DESIGN DEVELOPMENT AND RESULTS OF EXPERIMENTAL RESEARCH ON GRAIN DAMAGE BY A NEW SCREW CONVEYOR
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РОЗРОБКА КОНСТРУКЦІЇ ТА РЕЗУЛЬТАТИ ЕКСПЕРИМЕНТАЛЬНОГО ДОСЛІДЖЕННЯ ПОШКОДЖЕННЯ ЗЕРНА НОВИМ ГВИНТОВИМ КОНВЕЄРОМ

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ABSTRACT
The article presents an experimental stand for laboratory research of a screw conveyor with a bladed working body. Based on the results of experimental studies, the corresponding response surface regression equations were constructed to establish the influence of controllable factors upon the degree of damage to the grain materials. It was established that the main factor affecting the increase in the amount of the grain damage was factor $x_3(n)$, the rotation frequency of the bladed working body. The increase in factors $x_1(D)$ and $x_2(\psi)$ led to a decrease in the amount of the grain damage. Based on the results of comparative experimental studies to determine the degree of damage to the grain material during its transportation by the screw and blade working bodies, it was established that the bladed working body provided a reduction in the degree of damage to the grain material with a simpler manufacturing technology.

АНОТАЦІЯ
В статті представлена експериментальна установка для дослідження шнекового транспортера із лопатевим робочим органом. За результатами експериментальних досліджень побудовані відповідні рівняння регресії, поверхні відгуку для встановлення впливу на ступінь пошкодження зернових матеріалів керованих факторів. Встановлено що основним фактором, який впливає на збільшення величини травмування зерна є фактор $x_3(n)$, частота обертання лопатевого робочого органу. Збільшення величин факторів $x_1(D)$ та $x_2(\psi)$ призводить до зменшення величини травмування зерна. На основі результатів порівняльних експериментальних досліджень з визначення ступеня травмування зернового матеріалу при його транспортуванні гвинтовим та лопатевим робочими органами встановлено, що лопатевий робочий орган забезпечує зменшення степеня пошкодження зернового матеріалу при простішій технології виготовлення.

INTRODUCTION
Screw conveyors are widely used in the transportation of grain, seed materials, and granular mineral fertilizers, which experience significant damage during their transportation. The main causes of damage to the agricultural materials are the entry of their particles into the gap between the rotating working body and the stationary inner surface of the guide pipe, resulting in damage to the materials. It has been established that the existing designs of the working parts of screw conveyors do not fully satisfy the functional requirements for damage to the grain materials.

Thus, the designs of screw conveyors with the working bodies of a round cross-section are made of high-carbon steels that are subjected to heat treatment *(Hewko et.al., 2015; Sokil et.al., 2018; Aulin et.al., 2019; Lyashuk et.al., 2019; Hevko et.al., 2019)*. However, such spirals can only be produced in an uncalibrated state, with subsequent calibration per step, with a length of 3...6 m. Therefore, their thermal treatment is too complicated. They also have low productivity since the circular cross-section of the spiral does not provide a concentrated guiding force in the axial direction when transporting the material.

Strip spirals are characterized by significantly higher efficiency, but they have low durability, since the low-carbon steels used in their manufacture are quickly destroyed when the spirals operate at small radii of curvature, due to the occurrence of banner stresses during rotation *(Hevko et.al., 2015; Hevko et.al., 2016; Bulgakov et.al., 2022)*.

Also, the selection of constructive and kinematic parameters of the working bodies of conveyors, depending on the rheological properties of grain materials, cannot completely solve this problem *(Pascuzzi et.al., 2024; Bulgakov et.al., 2022)*.

Therefore, the task of developing new constructions of working bodies of conveyors, which will have a simple manufacturing technology and ensure the implementation of the process of transportation of grain materials with less damage to the grain material, is urgent.

