EXPERIMENTAL INVESTIGATION OF A SECTIONAL PNEUMATIC SCREW CONVEYOR FOR BULK MATERIAL TRANSPORT IN THE FOOD INDUSTRY
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ДОСЛІДЖЕННЯ ПНЕВМОШНЕКОВОГО СЕКЦІЙНОГО КОНВЕЄРА ПРИ ТРАНСПОРТУВАННІ СИПКИХ МАТЕРІАЛІВ, ЩО ВИКОРИСТОВУЮТЬСЯ В ХАРЧОВІЙ ПРОМИСЛОВОСТІ

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ABSTRACT
The article presents a developed design of a sectional pneumatic screw conveyor intended for laboratory experimental studies on the transport of bulk materials used in the food industry. To determine the influence of bulk material transport parameters and conveyor design parameters on productivity (the optimization parameter Q), a full factorial experiment was conducted. Based on the experimental results, corresponding regression equations and response surfaces were developed to establish the influence of the controlled factors on productivity. Investigation of the transport process made it possible to determine the dependence of productivity on several factors characterizing the process, namely: the screw rotational speed n (rpm), the outlet opening area of the conveyor hopper S (cm^2), the moisture content of the transported material W (%), and the air pressure P (MPa). Thus, productivity can be expressed as a functional relationship of the form:
Q = f (n, S, W, P).

АНОТАЦІЯ
В статті представлена розроблена конструкція пневмошнекового секційного конвеєра для проведення експериментальних досліджень. Для визначення впливу параметрів транспортування сипкого матеріалу та конструктивних параметрів конвеєра для його переміщення (незалежних факторів x_i) на продуктивність (параметр оптимізації Q) проведено багатофакторний експеримент ПФЕ – 3^4. За результатами експериментальних досліджень побудовані відповідні рівняння регресії, поверхні відгуку для встановлення впливу на продуктивність керованих факторів. Дослідження процесу транспортування дали змогу визначити залежність продуктивності від багатьох чинників, що характеризують процес, а саме: частота обертання шнека, n, об·хв$^{-1}$, площа вихідного отвору бункера конвеєра S, см^2, вологість транспортованого матеріалу W, %, тиск повітря P, МПа, тобто Q = f (n, S, W, P).

INTRODUCTION
Technological processes in agricultural production and the food industry involve a large number of labor-intensive loading, unloading, and transport operations. In addition, these processes most often involve the handling and transport of bulk materials such as grain, flour, bran, sugar, and salt, which represent valuable raw materials for the production of a wide range of food products.

As transport mechanisms, pneumatic transport devices, bucket elevators, screw and spiral conveyors, and various types of throwers are mainly used. Pneumatic transport systems employ air or gas as the conveying medium, transporting materials through pipelines or ducts by means of a combination of air pressure and airflow *(Jones and Williams, 2021)*.

However, these systems are expensive to maintain, structurally complex, and require the use of cyclones to capture material particles from the dust-laden flow *(Klinzing, 2018)*.

The screw conveyors, as a separate technical element of the transport mechanisms, have found wide application in the layout schemes of machines for handling or moving bulk food materials due to their simple design, maintenance and the ability to load and unload material at any point in the process line (*Mei et al., 2022*).

However, one of the main problems arising during bulk material transport is the high degree of material damage, which occurs due to the ingress of particles into the gap between the stationary inner surface of the casing and the outer edge of the screw flight. This interaction causes not only material degradation but also an increase in energy consumption during the transport process *(Hevko et al., 2016a; Hevko et al., 2019; Hevko et al., 2016b)*. Adjusting the clearance between the screw periphery and the inner surface of the pipe, as well as using different profiles of the screw flight edges depending on the geometric and rheological properties of agricultural food materials, does not fully eliminate this problem. Research directions aimed at overcoming these limitations and increasing the productivity of screw conveyors are discussed in the literature *(Roberts and Bulk, 2015; Pylypaka et al., 2017).*

