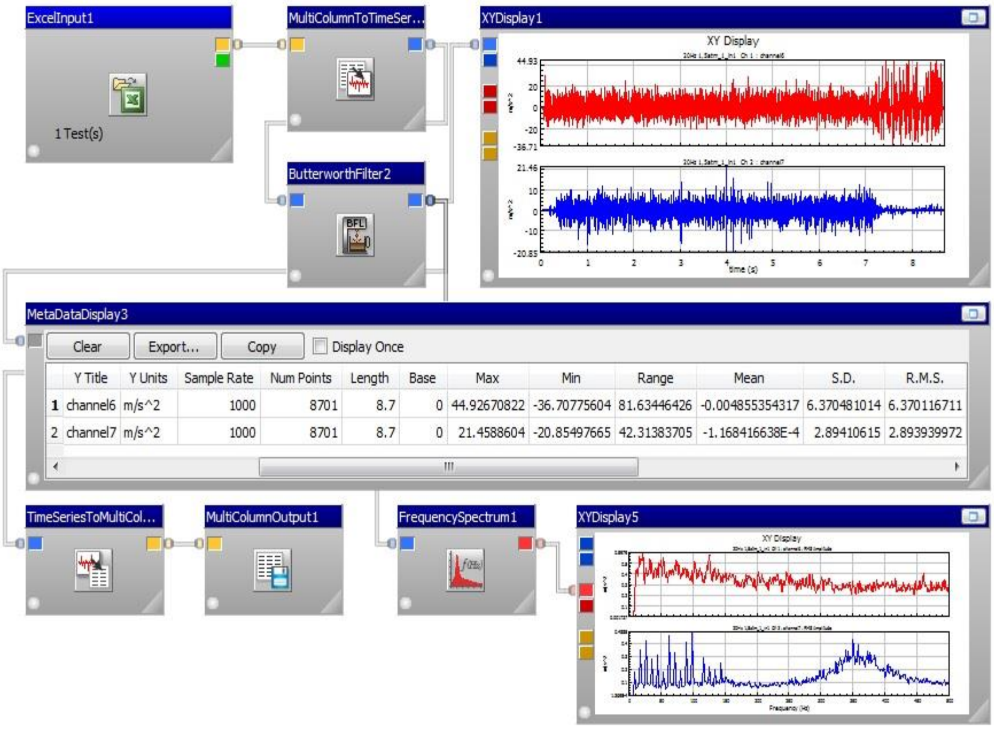

Fig. 7 – General view of the operation project in nCode GlyphWorks environment

The results of experimental data processing by nCode GlyphWorks for individual combinations of the investigated parameters are shown in Figs. 8 -11.

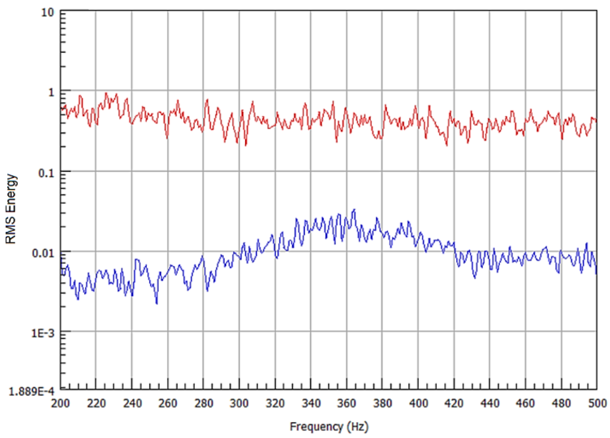

Fig. 8 – Frequency spectrum of the mean square deviation of the oscillations' energy density (10 Hz, 200 r/min)

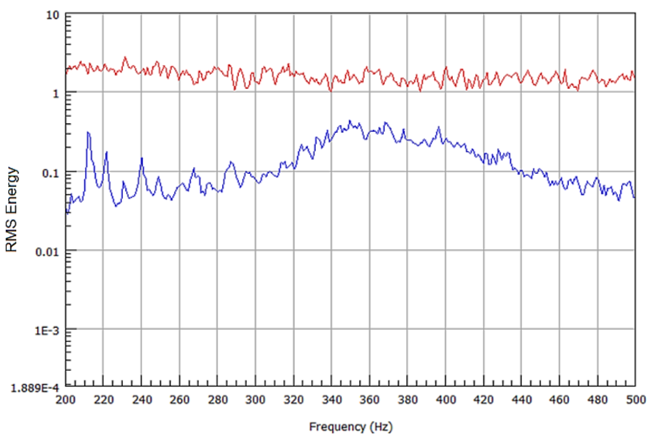

Fig. 9 – Frequency spectrum of the mean square deviation of the oscillations' energy density (20 Hz, 300 r/min)