An urgent task in development is new constructions of the working bodies of conveyors that will have a simple manufacturing technology and ensure implementation of the process of transportation of the grain materials with less damage to the grain material. The purpose of research is to reduce damage to the grain materials during their transportation by a screw conveyor, by creating an improved screw construction with bladed working parts, and experimental justification of its parameters.

MATERIALS AND METHODS

To solve this problem, an experimental stand has been developed to study a screw conveyor with a bladed working body, the diagram of which is shown in Fig. 1. It consists of frame *10* on which a screw conveyor is placed, containing a guide pipe *7* in which a bladed working body *6* is located. On the loading side of the material hopper *5* is installed, and in the unloading area there is a window with an adjustable damper *9* and a brake on the auger shaft *8*. The working element is driven from the electric motor *3* through a safety clutch *4*.

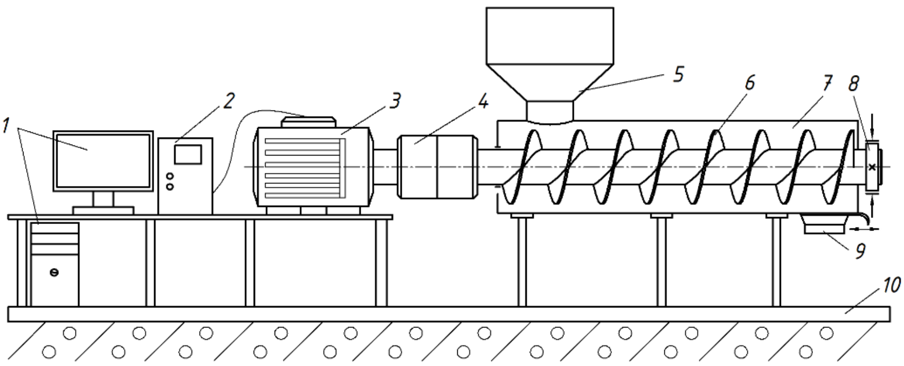


Fig. 1 - Diagram of an experimental stand for the investigation of the screw conveyor with a bladed working body

To start the engine and adjust its rotation speed, frequency converter 2 (Altivar 71) with Power Suite v.2.5.0 software is used. The Altivar 71 system is connected to the network and computer 1.

When the required rotation speed is set, using a computer through the Altivar 71 system, a command is transmitted to the electric motor, and through a safety clutch it begins to rotate the shaft of the blade working body with the set parameters. First, the grain material is loaded into the hopper and, at a certain rotation speed of the working body and according to specified parameters, the material is transported to the unloading zone into a measuring vessel.

A general view of the stand for studying the screw conveyor and the bladed working body is shown in Fig. 2.

a) **b)**

Fig. 2 - General view of the stand for the investigation of the screw conveyor (a) and a screw working body, consisting of individual blades (b)

It is advisable to manufacture the blades for the working body of the conveyor by twisting a sheet material and then welding them to a cylindrical shaft. It has been established that it is advisable to use flat blades with a mirror reflection relative to the vertical in the range from 0º to 90º (full range 180º), since it is not rational to produce blade sectors with an angular pitch of up to 20º, both from the point of view of their manufacture (large quantity) and from point of view of their composition *(Hevko, et.al., 2019)*.

To determine the degree of damage to the grain material during its transportation by the developed bladed working body of the auger conveyor into a measuring vessel, taking into account the dimensional and geometric parameters of the grain, which contained about 100 grains, three grain samples were first taken before moving. Next, the number of the damaged grains was checked and the percentage of the damaged grain material was determined before its transportation. Grains with knocked out germs were not taken into account, and only crushed grains were consider. Based on the difference in the number of damaged grains before and after transportation, the degree of damage to the grain material was determined depending on the changing structural and kinematic parameters of the blade working body of the screw conveyor.