To transport bulk materials in agricultural and food production (e.g., grain materials) with minimal damage, a combination of conventional mechanical feeding by a screw feeder and the simultaneous injection of compressed air into the central region of the guiding casing is often employed. The compressed air, supplied in the direction of material transport, promotes material dispersion, facilitates the separation of fine impurities, and reduces particle damage. These effects are further enhanced when a swirling airflow is generated. Accordingly, the combined application of mechanical feeding and pneumatic action is particularly effective in grain mixture separation systems, which form the basis of food concentrate production. Therefore, theoretical principles governing the transport of finely dispersed bulk food products can be applied to the study of transport processes in sectional pneumatic screw conveyors, enabling the formation of vortex flows (Adamchuk et al., 2021). Moreover, when compressed air is supplied discretely to the inner region of the screw, at varying temperatures, and in conjunction with induced vibration of the transported material in the direction of the swirling airflow, favorable conditions are created for efficient drying with vibration assistance during transport. This approach significantly enhances the transport capabilities of the device *(Bulgakov et al., 2020; Berna, Balot et al., 2024; Hevko et al., 2015)*.

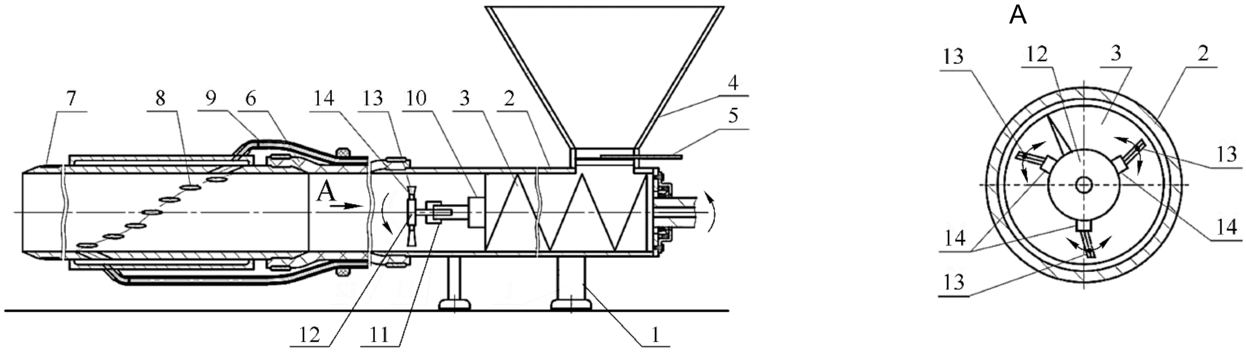
A significant number of screw and pneumatic conveyors have been developed for the transport of bulk materials in a horizontal plane or at small inclination angles. In vertical transport applications, pneumatic assistance is commonly used as an auxiliary element to enhance the operational efficiency of screw conveyors *(Hevko et al., 2018; Trokhaniak, 2021; Hevko et al., 2021)*. The operation of the pneumatic system creates a reduced-pressure zone within the screw conveyor, causing the bulk material to enter a fluidized state. This condition leads to a reduction in friction forces and, consequently, a decrease in damage to the transported material.

Consequently, among the current tasks of agro-industrial production and the food industry, it is important to develop and justify rational parameters of pneumatic screw conveyors that would ensure efficient transport of bulk food materials with their simultaneous cleaning from small impurities and drying. In the food industry the bulk materials include wheat, corn, buckwheat, rice and mixtures, based on their components (cereals, pasta, flakes, bran, etc.).

The purpose of this study is to investigate the influence of the main process parameters, namely, the screw rotational speed n (rpm), the outlet opening area of the conveyor hopper S (cm^2), the moisture content of the transported material W (%), and the air pressure P (MPa), on the productivity of bulk material transport and on the prevention of material accumulation within the pipelines of a pneumatic screw conveyor. The analysis aims to ensure efficient material movement along technological routes of various spatial configurations while maintaining an acceptable level of material damage.

MATERIALS AND METHODS

To increase the transport productivity of bulk materials in the food industry and to prevent their accumulation inside pipelines, a sectional pneumatic screw conveyor was developed. The design schematic of the conveyor is presented in Fig. 1a, while Fig. 1b shows the experimental laboratory setup used to investigate the sectional pneumatic screw conveyor.



a)

b)

Fig. 1 – Structural diagram (a) and general view (b) of a pneumatic screw conveyor during experimental laboratory studies

