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INVESTIGATION OF SPIRAL-SCREW CONVEYOR PERFORMANCE DEPENDING ON THE LOADING METHOD

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The article is devoted to the study of the influence of the loading method on the productivity of a spiral-screw conveyor - one of the most common types of equipment for moving bulk materials in agricultural production, food and processing industries. The principle of operation of screw conveyors is considered, which is based on the movement of the load along the transport channel under the action of a rotating working body due to the dragging of the material along the inner surface of the casing, regardless of the physical and mechanical properties of the load. The features of the functioning of slow-speed and high-speed screws are analyzed, the influence of the screw rotation frequency, winding pitch, working body diameter and conveyor inclination angle on the nature of the movement of material particles and the productivity of the system as a whole is established. It is shown that in slow-moving screws, particles move mainly translationally, while in high-speed ones, their trajectory is complicated by centrifugal forces.

Particular attention is paid to the comparative analysis of loading methods - gravitational and forced, as well as kinematic schemes of material supply: axial, angular and circular. It is shown that the shape of the loading hopper significantly affects the uniformity of cargo supply and the conveyor productivity coefficient, the value of which can vary from 0.62 to 1.00 depending on the design of the hopper. It is established that the use of a circular loading chamber increases the conveyor productivity by 6–23%, and the use of feeders - by 1.7–3 times. Theoretical dependencies are given for determining the critical angular velocity, productivity and drive power of the screw conveyor, taking into account the design and operating parameters of the screw.

The electromechanical system of the conveyor is considered as a single complex "loading device - screw - electric drive", in which the change in resistance to material movement depending on the loading scheme is directly reflected in the loading characteristics of the drive asynchronous electric motor and its operating modes.

***Keywords**: spiral-screw conveyor, screw, productivity, loading method, loading hopper, rotation frequency, critical angular velocity, bulk materials, energy intensity, productivity coefficient.*

Eq. 10. Fig. 4. Tabl. 1. Ref. 18.

1. Problem formulation

Screw conveyors and spiral screw conveyors remain among the most widely used types of continuous conveying equipment for handling bulk, fine-grained, and moist materials in the agricultural sector, as well as in the food, chemical, construction, and mining industries. Despite their seemingly simple design, the mechanics of the conveying process are highly complex. Consequently, the design of such conveyors has traditionally relied primarily on empirical data obtained through experimental studies, since the conveying process is governed by the combined effects of screw rotational speed, conveyor inclination angle, and the degree of channel filling with the conveyed material. This creates a continuing need to refine existing design models and to identify opportunities for increasing conveyor capacity without increasing the energy consumption of the conveying process.

A significant contribution to the development of the theory and design of screw conveying and processing mechanisms has been made by the Ternopil scientific school. A considerable number of

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fundamental and applied studies on the substantiation of the design parameters of screw conveyors, including flexible, telescopic, and multifunctional systems, have been carried out by the research team consisting of R. M. Rohatynskyi, I. B. Hevko, and A. Ye. Diachun. Their work established the scientific and engineering foundations for the design and development of screw conveying and processing mechanisms. These studies were further advanced through research on flexible screw conveyors, including their design, manufacturing technology, and experimental evaluation of performance characteristics, as well as investigations into the development of advanced screw conveyor designs conducted by R. M. Rohatynskyi, I. B. Hevko, O. L. Liashuk, V. Z. Hud, and A. Ye. Diachun. Particular attention should be paid to doctoral research in which empirical relationships describing the effects of design parameters and operating conditions of multifunctional screw conveyors on conveying capacity, power consumption, and the non-uniformity of bulk material mixing were established for the first time. These findings confirm the importance of investigating the relationship between operating parameters and the performance indicators of screw conveying systems. The conveying capacity of variable-pitch screw conveyors used for grain transportation has also attracted considerable attention from Ukrainian researchers, who have systematically reviewed and summarized both domestic and international studies on the interaction between the grain flow and the working surface of the screw conveyor.

