EXPERIMENTAL STUDIES OF SPECIFIC POWER CONSUMPTION OF COMBINED SCREW CONVEYOR

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Abstract. In the agricultural sector of crop production, as well as in the processing and food industries, mechanical screw mechanisms are widely used. The specificity of their application is determined by the wide range of technological processes involved in harvesting and processing agricultural products. One of the most common representatives of such mechanisms is the screw conveyor, which consists of a guiding casing and a screw conveyor mounted inside it. Depending on their design features, screw conveyors, in addition to material transportation, can simultaneously perform auxiliary functions such as product mixing, material crushing, dosing, and impurity separation. An increase in the functional capabilities of screw conveyors is achieved through the development of combined screw conveyors, which ensure simultaneous conveying and crushing of materials by means of cutting knives installed in the inter-flight space of the screw conveyor. This paper presents the results of experimental studies aimed at determining the specific power consumption of a screw conveyor during the simultaneous crushing and conveying of chopped fodder beet root fragments. It was established that the main range of approximated values of the specific power consumption of the screw conveyor lies within 0.03-0.17 $kWs \cdot kg^{-1} \cdot m^{-1}$. With an increase in the screw diameter from 0.12 to 0.20 m and the knife installation angle from 15° to 30°, the specific power consumption decreases by factors of 8.5 and 1.5, respectively, at the first screw flight pitch of 0.05 m. A further increase in the knife installation angle from 30° to 45° results in an increase in specific power consumption by approximately 1.15 times.

Keywords: screw conveyor, helical flight, cutting knife, root crop crushing, planned factorial experiment.

Introduction

Transport machines are widely used as conveying mechanisms in heavy industry, construction, and agricultural production for transportation of bulk materials (such as coal, cement, sand, soil, grain, and root crops) as well as unit loads (including bricks, timber, and pipes) [1]. Continuous conveying machines constitute the basis for the comprehensive mechanization of loading–unloading and production processes, significantly increasing labor productivity and improving the overall efficiency of industrial operations. Their application enables effective organization of continuous mechanized and automated production systems [2].

In the agricultural sector, as well as in the processing and food industries, mechanical conveyors are commonly employed due to the wide range of technological processes involved in harvesting, transportation, and processing of agricultural products. Owing to their structural features, mechanical conveyors are capable of performing several related technological functions simultaneously, including mixing of materials, crushing or grinding, dosing, and separation of impurities [3; 4].

The improvement of existing screw conveyor designs allows a significant increase in productivity and expansion of the functional capabilities of conveying mechanisms, which contributes to the further development of production technologies. Enhancement of the functional capabilities of screw mechanisms, as well as improvement of material transportation processes, can be achieved through the development of combined screw conveyors capable of simultaneously transporting and crushing materials. The solution of these tasks requires further improvement of the methodology for optimizing the technological parameters of root crop transportation processes, as well as the design parameters and operating modes of transport systems.

The analysis of the functioning of screw transport mechanisms [5-8] showed that there are certain prerequisites for further scientific work aimed at the development and research of energy-saving, multifunctional combined screw conveyors capable to ensure effective performance of related operations, both transportation and simultaneous grinding of raw materials from agricultural products during their processing.

Materials and methods

In general, the object of the research in the prototype of the combined screw crusher is the technological process of simultaneous movement and crushing of root crops, and the constituent components are the study of changes in specific energy consumption depending on the design and technological parameters of the structural elements of the screw crusher, or the main working body – the screw conveyor.

To determine the specific consumption of the power P_{ke} of the screw crusher, experimental studies of the prototype of the laboratory installation were conducted, the structural scheme and general appearance of which are shown in Fig. 1 [5].