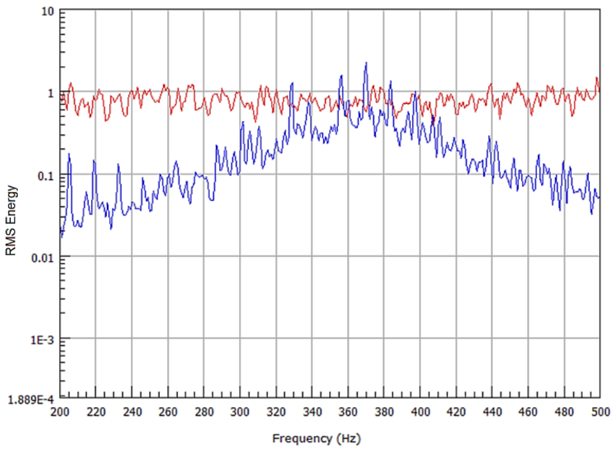

Fig. 10 – Frequency spectrum of mean square deviation of the oscillations' energy density (30 Hz, 400 r/min)

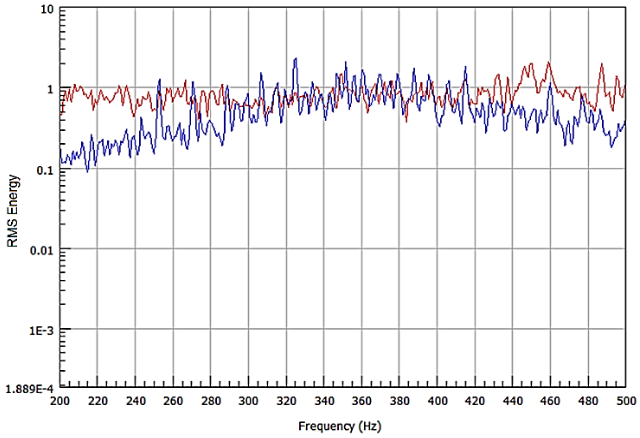

Fig. 11 – Frequency spectrum of mean square deviation of the oscillations' energy density (40 Hz, 500 r/min)

Using the SOLIDWORKS software package, a computer simulation of a screw conveyor for transporting bulk materials was created. To model the per-second throughput of the screw conveyor, the discrete element method (Rocky DEM) - a numerical method designed for calculating the movement of a large number of particles such as molecules, sand grains, gravel, and other granular media—was employed (Fig. 12).