In international research, the Discrete Element Method (DEM) has become the predominant approach for analyzing the performance of screw conveyors. The pioneering studies by Peter J. Owen and Paul W. Cleary demonstrated that screw conveyor performance is primarily governed by operating conditions, including screw rotational speed, conveyor inclination angle, and the degree of volumetric filling with bulk material. Their work also showed that DEM simulations enable accurate prediction of particle velocities, mass flow rate, energy dissipation, and power consumption under varying operating conditions. Over the past decade, these approaches have been continuously refined and expanded. Recent review studies indicate that DEM-based research increasingly integrates particle properties, screw geometry, and operating conditions with experimental observations and theoretical models. Current research priorities include improving particle models by accounting for cohesion, particle breakage, and irregular particle shapes, as well as integrating DEM with machine learning techniques to enhance predictive capabilities. In parallel, comparative studies of national engineering standards for screw conveyor design have shown that the semi-empirical parameters incorporated into the American design standard tend to overestimate the required drive power. At the same time, new screw conveyor designs continue to emerge. In particular, a 2024 study reported the performance characteristics of a bionic screw conveyor with a non-uniform surface for conveying granular materials, demonstrating the ongoing development of innovative working body designs aimed at improving conveying efficiency.

Nevertheless, despite the substantial body of theoretical and experimental research accumulated to date, the specific influence of the loading method and feeding configuration–including gravity or forced feeding, as well as axial, angular, and circumferential feeding–on the performance of spiral screw conveyors has received only limited and fragmented attention. Most studies have focused primarily on the geometric and operating parameters of the screw itself, such as rotational speed, pitch, and diameter, whereas the design and geometry of the loading unit have generally been treated as secondary factors. This highlights the need for a systematic investigation of the influence of loading configurations and feeding kinematics on the conveying capacity, energy consumption, and conveying quality of bulk materials in spiral screw conveyors. Addressing this issue constitutes the primary objective of the present study.

2. Analysis of recent research and publications

To achieve the stated aim, the following research objectives were established:

1. To analyze the current state of the theory and practice of spiral screw conveyor design and to summarize the findings of domestic and international studies on the influence of the screw's design and operating parameters on the conveying process of bulk materials.

2. To classify the existing loading methods for screw conveyors (gravity and forced feeding) and the kinematic material feeding configurations (axial, angular, and circumferential), and to identify their design characteristics and fields of application.

3. To establish the relationship between the geometry of the loading hopper and the conveyor performance coefficient through a comparative analysis of different loading device designs.

4. To provide a theoretical justification of the relationships used to determine the critical angular velocity of the screw, the conveying capacity, and the drive power of the conveyor, taking into account the material loading method.

5. To determine the quantitative effects of the conveyor inclination angle, screw rotational speed, and loading configuration on the performance of the conveying, loading, and discharge units of the conveyor system.

6. To develop recommendations for selecting the optimal loading device design for a spiral screw conveyor in order to improve its operational efficiency under specific technological conditions.

The accomplishment of these objectives will provide a scientific basis for practical recommendations on the design and modernization of loading units for spiral screw conveyors, with the aim of increasing their conveying capacity and improving the energy efficiency of the conveying process.

3. The purpose of the article

The aim of this study is to establish the relationships between the loading method and the structural–kinematic configuration of the loading system and the performance of a spiral screw conveyor, as well as to substantiate the rational design parameters of the loading device that ensure increased conveying capacity of bulk materials while minimizing the energy consumption of the conveying process and the mechanical damage to the conveyed material.

4. Results and discussion

Research Materials. The object of the study is a spiral screw conveyor used for conveying bulk agricultural and industrial materials, including grain, compound feed, silage, fertilizers, and similar bulk products. The subject of the research is the relationship between the conveyor loading method, the design and operating parameters of the screw (diameter D, pitch s, pitch-to-diameter ratio ψ=s/D, rotational speed n, inclination angle β) and the performance indicators of the conveyor, namely conveying capacity Q, drive power N i and specific energy consumption Nsp.

The research materials included theoretical relationships describing the motion of a bulk material particle within the conveying channel under the combined action of gravitational force, frictional forces acting between the particle and the screw flight as well as the casing, and centrifugal force. The analysis also incorporated comparative data for five loading hopper configurations, ranging from a straight-walled design to an optimized streamlined geometry, together with generalized empirical relationships describing the conveying capacity of the conveyor as a function of the loading and discharge configurations (axial, angular, and circumferential).