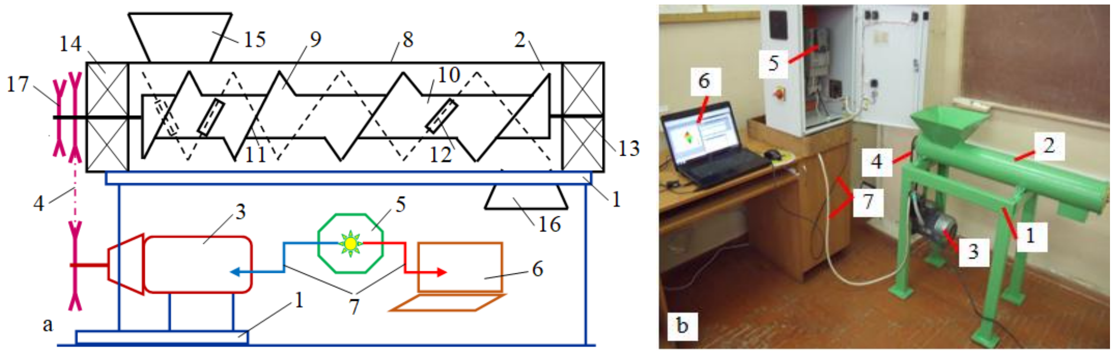

Fig. 1. **Structural diagram (a) and general view (b) of the laboratory installation:** 1 – frame; 2 – combined screw crusher; 3 – electric motor; 4 – V-belt drive; 5 – Altivar 71 control device; 6 – computer; 7 – switching connection; 8 – guide pipe; 9 – screw conveyor; 10 – drum; 11 – spiral coil; 12 – knife; 13 – shaft; 14 – bearing support; 15, 16 – loading and unloading neck; 17 – pulley

The laboratory installation consists of a frame 1 on which an electric motor 3 is installed, a screw grinder 2, a multi-system device 5 Altivar 71 for controlling the operation of the electric motor, a computer 6, a communication connection 7. The screw grinder is made in the form of a guide pipe 8, at the ends of which bearing supports 13 are installed, and a screw conveyor 9 is mounted in the space of the pipe. The screw conveyor is a drum 10, on which spiral turns 11 are fixed along the helical line, and the shaft 13 is installed in the bearings 14. The screw conveyor is driven into rotational motion by an electric motor through V-belt transmission 4.

The loaded root crops from the hopper 15 enter the inter-turn space of the screw conveyor 9. The knives 12, which are fixed on the side surfaces of the spiral turns 11, grind the root crops due to their rotation, and the crushed parts of the root crops move along the surface of the spiral turns to the gate 16 and are unloaded from the screw crusher.

Experimental studies of the specific consumption costs of the power P_{ke} were conducted based on the implementation of a four-factor experiment at three levels of factor variation or a planned experiment of the PFE 3^4 type, Table 1.

Table 1

Factors and levels of their variation

Factors	**Factor variation interval**	**Factor variation levels: natural/coded**		
Frequency of rotation of the screw conveyor n_k, rpm	100	100/-1	200/0	300/+1
Diameter of the screw conveyor D_k, m	0.04	0.12/-1	0.16/0	0.2/+1
Pitch of the spiral turns T_s, m	0.03	0.05/-1	0.08/0	0.11/+1
Knife installation angle α_y,°	15	15/-1	30/0	45/+1

The methodology for implementing experimental research on the screw root crop chopper was based on mathematical planning and conducting multifactorial experiments [9] using the asymmetric Box-Benkin plan matrix [10].

In this case, the specific power consumption P_{ke} was determined by the formula

$$P_{ke} = K_z \cdot N_{ne} / 100 Q_{ke} L_k , \quad (1)$$

where P_{ke} – specific power consumption, kW·s kg^{-1}·m^{-1};
K_z – utilization factor of the rated power of the electric motor during the experiment, %;
N_{ne} – rated power of the electric motor of the prototype of the laboratory installation, kW;
Q_{ke} – productivity of the screw crusher, kg·s^{-1};
L_k = 0.95 m – length of the working part of the screw conveyor.

Results and discussion

The approximating function in natural quantities, which functionally describes the consumption power costs P_{ke} depending on the variable input factors, determined experimentally, was found in the form of a mathematical model of a complete polynomial of the second degree.