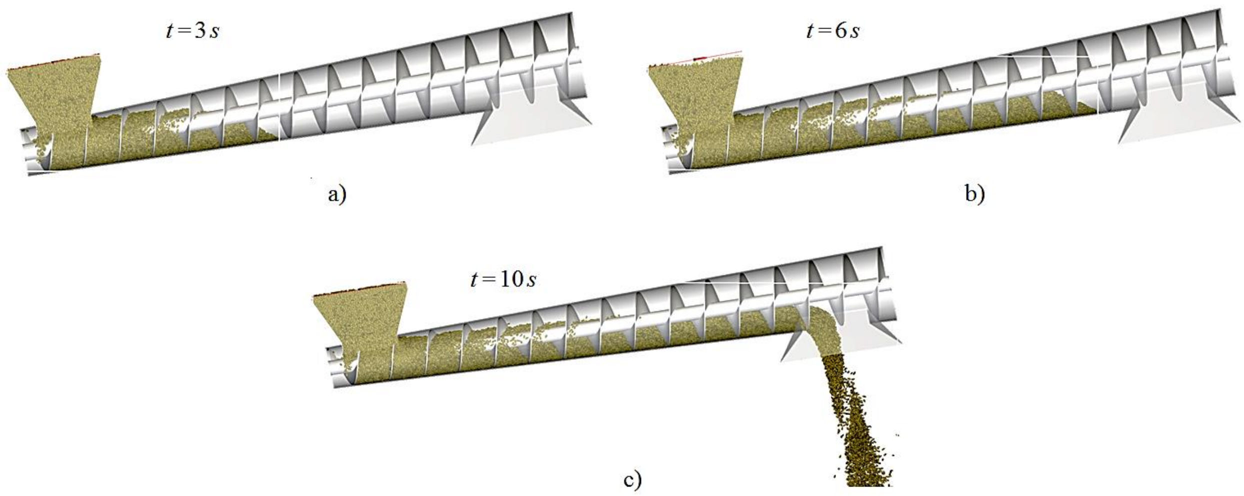

Fig. 12 – Graphical dependences of the second efficiency *Q* of the screw conveyor on the rotational speed of the operating body *n* = 300 r/min at α = 10 deg

During the simulation of the screw conveyor for transporting bulk material, it was established that for an inclination angle of α = 10° and a rotational speed of n = 300 rpm, the maximum throughput of the screw conveyor is observed between 7 and 10 seconds after startup when the hopper is filled with material. It was precisely within this time interval that samples were taken and the grain material was weighed to determine the per-second throughput of the screw conveyor.

Based on the analysis of computer simulation results of the grain material transportation process, it has been established that the per-second throughput Q of the screw conveyor increases linearly with the rotational speed *n* of the working element in the range from 200 to 500 r/min. However, a further increase in *n* does not contribute to the conveyor's throughput growth and even slightly decreases its value. This is explained by the fact that significant centrifugal forces hinder the normal loading of the conveyor. When determining the per-second throughput of the screw conveyor for other values of *α* and *n*, corresponding time intervals were identified during which the conveyor's throughput was maximal. Specifically, by increasing the internal diameter of the casing from 150 to 200 mm and within the inclination angle range of the working element to the horizon *α* = 0…10, the throughput of the transportation process increases by 1.18–1.23 times.

CONCLUSIONS

The technological process of bulk materials transportation by conical screw conveyor is theoretically substantiated in order to determine the kinematic and operational parameters that ensure its stable operation. The analytical dependences for determining the change in the outer radius of the screw R and the inner casing radius at which the initial radius of the screw R_0 increases by value ΔR at each subsequent turn, are obtained. It is found that the increase in ΔR of the cargo movement radius on one (each subsequent) turn of the conical screw conveyor significantly affects the increase in cargo velocity, which contributes to the intensification of the mixing process. In particular, with the increase in radius ΔR of the cargo movement on one (each subsequent) turn from 1 mm to 5 mm, the load movement velocity increases from 1.28 times to 2.44 times.

Bench equipment for the investigation of the bulk materials transportation efficiency was developed and manufactured. In the course of experimental studies, it was testified that with the increase in the inclination angle of the screw conical surface, the screw rotation frequency and the decrease in the screw pitch growth at each subsequent turn, the maximum efficiency during wheat transportation was 9.44 t/h, and the minimum was 3.8 t/h. With the increase of the conical screw velocity n from 200 r/min to 500 r/min, the efficiency increases by 2 times. At the same time, the increase in the inclination angle α of the forming surface of the conical screw from 1 degree to 2 degrees provides 1.18-fold increase in efficiency, and the change in the value of the screw pitch growth on each subsequent turn ΔT from 0.004 m to 0.01 m results in 1.07-fold decrease in efficiency.

REFERENCES

[1] Aulin V., Lyashuk O., Tykhyi A., Karpushyn S., Denysiuk N., (2018), Influence of rheological properties of a soil layer adjacent to the working body cutting element on the mechanism of soil cultivation, *Acta Technologica Agriculturae*, Vol. 21, no.4, pp.153–159, Nitra/Slovakia;

[2] Aulin V., Lysenko S., Lyashuk O., Holub D., Chernai A., (2019), Wear resistance increase of samples tribomating in oil composite with geo modifier KgMf-1, *Tribology in Industry*, Vol. 41, no.2, pp.156–165, Kragujevac/ Serbia;

[3] Bulgakov V., Trokhnaniak O., Adamchuck V., Chernovol M., Korenko M., Dukulis I., Ivanovs S.A., (2022), Study of dynamic loads of a flexible sectional screw conveyor, *Acta Technologica Agriculturae,* Vol.25, no3, pp.131–136, Nitra/Slovakia;