The sectional pneumatic screw conveyor has frame *1* on which feeder *2* is installed, formed by a cantilevered driven screw *3* (the driver not shown), housed in a fixed casing. A loading hopper *4* equipped with an opening and valve *5* is installed above the feeder *2*. An elastic casing *6* forming the first conveyor section is connected to the outlet of the feeder casing. A connecting sleeve *7* is inserted into this elastic casing. The sleeve contains openings *8* arranged along a helical line, with the openings inclined in the direction of bulk material transport. The upper part of the sleeve is enclosed by a casing fitted with compressed air pipelines *9* connected to an external pneumatic supply. An elastic casing, similar to casing *6*, is attached to the right end of the connecting sleeve *7* to form the subsequent conveyor section. The diameter of each successive connecting sleeve is smaller than that of the previous one, resulting in a gradual reduction of the flexible conveyor section diameter along the transport path. A telescopic tube *10* is mounted coaxially on the cantilever shaft of the feeder screw *3*. One end of the tube is fixed using a length-adjustment and locking mechanism *11* (e.g., a screw mechanism). At the opposite end, a hub *12* in the form of a bladed rotor is installed. The hub carries three flat blades *13* mounted on its outer surface and inclined relative to the longitudinal axis of the feeder shaft. The blade inclination angles can be adjusted using adjustment devices *14*. The compressed air pipelines *9* of all connecting sleeves *7* - which may be numerous - are connected to a central air supply line *15* linked to the pneumatic system.

The sectional pneumatic screw conveyor operates as follows. Bulk material from the hopper *4* enters the conveyor through the valve *5* and is fed into the screw feeder *2*, which is mounted horizontally on the frame *1* and performs rotational motion. The valve regulates the loading of the screw conveyor *3*. The material is captured by the screw flights *3* and conveyed toward the elastic casing *6* of the first section with the connecting sleeve *7*. Due to gravitational effects, the bulk material is primarily concentrated in the lower part of the fixed casing of the screw conveyor. A telescopic tube *10* is mounted coaxially on the cantilever shaft of the feeder screw *3*. At its free end, a hub *12* in the form of a bladed rotor is installed, carrying three flat blades *13* mounted on the outer surface of the hub and inclined relative to the longitudinal axis of the feeder shaft. This configuration creates conditions for additional capture of the bulk material and its forced projection toward the inner walls of the connecting sleeve *7*.

In fact, the rotor blades *13* create a turbine-like effect when they capture (and blades *13* are located on hub *12* at angles to the longitudinal axis of the feeder shaft *2*) portions of the bulk material from below and are thrown with acceleration in the direction of the generating circle of the inner cavity of sleeve 7.

Further, due to the fact that the connecting sleeve *7* contains openings *8*, located along the helical line, and the openings *8* themselves inside the sleeve *7* have slopes in the transport direction of the bulk material, the flow of the bulk material is twisted in the direction of its transport.

This significantly increases the speed of transport of the bulk material inside the first section. The bulk material itself is efficiently distributed in the internal space of the elastic casing *6* and, accordingly, the transport productivity increases.

Because the openings *8* in the connecting sleeve *7* are inclined in the direction of bulk material transport and the sleeve is sealed at the top by a collar equipped with compressed air pipelines *9* supplied from an external source, the pneumatic force is efficiently transmitted to the material within the sectional pneumatic screw conveyor, driving it in the direction of transport with minimal losses. Moreover, the helical arrangement of the openings *8* induces a spiral (swirling) motion of the bulk material inside the conveyor, which is maintained from one section to the next. This flow pattern significantly increases the material transport velocity and substantially enhances overall transport productivity.

Because the diameter of each connecting sleeve *7* on the side of the subsequent section is smaller than that of the preceding sleeve, the flexible part of the sectional pneumatic screw conveyor gradually decreases in diameter starting from the feeder *2*. This design feature does not reduce the conveying speed; on the contrary, it contributes to an increase in transport productivity.

Besides that, since the compressed air pipelines *9* for all the connecting sleeves *7* are connected to the central line *15*, which, in turn, is connected to the pneumatic system, a uniform and identical air pressure is provided, supplied inside each flexible section of the conveyor, regardless of its distance from feeder *2*. This uniformity helps prevent the bulk material from accumulation and clogging of the interior space of the pneumatic conveyor. It also ensures uniform air flow and does not increase the energy consumption of the conveying process. This also contributes, on the whole, to simplification of the design.