To obtain a comparative indicator of the damaged material, the mass of the damaged grain in the sample mass was recalculated using the formula:

$$T = \frac{m_1 - m_2}{m_n} \cdot 100 \text{ , \%,} \tag{1}$$

where m_1 – mass of the damaged grain after its moving by the conveyor, kg; m_2 – mass of the damaged grain after moving by the conveyor, kg; mass of the damaged grain for transportation, kg; m_n – mass of the sample, kg.

The damaged grains were those that had the following damage: crushed germs, damaged germs, damaged grain shell, damaged endosperm, damaged endosperm shell, broken grain, mechanically compressed grain. This damage for various crops, the transportation of which was experimentally studied, is shown in Fig. 3.

a b c

Fig. 3 - General view of grains with damage:

a – peas; b – maize; c – wheat

In addition, there are presented grains, selected from the total mass with standard volumes (up to 1 decimeter per cube) after their transportation. As it is evident from the photos, presented in Fig. 3. damage occurs during transportation of all the types of grains. The most damage occurs to the maize grains. In all cases, the greatest damage is damage (chips) of the outer surfaces, as well as continuous transverse cracks, splitting of seeds into two approximately equal parts, etc.

When conducting a multifactorial experiment in order to determine the degree of damage to the grain material by the bladed working body, the variable factors were: the pipe diameter *D*, the filling factor *ψ* of the conveyor and the rotational speed *n* of the bladed working body.

Since during the experiments the variable independent factors are heterogeneous and have different units of measurement, and the numbers expressing the value of these factors are of different orders, they were brought to a unified calculation system by moving from actual values to coded ones, presented in Table 1.

The investigation of the material damage made it possible to determine its dependence on many factors characterizing the process, namely: the internal diameter of the pipe *D*, (m); the filling factor *ψ*; the rotation speed *n* (rpm) of the blade working body.

Investigations on damage to the grain material with a bladed working body were carried out during transportation of such materials with the corresponding volumetric mass: peas – 700 kg·m^{-3}; wheat – 760 kg·m^{-3}; maize – 800 kg·m^{-3} with moisture content *W* = 12...15%, which made it possible to construct analytical regression equations.

Table 1

Results of the factor coding and levels of their variation in the research of damage to grain material

Factors	Designation		Interv. of variation	Levels of variation, natur. / codified		
	Code	Natur.				
The inner diameter of the pipe *D*, m	X_1	x_1	0.02	0.06/–1	0.08/0	0.1/+1
The filling factor of the conveyor, *ψ*	X_2	x_2	0.2	0.3/–1	0.5/0	0.7/+1
Rotation speed *n* of the blade working body, rpm	X_3	x_3	200	200/–1	400/0	600/+1

The processing of the data, obtained from the experimental array, was carried out on a PC, using well-known methods and methods of statistical processing, using the well-known methods of the correlation and regression analysis to ultimately obtain empirical regression equations *(Adler, et.al., 1976; Dushinskyi, 1998)*. To obtain a regression model for the optimization parameter, an appropriate multifactorial experimental design was selected, which was implemented in the following sequence.

The response function (optimization parameter), i.e., determined in an experimental way, are presented as mathematical models of a full quadratic polynomial *(Adler et.al., 1976; Dushinskyi 1998)*:

$$T = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3 + b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^2, \quad (2)$$

where $b_0, b_1, b_2, b_3, b_{12}, b_{13}, b_{23}, b_{11}, b_{22}, b_{33}$ – coefficients of the corresponding values x_i; x_1, x_2, x_3 – relevant factors to be coded.

The values of the coefficients of the regression equations, presented in Table. 2.