[4] Bulgakov V., Pascuzzi S., Adamchuck V., Olt J., Ruzhylo Z., Trokhnaniak O., Santoro F., Arak M., Nowak J., Beloev H., (2023), Research into power and load parameters of flexible screw conveyors for transportation of agricultural materials, *Farm Machinery and Processes Management in Sustainable Agriculture*, Vol. 289, pp. 61–75;

[5] Haaker G., Poppelen M.P., Jongejan M.P., Bekhuis J.H., (1993), Improvement of Screw Feeder Geometry for Better Draw-Down Performance. *International Symposium of Reliable Flow of Particulate solids*, pp. 551-561. Oslo/ Norway;

[6] Hevko R.B, Zalutskyi S.Z., Tkachenko I.G., Lyashuk O.L., & Trokhaniak O. (2021), Design development and study of an elastic sectional screw operating tool. *Acta Polytechnica*, Vol. 61, no. 5, pp. 624–632, Prague/ Czech Republic;

[7] Hewko B.M., Popovich P.V., Diachun A.Y., Lyashuk O.L., Liubachivskyi R.O., (2015), The study of bulk material kinematics in a screw conveyor-mixer, *INMATEH: Agricultural Engineering*, Vol.47, no.3, pp.156-163, Bucharest/Romania;

[8] Hud V., Lyashuk O., Hevko, I., Ungureanu N., Vlădut N-V., Stashkiv M., Hevko O., Pik A., (2023), Enhancement of Agricultural Materials Separation Efficiency Using a Multi-Purpose Screw Conveyor-Separator. *Agriculture*, Vol.13, p. 870;

[9] Fernandez J.W., Cleary P.W., McBride W., (2011), Effect of Screw Design on Hopper Draw Down by a Horizontal Screw Feeder. *Seventh International Conference on CFD in the Minerals and Process Industries CSIRO*, 9-11 December, pp. 1-6; Melbourne /Australia;

[10] Loveikin V., Rogatynska L., (2011), A Model of Loose Material Transportation by Means of High-Speed Conveyers with Elastic Operating Devices (Модель транспортування сипкого вантажу швидкохідними гвинтовими конвеєрами з еластичними робочими органами), *Bulletin of Ternopil Ivan Puluj National Technical University (Вісник ТНТУ ім. І. Пулюя)*, Vol.16, pp.66-70, Ternopil/Ukraine;

[11] Lyashuk O., Vovk Y., Sokil B., Klendii V., Ivasechko R., Dovbush T. (2019), Mathematical model of a dynamic process of transporting a bulk material by means of a tube scraping, *Agricultural Engineering International: CIGR Journal,* Vol. 21, no 1, pp. 74-81, Japan;

[12] Lyashuk O., Sokil M., Vovk Y., Levkovych M., Tson O., Kondratyuk D., Dmytrenko V., (2019), Analysis of resonance oscillations of extruder elastic screw conveyor, *International Journal of Engineering Research in Africa,* Vol.43, pp. 49–58, Switzerland;

[13] Lyashuk O.L., Hevko, I.B., Hud, V.Z., Tkachenko, I.G., Hevko, O.V., Sokol, M.O., Tson, O.P.; Kobelnyk, V.R., Shmatko, D.Z. & Stanko, A.I. (2022), Research of non-resonant oscillations of the "telescopic screw – fluid medium system". *INMATEH-Agricultural Engineering*, Vol.68, no. 3, pp. 499-510, Bucharest/Romania;

[14] Lyashuk, O.L., Sokil, M.B., Klendiy, V.M., Slobodian, L.M., Slobodian, N.O. (2018). Mathematical model of bending vibrations of a horizontal feeder-mixer along the flow of grain mixture, *INMATEH-Agricultural Engineering*, vol.55, no. 2, pp. 35-45, Bucharest/Romania;

[15] Lyashuk O., Rohatynskyi R., Hevko I., Dmytriv O., Tson O., Tkachenko I., Sokol M., Leshchuk R., Kobelnyk V. (2023) Investigation of bulk material transportation by screw conveyer with hinge-pan operating device, Key *Engineering Materials, Engineering Materials*, Vol. 948, pp. 169-182, Switzerland;

[16] Mondal D., (2021), Design consideration of a laboratory size screw conveyor with variable speed for experimentation purpose-a methodological approach, *Techno Societal*, Vol. 68, no. 2, pp. 705–714;