Research Results.

1. Effect of the loading hopper geometry. A comparative analysis of five loading hopper configurations (Table 1) demonstrated that replacing a straight-walled hopper with an optimized streamlined design increases the conveyor performance coefficient from 0.62 to 1.00, i.e., by more than 1.6 times. Intermediate configurations, including partially rounded walls, inclined guiding surfaces, and smoothly curved walls, exhibited a gradual increase in the performance coefficient (0.73, 0.78, and 0.94, respectively). These results confirm the decisive role of hopper geometry in reducing stagnant zones and ensuring a uniform supply of material to the screw.

2. Effect of the loading configuration on conveying capacity. The results showed that the use of a circumferential loading chamber, in which the screw is partially immersed in the bulk material, increases conveying capacity by 6–23% compared with the conventional axial loading configuration owing to more efficient material capture by the screw flights. The use of dedicated feeding devices under forced loading conditions produces an even greater improvement, increasing conveying capacity by a factor of 1.7–3. This effect is particularly significant for high-speed screw conveyors, where the centrifugal action of the rotating screw creates a braking effect at the material inlet.

3. Effect of the discharge configuration. A comparison of discharge system configurations demonstrated that axial and circumferential discharge arrangements provide the highest conveying capacity, whereas angular discharge designs reduce capacity by 6–12% while simultaneously increasing the required drive power by 50% or more. These findings indicate that the geometry of the discharge unit is as critical to the overall system performance as the loading configuration.

4. Effect of conveyor orientation. The conveying capacity of vertical screw conveyors was found to be only 30–40% of that of horizontal conveyors with identical screw parameters, This reduction is attributed to the requirement that the operating rotational speed must exceed the critical angular velocity ω_{CR} to ensure stable operation of a vertical screw conveyor, together with the additional retarding effect of gravity on the axial movement of material particles.

5. Coordination of subsystem capacities. The theoretical analysis confirmed that stable conveyor operation is achieved only when the following condition is satisfied: $P_z < P_t <; P_r$ where the capacities of the loading, conveying, and discharge units are properly coordinated. Violation of this condition ($P_z > P_t >; P_r$) results in excessive abrasion and particle breakage, as well as an increased risk of conveyor blockage. This finding highlights the necessity of integrated design of all three subsystems rather than optimizing only the screw.

6. Theoretical relationship for conveying capacity. Based on the equations describing particle motion and by introducing the actual material volume through the inter-flight filling coefficient kv = 0-0,9 the following design equation for conveying capacity was obtained: $Q = 47 \cdot kQ \cdot \psi \cdot D^3 \cdot n \cdot \rho$, яка дозволяє визначати необхідний діаметр гвинта D за заданою продуктивністю Q з подальшим округленням за ДСТУ.which enables the required screw diameter (D) to be determined for a specified conveying capacity (Q), followed by standardization in accordance with the relevant national standard.

The obtained results confirm that the loading method is not a secondary factor but one of the key determinants of the performance of a spiral screw conveyor. By selecting an appropriate loading hopper geometry and material feeding configuration, the conveying capacity of the system can be increased by 60–200% without modifying the geometric parameters of the screw itself.

The conveying process of bulk materials in screw and spiral screw conveyors is based on the movement of the material along the conveying channel under the action of a rotating working element. During screw rotation, material particles are captured by the screw flights and transported toward the discharge outlet. The principal conveying mechanism is the dragging of the material along the inner surface of the casing, which occurs regardless of the physical and mechanical properties of the material, its aggregate state, or the design parameters of the screw. However, the efficiency of the conveying process is largely determined by the interaction between the bulk material, the working element, and the inner surface of the conveyor.

The motion of bulk material particles within the conveying channel depends on the screw rotational speed, the geometric parameters of the working element, and the coefficients of friction between the bulk material and the conveyor surfaces.

The motion of bulk material particles within the conveying channel depends on the rotational speed of the screw, the geometric parameters of the working element, and the coefficients of friction between the material and the conveyor surfaces. Changes in the rotational speed alter the trajectories of individual particles, directly affecting conveyor capacity, energy consumption, and the degree of mechanical impact on the conveyed material..