Table 2

Value of coefficients of regression equations

Crop \ Coeffic.	b_0	b_1	b_2	b_3	b_{12}	b_{13}	b_{23}	b_{11}	b_{22}	b_{33}
peas	0.360	– 0.028	– 0.024	0.092	0	– 0.002	0	– 0.004	0.0060	– 0.0040
maize	0.318	– 0.022	– 0.026	0.085	0	– 0.0022	0	– 0.0036	0.0054	– 0.0036
wheat	0.270	– 0.025	– 0.026	0.075	0	– 0.002	0	– 0.0032	0.0048	– 0.0032

General form of the regression equation for the magnitude of the grain damage during transportation by a screw conveyor with a bladed working element depending on the pipe diameter *D*, the conveyor filling coefficient *ψ* and the rotation speed *n* of the bladed working element, i.e. $T_{(x_1,x_2,x_3)} = f(D, \psi, n)$ according to the results of full factorial experiments, 3^3 in coded quantities is equal to:

– for transportaion of peas:

$$T_{(x_1,x_2,x_3)} = 0.36 - 0.028x_1 - 0.024x_2 + 0.092x_3 + 0x_1x_2 - 0.002x_1x_3 + 0x_2x_3 - 0.004x_1^2 + 0.006x_2^2 - 0.004x_3^2; \quad (3)$$

– for transportaion of maize:

$$T_{(x_1,x_2,x_3)} = 0.318 - 0.022x_1 - 0.026x_2 + 0.085x_3 + 0x_1x_2 - 0.0022x_1x_3 + 0x_2x_3 - 0.0036x_1^2 + 0.0054x_2^2 - 0.0036x_3^2; \quad (4)$$

– for transportaion of wheat:

$$T_{(x_1,x_2,x_3)} = 0.27 - 0.025x_1 - 0.026x_2 + 0.075x_3 + 0x_1x_2 - 0.002x_1x_3 + 0x_2x_3 - 0.0032x_1^2 + 0.0048x_2^2 - 0.0032x_3^2. \quad (5)$$

The assessment of the statistical significance of the coefficients of the regression equation and the verification of the adequacy (correspondence) of the obtained theoretical distribution of random variables of the regression equations to the real experimental process were made according to method *(Lyashuk et.al., 2019)*. The statistical significance of the coefficient assessment of the regression equation and the verification of the adequacy (correspondence) of the obtained theoretical distribution of random variables of the regression equations to the real experimental process were carried out according to the method *(Lyashuk et.al., 2019)*. In natural quantities (coordinates), the regression equation (3 – 5), after transforming and simplifying the expressions, is accepted in its final form:

– for transportation of peas:

$$T_{(D,\psi,n)} = 0.252 + 0.511D - 0.275\psi + 0.0011n - 0.0014Dn - 10D^2 + 0.15\psi^2 - 0.00000033n^2; \quad (6)$$

– for transportation of maize:

$$T_{(D,\psi,n)} = 0.228 + 0.475D - 0.25\psi + 0.00101n - 0.001023Dn - 9D^2 + 0.135\psi^2 - 0.000000297n^2; \quad (7)$$

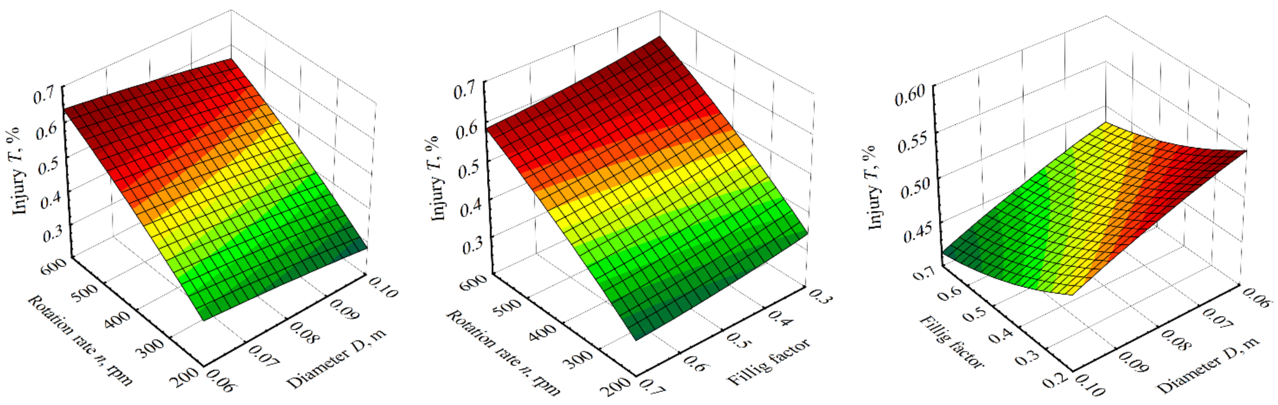
– for transportation of wheat:

$$T_{(D,\psi,n)} = 0.203 + 0.389D - 0.22\psi + 0.000903n - 0.00099Dn - 8D^2 + 0.12\psi^2 - 0.000000264n^2. \quad (8)$$

The obtained regression equations (6 – 8) may be used to determine the degree of the grain damage T during transportation by a screw conveyor with a bladed working body, depending on the diameter of the pipe D, the filling factor ψ of the conveyor and the rotation speed of the bladed working body when transporting peas, maize, wheat to the following limits of change in the input factors: $0.06 \le D \le 0.1$ (m); $0.3 \le \psi \le 0.7$; $100 \le n \le 500$ (rpm).

RESULTS

Using the developed STATISTICA application program for the PC, a graphical reproduction of intermediate general regression models in the form of quadratic responses and their two dimensional sections of the grain damage value T as a function of two variable factors $x_{i(1,2)}$ with a constant level of the corresponding third factor $x_{i(3)} = \text{const}$ (Fig. 4 – Fig. 6) was built.



a b c

Fig. 4 - Response surface of the magnitude of damage to the pea grains depending on:
a) $T = f(D; n)$; b) $T = f(n; \psi)$; c) $T = f(\psi; n)$

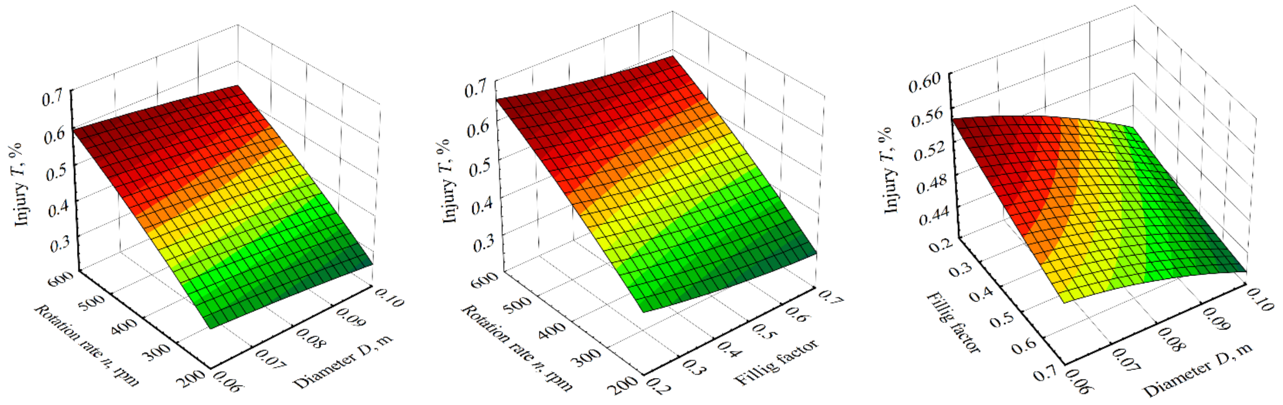


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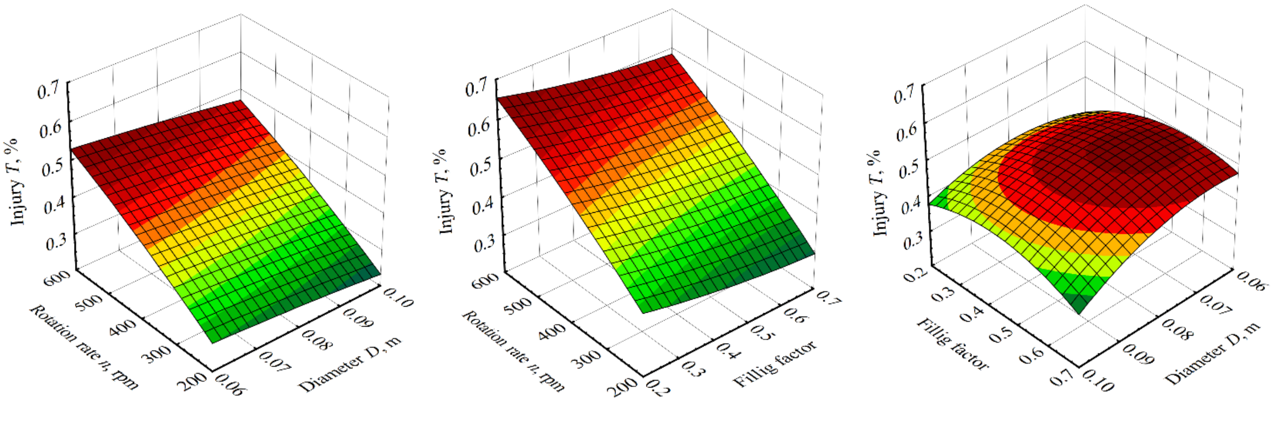
Fig. 5 - Response surface of the magnitude of the maize grain damage depending on:
a) $T = f(D; n)$; b) $T = f(n; \psi)$; c) $T = f(\psi; n)$



a b c

Fig. 6 - Response surface of the magnitude of the wheat grain damage depending on:
a) $T = f(D; n)$; b) $T = f(n; \psi)$; c) $T = f(\psi; n)$