[17] Moorthi S., Megaraj, M., Nagarajan L., Karthick A., Bharani M., Patil P.P., (2022), Dynamic analysis and fabrication of single screw conveyor machine, *Advances in Materials Science and Engineering*, Vol. 10, pp.1–10, United States;

[18] Pysarenko H.S., Yakovlev A.P., Matveev V.V., (1988), Reference on strength of materials (Справочник по сопротивлению материалов), *published by Naukova Dumka (видавництво Наукова думка)*, p.736, Kyiv/Ukraine;

[19] Nilsson I. G., (1971), On the vertical screw conveyor for non-cohesive bulk materials, *Acta Polytechnica Scandinavica, Mechanical Engineering Series*, no. 64, Stockholm;

[20] Roberts A. W., (1991), Determining Screw Geometry for Specified Hopper Draw-Down Performance. Proc. of Bulk 2000 Conference. *Institution of Mechanical Engineers*, pp. 111-116, London/United Kingdom;

[21] Rohatynskyi R. M., Hevko Iv. B., Diachun A. Ye., (2015), The research of the torsional vibrations of the screw in terms of impulsive force impacts, *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu (Науковий вісник Національного гірничого університету)*, Vol.149, no.5, pp. 64-68, Dnipropetrovsk/ Ukraine;

[22] Ross I. J., Isaacs G. W., (1961), Capacity of Enclosed Screw Conveyors Handling Granular Material, *Transactions of the ASAE*, Vol. 4, no. 1, pp. 97-104;

[23] Tian Y., Yuan P., Yang F., Gu J., Chen M., Tang J., Su Y., Ding T., Zhang K., Cheng Q., (2018), Research on the Principle of a New Flexible Screw Conveyor and Its Power Consumption, *Applied Sciences*, Vol.8, no.7, pp.1038;

[24] Trokhaniak O. M., Hevko R. B., Lyashuk O. L., Dovbush T. A., Pohrishchuk B. V., Dobizha N. V., (2020), Research of the of bulk material movement process in the inactive zone between screw sections, *INMATEH: Agricultural Engineering*, Vol. 60, no. 1, pp. 261–268, Bucharest/Romania;

[25] Yongqin Yu. (1997), Theoretical modelling and experimental investigation of performance of screw feeders, Doctor of Philosophy thesis, p. 226;

[26] Yu W., Zhang K., Li D., Zou D., Zhang S., (2022), Numerical modeling of concrete conveying capacity of screw conveyor based on DEM, *Powder Technology*, Vol. 29, no.6, pp.361–374, Netherlands;

[27] Zaica A., Olan M., Bunduchi G., Zaica A., Gageanu P., Paun A., (2020), Factors that influence coverage degree in seed treatment equipment having brush screw conveyor, *Engineering for rural development*, 20.-22.05.2020, pp.1325-1330, Jelgava/Latvia;

[28] Zaica A., Visan A., Paun A., Gageanu P., Bunduchi G., Zaica A., Stefan V., Manea D., (2016), The coating process of corn grains using a treatment machine with brush screw conveyor*, Proceedings of the 44th International Symposium on Agricultural Engineering: Actual Tasks on Agricultural Engineering*, 23-26 February 2016, pp.333-345, Opatija/Croatia;

[29] Zaica A., Visan A., Zaica A., Olan M., Bunduchi G., (2019), Coating process of corn grains using treatment machine with brush screw conveyor, *Engineering for rural development*, 22.-24.05.2019, pp.233-238, Jelgava/Latvia;

[30] Zalutskyi S.Z., Hevko R.B., Hladio Y.B., Tkachenko I.H., Klendii O.M., (2018), Loose material flow motion on surface of screw with overlapping elastic sections (*Рух потоку сипкого матеріалу по поверхні шнека з еластичними секціями, що перекриваються між собою), Kharkiv P. Vasylenko National Technical University of Agriculture (Харківський національний технічний університет сільського господарства імені Петра Василенка)*, Vol.11, pp.81-90, Kharkiv/Ukraine;

[31] Zareiforoush H., Komarizadeh M.H., Alizadeh M.R., (2010), Review on screw conveyors performance evaluation during handling process, *Journal of Scientific Review*, Vol. 2, no. 1, pp.55–63;

[32] ***https://www.hbmprenscia.com;

[33] ***https://www.ncode.com.