Due to the fact that a telescopic tube *10* with mechanism *11* for adjusting and locking its length is secured at one end to the cantilever shaft of feeder *2*, i.e., to the screw *3*, on its longitudinal axis, it is possible just to vary the distance of the rotor from the end of screw 3. And vice versa, in case less bulk material, such as corn grains, is transported, to ensure that a denser transported flow is captured, hub *12* must be moved by means of the telescopic pipe *10* and the mechanism *11*, further away from the end of screw *3*. Therefore, the blade rotor, depending on the material being transported, must be moved using the telescopic tube *10*. Since the rotor has three flat blades *13* on the outer generating surface, fixed on the generating surface of hub *12* at angles to the longitudinal axis of the feeder shaft, this, in the space, located close to the internal cavity of sleeve *7*, creates conditions for a guaranteed capture of parts of the bulk material and throwing it with significant acceleration into the internal space of sleeve *7*.

In addition, due to devices *14* for changing the angles of rotation of flat blades *13*, the condition of guaranteed capture of portions of the bulk material from below is achieved, depending on its condition. Thus, the more bulk material will with guarantee be captured and, accordingly, effectively ejected when the angle of inclination of blades *13* to the longitudinal axis of feeder *2* is greater. The use of exactly three blades *13* ensures conditions for a slight overlap of the "live" cross-section between the rotor and the internal cavity of both feeder *2* and sleeve *7*. The rotational speed of the feeder *2*, the dimensions of the openings *8*, and the pitch of the helical line along which they are arranged in the connecting sleeve *7*, as well as the inclination angles of the openings relative to the transport direction, are selected based on the physical and mechanical properties of the bulk material to be conveyed. The diameter of the screw *3* and the connecting sleeve *7* is also determined according to the required transport capacity. The air pressure is selected while taking into account the properties of the transported material, particularly the windage (drag) coefficient and the particle mass. These design requirements are intended to ensure non-destructive transport conditions, especially for agricultural bulk materials.

To study the performance of the developed sectional pneumatic screw conveyor, the bulk material from the agro-industrial and food industries, such as wheat (or its grain mixture) with a bulk density of 720 kg·m^{-3}, was used.

The moisture content of the transported bulk material was determined as follows. A sample of wheat or a mixture (flour) was weighed, dried to a constant weight in a drying oven, and weighed again and the loss in the weight was calculated as the moisture content.

During the experimental laboratory investigations, an Altivar 71 converter with PowerSuite v2.5.0 software was used to the power supply and a computer, enabling smooth start-up and control of the conveyor electric motor. The motor supply voltage was 380 V, while the operating corresponding to a conveyor screw rotational speed ranging from 0 to 450 rpm. The required operating air pressure in the pneumatic hoses was set using a compressor.

The developed experimental setup for studying the sectional pneumatic screw conveyor had the following technical characteristics: the rotational speed – 120…450 rpm; the compressor power – 2 kW, electric motor – 2.2 kW; the pressure in the pneumatic system – 8 MPa; the compressor capacity – 2.5 l·s^{-1}; weight, approximately 150 kg; conveyor line diameter – 80 mm.

During the experiments to determine the productivity of the sectional pneumatic screw conveyor, the corresponding bulk material was poured into the hopper of the setup and, when a stable transport process was established, the material was collected into a measuring container, with the time of its filling recorded. Next, the selected material was weighed on electronic scales and the volume was measured, using a measuring container. The experiments were conducted in triplicate.

To determine the influence of bulk material transport parameters and conveyor design parameters (independent factors x_i) on productivity (optimization parameter *Q*), a full factorial experiment was conducted. The investigation of the transport process made it possible to establish the dependence of productivity on the main factors characterizing the process, namely: the screw rotational speed *n* (rpm), the outlet opening area of the conveyor hopper *S* (cm^2), the moisture content of the transported bulk material *W* (%), and the supplied air pressure *P* (MPa). Thus, productivity can be expressed as: $Q = f(n, S, W, P)$.

Since, when conducting experiments, the variable independent factors are heterogeneous and have different units of measurement, and the numbers, expressing the values of these factors, are of different orders, they were brought to a single system of calculations by moving from actual values to coded ones.

When constructing the design matrix of multifactorial experiments, coded designations of the upper, lower, and zero levels of variation for each factor were introduced, which were respectively designated as (+1), (–1), (0). The coded values of the factors are presented in Table 1.