Analysis of the above regression equations shows that the main factor influencing the increase in the amount of the grain damage is factor $x_3(n)$, the rotation speed of the blade working body. An increase in factors $x_1(D)$ and $x_2(\psi)$ leads to a decrease in the amount of the grain damage. Therefore the rational value of the frequency is the rotation speed of the blade working body within the range of $100 \leq n \leq 500$ (rpm).

When the diameter D of the guiding pipe changes within 0.06...0.1 m, the damage to the grain material, namely peas, maize and wheat, decreases by 12...13.5%; when the rotation speed of the blade working body changes within 200...600 rpm, the damage to the grain increases by 48...50%, and in the range of changes in the conveyor filling coefficient ψ from 0.3 m to 0.7 m, the damage is reduced by 10%.

The results of comparative experimental investigations to determine the degree of damage to the grain material during its transportation by a screw working body (a solid line), as well as by a bladed working body (a dashed line) on the rotation speed n at various values of the conveyor filling coefficient ψ and on the diameter D of the guiding pipe also at different values of the conveyor filling coefficient ψ are respectively presented in Fig. 7 and Fig. 8.

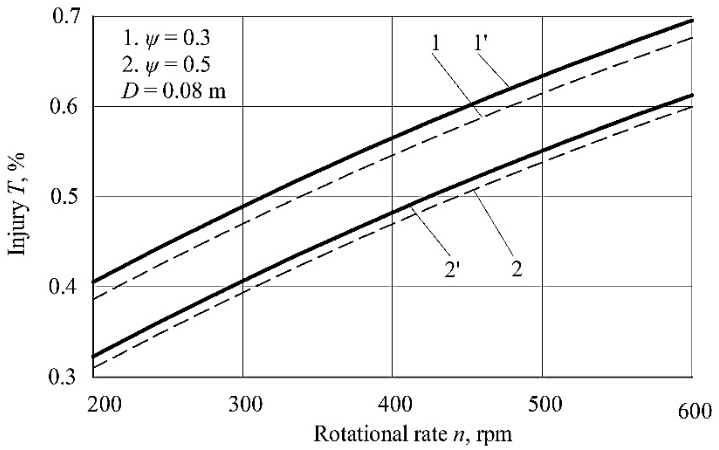


Fig. 7 - Dependences of damage to the grain material *T*, %, caused by the screw working body (a solid line)

Analysis of the graphical dependencies, depicted in Figs. 6 and 7. showed that the use of a bladed working body, in comparison with the screw one, ensures a reduction in the degree of damage to the grain material.