The calculated natural numerical values of the coefficients of the regression equation are given in Table 1. It was found that the coefficients of the regression equation b_{12} = 0.22 10^{-2}, b_{14} = 0.48 10^{-5}, b_{24} = 0.82 10^{-2}, b_{11} = 0.77 10^{-6} are not significant, that is, they can be neglected.

Table 2

Natural values of the coefficients of the regression equation

	Values of the coefficients				
$P_{ke} = f_P(n_k; D_k; T_1; \alpha_y)$	b_0	b_1	b_2	b_3	b_4
	1.26	-0.11 10^{-2}	-7.59	-5.04	-0.88 10^{-2}
	b_{12}	b_{13}	b_{14}	b_{23}	b_{24}
	0.22 10^{-2}	0.66 10^{-3}	**0.48 10^{-5}**	22.92	**0.82 10^{-2}**
	b_{34}	b_{11}	b_{22}	b_{33}	b_{44}
	0.33 10^{-2}	**0.77 10^{-6}**	12.25	3.05	0.97 10^{-4}

After checking the adequacy of the approximating model and assessing the significance of the coefficients of the regression equation and the transition from coded factors to natural values, an empirical model was obtained that functionally describes the change in the specific energy consumption of the process of grinding root crops by the working bodies of the screw grinder

$$P_{ke} = 1.26 - 0.11 \cdot 10^2 n_k - 7.59 D_k - 5.04 T_s - 0.88 \cdot 10^{-2} \alpha_y +$$
$$+ 0.66 \cdot 10^{-3} n_k T_s + 22.92 D_k T_1 + 12.25 D_k^2 + 3.05 T_s^2 + 0.97 \cdot 10^{-4} \alpha_y^2 . \quad (2)$$

Analysis of the regression equation (2) and the response surface constructed according to it (Fig. 2a-4a) and its two-dimensional cross-section (Fig. 2b-4b) in the form of the functional $P_{ke} = f(n_k; D_k)$, $P_{ke} = f(D_k; T_s)$, $P_{ke} = f(T_s; \alpha_y)$ shows that the main array of approximated experimental values of the specific power consumption costs P_{ke} is:

- with respect to the nature of the change in the rotation frequency n_k and the diameter D_k of the screw conveyor – within 0.03…0.16 kWs·kg^{-1}·m^{-1};
- with respect to the nature of the change in D_k and the pitch of the spiral turn T_s of the screw conveyor – within 0.03…0.17 kWs·kg^{-1}·m^{-1};
- with respect to the nature of the change in T_s and the angle of installation of the knife α_y – within 0.025…0.11 kWs·kg^{-1}·m^{-1}.

The functional change in the specific consumption of power P_{ke} depending on the change in the rotation frequency n_k and diameter D_k of the screw conveyor has a proportional inverse character – with an increase in the rotation frequency n_k and diameter D_k of the screw conveyor, the specific consumption of power P_{ke} decreases in proportion to the increase in the rotation frequency n_k and D_k of the screw conveyor Fig. 2a-4a.

The reverse functional nature of the decrease in the specific power consumption costs P_{ke} relative to the increase in the rotation frequency n_k and the diameter D_k of the screw conveyor is a direct consequence of the increase in the productivity of the screw grinder of root vegetables.