Table 1

Results of coding the factors and their variation levels when investigating the output of a sectional pneumatic screw conveyor

Factors	Designation		Variation interval	Levels of variation, natural/coded		
	Code	Natural value				
Screw rotational speed *n*, rpm	X_1	x_1	140	120/–1	260/0	400/+1
Conveyor hopper outlet area *S*, cm^2	X_2	x_2	15	10/–1	25/0	40/+1
Moisture of the transported material *W*, %	X_3	x_3	6	8/–1	14/0	20/+1
Air pressure *P*, MPa	X_4	x_4	0	0.25	0.35	0.45

After coding the factors, a design matrix for the corresponding multifactorial experiment was constructed, with a total of $N = 3^4$. To eliminate the influence of uncontrolled and unregulated factors on the experimental results, the order of the experiments was randomized using the random balance method, which was implemented by randomly selecting the sequence numbers of the experiments.

The processing of the obtained data from the experimental array was carried out by means of well-known methods and techniques of statistical processing, using well-known methods of correlation and regression analysis, to obtain empirical regression equations as a final result. To obtain a regression model of the optimization parameter, an appropriate multivariate experimental design was selected. A similar method was proposed in (*Vijayaragunathan and Srinivasan*, *2022*).

The response function (optimization parameter), i.e. output $Q = f\,(n, S, W, P)$, determined experimentally, is presented in the form of a mathematical model of a complete quadratic polynomial:

$$Q = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{14}x_1x_4 + b_{23}x_2x_3 + b_{24}x_2x_4 + b_{34}x_3x_4 \quad (1)$$

where: $b_0, b_1, b_2, b_3, b_{12}, b_{13}, b_{23}, b_{14}, b_{23}, b_{24}, b_{34}$ – coefficients of the corresponding values;

x_i; x_1, x_2, x_3, x_4 – the corresponding coded factors.

The statistical significance of the regression equation coefficients $b_{i\,(jk)}$ was assessed using Student's *t*-test. Coefficients $b_{i\,(jk)}$ that did not satisfy the significance criterion were considered statistically insignificant (equal to zero), and the corresponding terms x_i were excluded from the regression equation.

The values of the regression equation coefficients are presented in Table 2.

Table 2

Regression equation coefficients

b_0	b_1	b_2	b_3	b_{24}	b_{34}
9.132	0.907	2.357	–0.193	–2.24	0.401

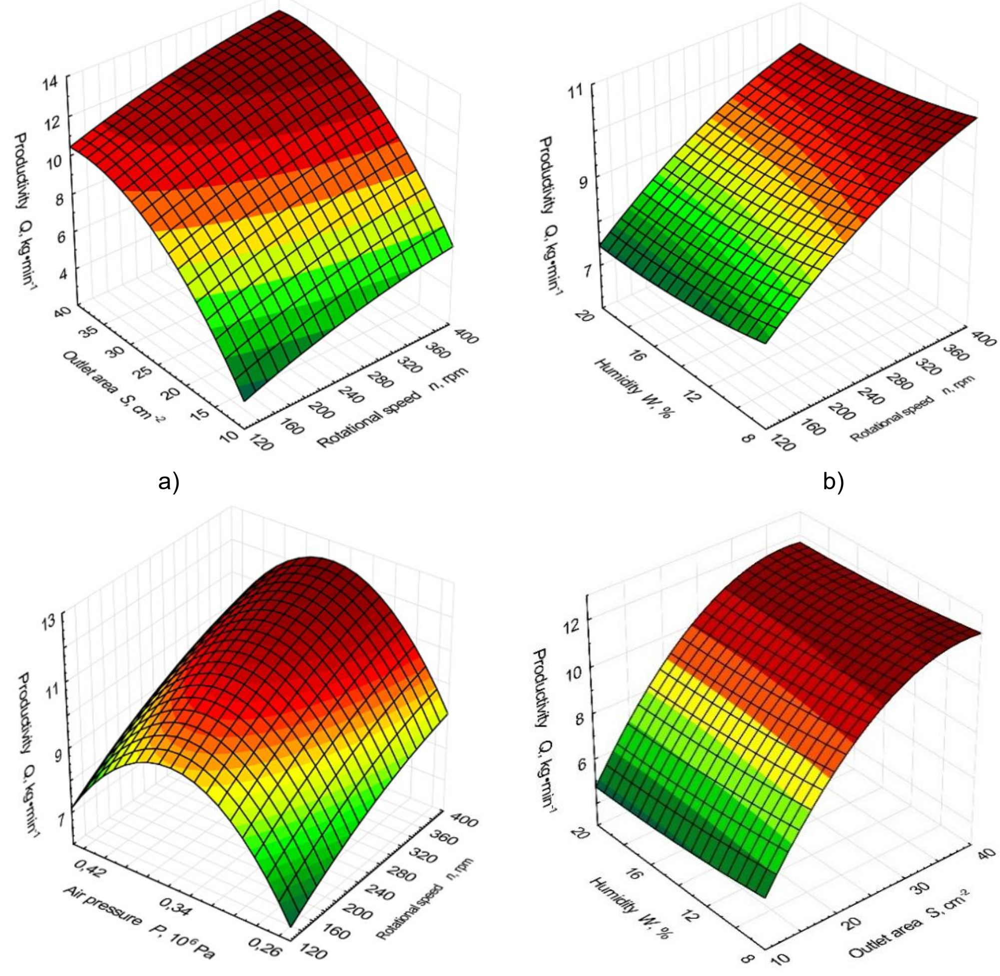
In natural values (coordinates) the performance equation for a pneumatic screw conveyor, used for transporting bulk materials in the food industry, based on the results of the MFE – 3^4, is:

$$Q = 4.231 - 0.006 \cdot n + 0.307 \cdot S - 0.01 \cdot W + 18.3 \cdot P - 1.494 \cdot S \cdot P + 0.668 \cdot W \cdot P \ . \tag{2}$$

The obtained regression equation (2) may be used to determine the productivity of a sectional pneumatic screw conveyor depending on the screw rotational speed *n*, the outlet opening area of the conveyor hopper *S*, the moisture of the transported material *W* and the air pressure *P* within the following limits of change of the input factors: $120 \le n \le 400$ (rpm.); $10 \le S \le 40$ (cm^2); $8 \le W \le 20$ (%); $0.25 \le P \le 0.45$ (MPa). The obtained regression equation (2) can be used to determine the productivity of a pneumatic screw conveyor depending on the screw rotational speed *n*, the outlet opening area of the conveyor hopper *S*, the moisture of the transported material *W* and the air pressure *P* within the following limits of change in the input factors: *n* within 120…400 (rpm.); *S* within 10 … 40 (cm^2); *W* within 8…20 (%); *P* within 0.25…0.45 (MPa).

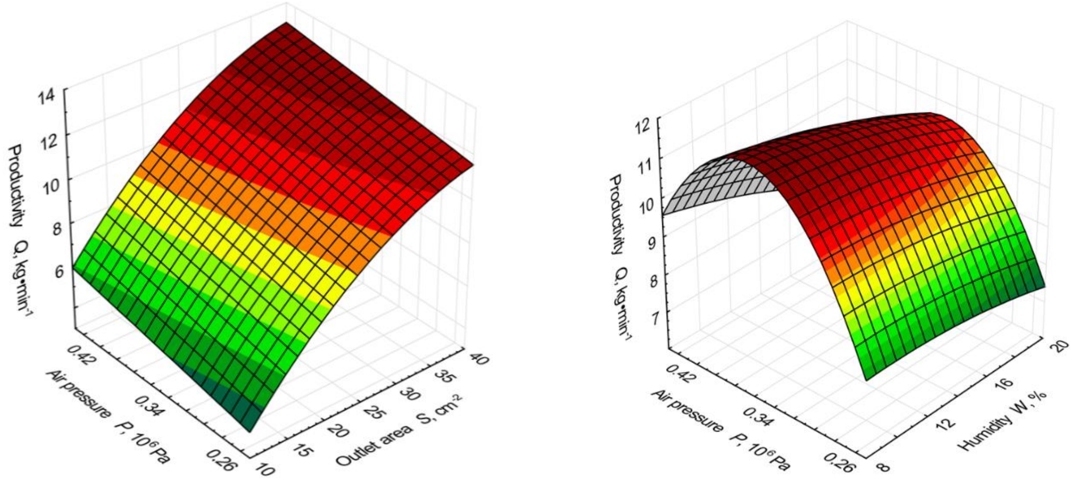
RESULTS

Using the Statistica software package, graphical representations of the intermediate generalized regression models were generated in the form of quadratic response surfaces describing changes in the productivity of the sectional pneumatic screw conveyor *Q* as a function of two varying factors $x_{i\,(1,\,2)}$, while the remaining third and fourth factors were held constant $x_{i\,(3,\,4)}$ = const at their zero (coded) levels (Fig. 2).