So, for the rotation speed of the blade working body, which is in the range of 200...600 rpm, the degree of damage to the grain material decreases by 1.07...1.1 times.

When the diameter of the guiding pipe D changes within 0.06...0.1 m, the degree of damage to the grain material, when using a bladed working body, decreases by 1.04...1.07 times.

Therefore it is advisable to use instead of helical spirals flat blades inclined to the axis of rotation, which are attached to the cylindrical shaft of the base. It is advisable to produce such blades by cutting and trimming the sheet material, followed by welding them to the cylindrical shaft.

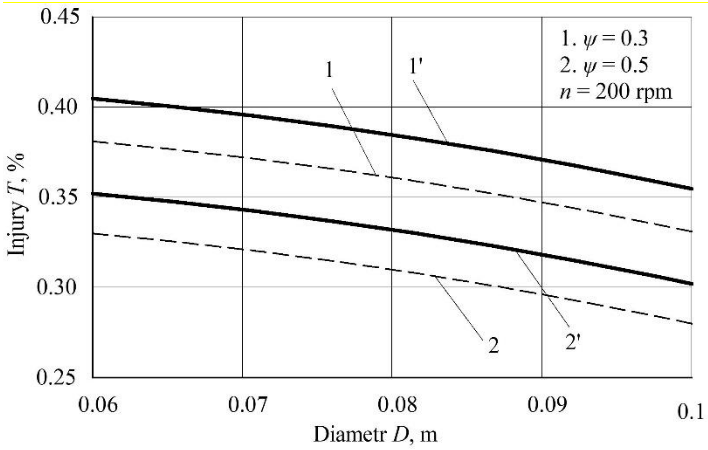


Fig. 8 - Dependences of damage to the grain material *T*, %, caused by the screw working element (a solid line) and a bladed one (a dashed line) on the diameter of the guide pipe *D* at different conveyor filling coefficients *ψ*

Consequently, the proposed design of the bladed working body provides stable standard dimensions of the working body section at low cost and simpler manufacturing technology, and also carries out the process of transporting the grain materials with less damage.

CONCLUSIONS

Based on the analysis of literary sources and patent search, an experimental stand was developed and manufactured to study a screw conveyor with a bladed working body, which will improve the functional and operational characteristics of screw conveyors. The proposed design of the blade working body ensures stable standard dimensions of the working body section at low cost and simpler manufacturing technology, and also carries out the process of transporting the grain materials with less damage.

Based on the results of experimental studies, the corresponding response surface regression equations were constructed to establish the influence of controllable factors on the degree of damage to the grain materials. It has been found out that the main factor influencing the increase in the amount of the grain damage is factor $x_3(n)$, rotation speed n of the blade working body. An increase in factors $x_1(D)$ and $x_2(\psi)$ leads to a decrease in the amount of the grain injury. Therefore, a rational value of frequency n is the rotation speed of the blade working body within the range of $100 \leq n \leq 500$ (rpm).

Analysis of the results of the comparative experimental investigations to determine the degree of damage to the grain material during its transportation by a screw working body and a bladed working body at different values of the conveyor filling factor from the rotation speed n and the diameter of the guiding pipe D showed that a bladed screw conveyor provides a reduction in the degree of damage to the grain material.

The proposed design of the blade working body ensures stable standard dimensions of the working body section at low cost and simpler manufacturing technology, and also carries out the process of transporting the grain materials with less damage.

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