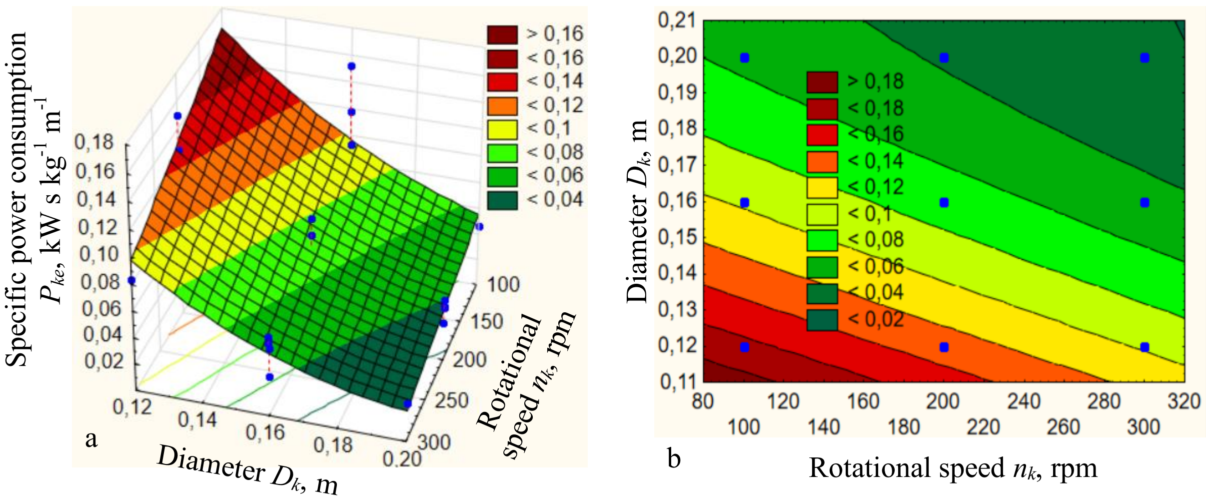

Fig. 2. **Response surface (a) and two-dimensional cross-section (b) of the response surface of the functional change in specific energy consumption of a screw root crop chopper as a function $P_{ke} = f(n_k; D_k)$**

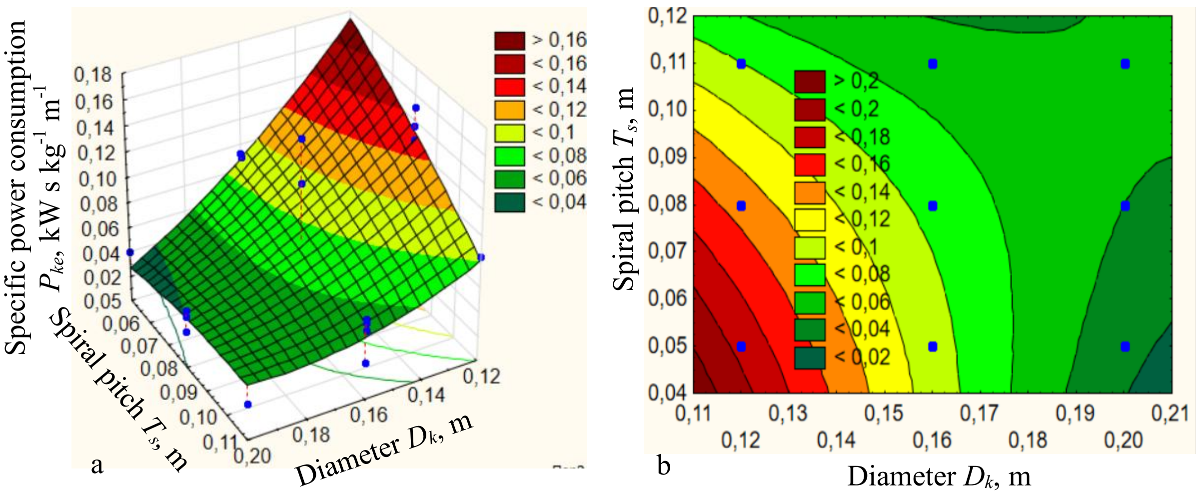

Fig. 3. **Response surface (a) and two-dimensional cross-section (b) of the response surface of the functional change in specific energy consumption of a screw root crop chopper as a function $P_{ke} = f(D_k; T_s)$**