a) b)

c) d)



e) f)

Fig. 2 – Performance response surface of a pneumatic screw conveyor as a function of:
a – $Q = f(n; S)$; b – $Q = f(n; W)$; c – $Q = f(n; P)$; d – $Q = f(S; W)$; e – $Q = f(S; P)$; f – $Q = f(W; P)$

When changing the rotational speed of the screw within the range of 120...400 rpm, productivity *Q* increases by 31.7 %; when changing the outlet opening area of the conveyor hopper *S* from 10 cm^2 to 40 cm^2, productivity *Q* increases by 57.4 %; and when changing the moisture of the transported bulk material *W* within the range of 8...20 %, productivity *Q* decreases by 17.2 %. This occurs due to adhesion of the bulk particles of the material and an increase in its mass, which leads to a decrease in the speed of its movement.

The productivity of a sectional pneumatic screw conveyor, depending on the combination of factors of the air pressure *P* from 0.25 MPa to 0.45 MPa and change in the rotational speed of the screw within 120...400 rpm, productivity *Q* increases by 41.7 %; the combination of factors of the air pressure *P* from 0.25 MPa to 0.45 MPa and change in the outlet opening area of the conveyor hopper *S* from 10 cm^2 to 40 cm^2, productivity *Q* increases by 61.5 % and the combination of factors of the air pressure *P* from 0.25 MPa to 0.45 MPa and change in the moisture of the bulk transported material *W* within 8...20 %, productivity *Q* changes by 27.3 %. When changing the air pressure *P* from 0.25 MPa to 0.45 MPa, productivity *Q* increases by 15.9 %, which confirms the feasibility of using the developed sectional pneumatic screw conveyor for transport of bulk materials in the agro-industrial production and the food industry.

Several studies have reported the results of investigations into the influence of design and operating parameters of combined pneumatic screw conveyors on grain transport productivity *(Hevko et al., 2018; Trokhaniak, 2021; Hevko et al., 2021)*. These studies present graphical relationships between the material movement force and air pressure, as well as the effect of transporting various bulk materials on their volume at a constant air pressure. In addition, research methodologies have been proposed for determining performance indicators arising during the movement of bulk materials under the combined influence of air pressure and material volume for different grain types. However, the productivity values *Q* of the developed sectional pneumatic screw conveyor presented in this study exceed those reported in previous works *(Hevko et al., 2021)* by approximately 11–14% when transporting wheat grain.

The increase in conveyor productivity is attributed to the helical arrangement of the openings within each connecting sleeve of the conveyor line and to the installation of a bladed rotor with flat blades at the free end of the feeder cantilever shaft. These design features significantly increase the bulk material transport velocity and, consequently, enhance overall transport productivity.

CONCLUSIONS

Based on the analysis of relevant literature and patent sources, a sectional pneumatic screw conveyor was developed for experimental investigation of bulk material transport in the food industry.

Experimental laboratory studies enabled the construction of regression equations and response surfaces to determine the influence of the controlled factors on conveyor productivity. Analysis of the regression models showed that the screw rotational speed $x_1(n)$ and the outlet opening area of the conveyor hopper $x_2(S)$ are the dominant factors contributing to productivity enhancement.

An increase in the moisture content of the bulk material $x_3(W)$ results in a reduction in productivity, whereas an increase in air pressure $x_4(P)$ leads to higher productivity.

When the screw rotational speed was increased from 120 to 400 rpm, the conveyor productivity *Q* increased by 31.7%. Increasing the hopper outlet opening area from 10 cm^2 to 40 cm^2 resulted in a 57.4% increase in productivity. Conversely, increasing the bulk material moisture content from 8% to 20% caused a 17.2% decrease in productivity due to increased material adhesion and mass, which reduced transport velocity. Increasing the supplied air pressure from 0.25 MPa to 0.45 MPa led to a 15.9% increase in productivity.

The obtained results confirm the effectiveness of the proposed conveyor design and justify further experimental and design optimization aimed at improving the performance of pneumatic screw conveyors for bulk food materials.

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