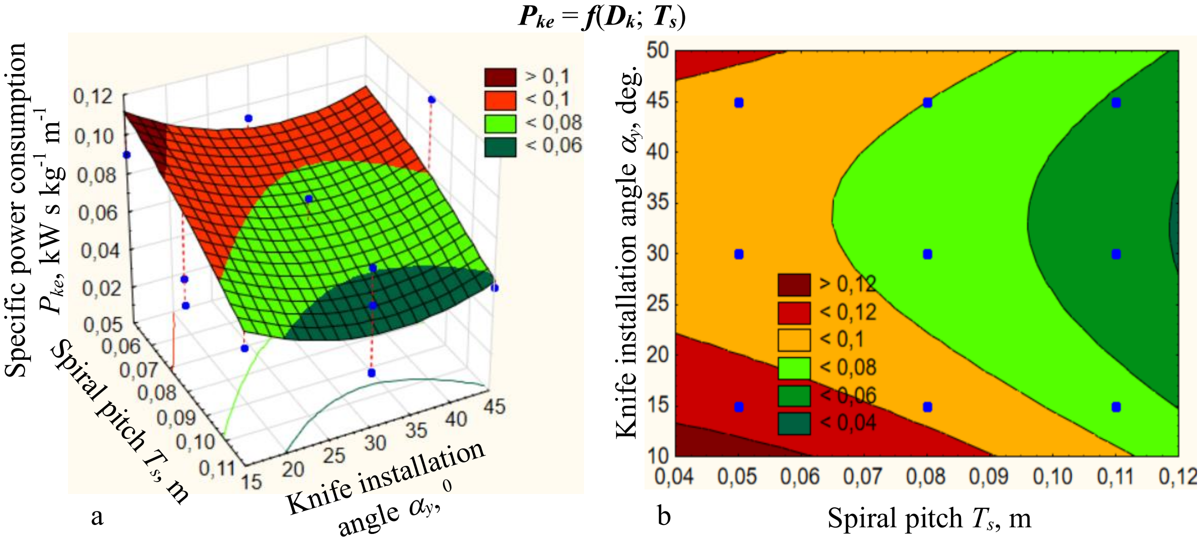

Fig. 4. **Response surface (a) and two-dimensional cross-section (b) of the response surface of the functional change in specific energy consumption of a screw root crop chopper as a function $P_{ke} = f(T_s; \alpha_y)$**

At the same time, within the limits of the increase in the rotation frequency of the screw conveyor from 100 to 300 rpm, the specific power consumption costs P_{ke} of the process of grinding root vegetables by the screw grinder decrease on average by 0.03…0.06 kWs·kg^{-1}·m^{-1} depending on the corresponding value of the diameter of the screw conveyor.

The dominant factor that has a significant impact on the change in P_{ke}, or the increase of which leads to a significant decrease in the specific consumption of power P_{ke}, is the diameter D_k of the screw conveyor – with an increase in D_k from 0.12 to 0.2 m, the specific consumption of power P_{ke} decreases on average by 0.06...0.1 kWs·kg^{-1}·m^{-1}. The most significant decrease in the specific consumption of power P_{ke} relative to the increase in the diameter D_k of the screw conveyor was obtained for the value of the spiral turn pitch T_s = 0.05 m, while P_{ke} decreases by 8.5 times – from 0.17 kWs·kg^{-1}·m^{-1} for the value D_k = 0.12 m to 0.02 kWs·kg^{-1}·m^{-1}for the value D_k = 0.2 m. Based on the analysis of the two-dimensional section (Fig. 2b), it was established that the lowest values of the specific consumption of power P_{ke} = 0.029 kWs·kg^{-1}·m^{-1} were obtained at the speed of rotation n_k = 300 rpm and diameter D_k = 0.2 m of the screw conveyor.

The functional change in the specific power consumption of the root crop grinding process depending on the change in the pitch T_s of the spiral turn of the screw conveyor is inversely proportional – with an increase in T_s within the range from 0.05 to 0.11 m, the specific power consumption P_{ke} decreases in proportion to the increase in T_s due to an increase in the productivity of the screw crusher. The most significant decrease in the specific power consumption P_{ke} relative to the increase in the pitch T_s of the spiral turn of the screw conveyor was obtained for the value of the screw conveyor diameter D_k = 0.12 m, while P_{ke} decreases by 3 times – from 0.15 kWs·kg^{-1}·m^{-1} for D_k = 0.12 m to 0.05 kWs·kg^{-1}·m^{-1} for D_k = 0.2 m and the angle of installation of the knife α_y = 45 degrees.

Based on the analysis of the two-dimensional cross-section (Fig. 3b), it was established that the lowest values of P_{ke} = 0.029…0.03 kWs·kg^{-1}·m^{-1} were obtained with a pitch T_s of the spiral turn in the range from 0.05 to 0.08 m and a diameter D_k = 0.2 m of the screw conveyor.

The functional change in the specific power consumption of the process of grinding root crops with a screw grinder depending on the change in the angle α_y of the installation of the knife-grinder has a twofold character:

- with an increase in the angle α_y in the range from 15° to 30° degrees the specific power consumption P_{ke} decreases significantly – from 0.08…0.086 to the value of 0.05…0.056 kWs·kg^{-1}·m^{-1}, i.e. P_{ke} decreases on average by 1.5 times;
- further increase in the angle α_y of the knife installation from 30 to 45 degrees. leads to an increase in the specific consumption costs of power to the value of P_{ke} = 0.058…0.065 kWs·kg^{-1}·m^{-1}, or P_{ke} increases by an average of 1.15 times.

Conclusions

The analysis of the graphical dependences shows that the functional variation of the specific energy consumption of the prototype combined screw conveyor depending on the input variables exhibits a clearly defined optimum. The minimum values of the response function $P_{ke} = f(n_k; D_k; T_s; \alpha_y)$, ranging from 0.029 to 0.04 kWs·kg^{-1}·m^{-1}, described by the functional expression, are achieved within the following parameter ranges: screw rotational speed 200-300 rpm, screw diameter 0.20 m, pitch of the first helical flight of the screw conveyor 0.08-0.11 m, and knife installation angle 30°.

An optimization analysis of regression equation (2) was performed using the method of second derivatives, together with the graphical analysis of two-dimensional cross-sections of the response surfaces (Fig. 2b-4b). The obtained results show that, under the considered technological conditions of simultaneous transportation and crushing of root crops, the specific energy consumption of the prototype combined screw conveyor reaches its minimum value at the following parameter values: screw rotational speed 300 rpm, screw diameter 0.20 m, pitch of the first helical flight 0.11 m, and knife installation angle 30°.

The optimization criterion corresponding to the approximated numerical value of the specific energy consumption of the prototype combined screw conveyor, calculated using regression equation (2) at this point, is 0.029 kWs kg^{-1}·m^{-1}, which corresponds approximately.

Thus, based on the performed analysis of the specific energy consumption of the prototype combined screw conveyor, it can be concluded that its rational operation, in terms of minimizing the specific energy consumption, is achieved under the following parameters: screw rotational speed 300 rpm, screw diameter 0.20 m, pitch of the first helical flight 0.11 m, and knife installation angle 30°.

The obtained experimental results regarding the specific energy consumption of the prototype combined screw conveyor dependence represent a further step toward the development of methodological approaches for optimizing the design parameters and operating modes of improved combined screw conveying mechanisms. These results can be used by specialists in engineering design bureaus during the development of new or modernization of existing combined screw conveyors.

Author contributions

Conceptualization, Viktor Baranovsky and Vitalii Pankiv; methodology, Natalia Dubchak and Vitalii Pankiv; software, Viktor Baranovsky and Andrii Pastushenko; formal analysis, Vitalii Pankiv and Oleg Huryk; investigation, Viktor Baranovsky and Natalia Dubchak; structural diagram of the conveyor of the root crop chopper-displacer, Vitalii Pankiv; writing – original draft preparation, Natalia Dubchak and Andrii Pastushenko; writing – review and editing, Viktor Baranovsky and Vitalii Pankiv. All authors have read and agreed to the published version of the manuscript.

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