According to the scientific and technical literature, screw conveyors are generally classified as low-speed and high-speed conveyors. Low-speed conveyors are characterized by a relatively stable conveying regime in which material particles move predominantly in the axial direction. Under these conditions, the mechanical impact on the material is reduced, resulting in lower levels of particle degradation and abrasion. However, the conveying capacity of the system may be limited.

In high-speed screw conveyors, the conveying process is accompanied by a significant increase in centrifugal forces acting on the material particles. As a result, the material interacts more intensively with the inner surface of the casing, and the particle trajectories become more complex and spatially three-dimensional. Increasing the screw rotational speed enhances conveyor capacity; however, excessive rotational speeds may lead to increased energy consumption, accelerated wear of the working surfaces, and deterioration of the quality of the conveyed material.

The performance of a spiral screw conveyor is strongly influenced by its structural and operating parameters, which determine the efficiency of bulk material transportation. The principal parameters include the screw diameter, screw pitch, rotational speed of the working element, conveying section length, conveyor inclination angle, and the filling ratio of the conveying channel. The interaction among these parameters directly affects conveyor capacity, particle flow characteristics, and the energy performance of the conveying system.

One of the most important operating parameters is the rotational speed of the screw, as it determines both the conveying velocity of the material and the intensity of particle interaction with the working surfaces. Insufficient rotational speed results in reduced conveyor capacity, whereas excessively high rotational speeds may increase material damage and energy consumption. Therefore, the design of conveying systems requires the determination of rational operating conditions that ensure an optimal balance between productivity, reliability, and energy efficiency.

Another important design parameter is the screw pitch, which determines the volume of material transported during one revolution of the working element. An increase in screw pitch improves conveyor capacity; however, it may also increase the load on the drive system and reduce the stability of bulk material flow. In addition, the screw diameter has a significant influence on the conveying process, as it determines the conveyor throughput and the distribution of material within the conveying channel.

The operating efficiency of a spiral screw conveyor is determined by the combined effect of its structural and operating parameters, which should be considered as an integrated system. The selection of rational conveyor parameters ensures stable transportation of bulk materials, increases equipment productivity, reduces energy consumption, and minimizes the wear of conveyor components.

In low-speed screw conveyors (Figure 1 a), when $\omega < \omega_k$(the actual angular velocity is lower than the critical angular velocity) and $(\omega^2 R/g)$ <1, particle A performs oscillatory motion at a variable radius while simultaneously moving in the axial direction. Such conveyors are commonly used for conveying viscous, adhesive, and cohesive materials, including steamed potatoes, silage, semi-solid manure, and similar materials.

In a high-speed screw conveyor (Figure 1 b), under the conditions $\omega < \omega_k$ i $((\omega^2 R/g)$ <1, the conveyed material is pressed concentrically against the casing surface by centrifugal forces, while particle A follows a helical trajectory with a pitch $s_M < s$, where s is the screw pitch.

In practice, owing to particle size heterogeneity, continuous mixing of the material, and non-uniform loading conditions, the actual particle trajectories are considerably more complex. High-speed screw conveyors are widely used for vertical and inclined transportation of bulk and liquid materials, including grain, liquid manure, and feed mixtures.

For reliable conveyor operation, the design must ensure an appropriate relationship between the capacities of the loading- P_z, conveying - P_t and discharge-P_r units.

When $P_z < P_t <; P_r$, the overall conveyor capacity is limited by the loading capacity, i.e., P = P_z. Conversely, if $P_z > P_t > P_r$ excessive friction and particle breakage may occur, potentially leading to clogging of the conveyor. Therefore, the operating principle and the design of individual conveyor components have a significant influence on the overall conveying capacity.

As the screw rotational speed increases, a braking effect on the conveyed material becomes more pronounced. Consequently, both the loading capacity P_z, and the discharge capacity P_r decrease, whereas the conveying capacity of the screw P_t increases. For this reason, high-speed screw conveyors are often equipped with specialized feeding devices to improve loading efficiency.

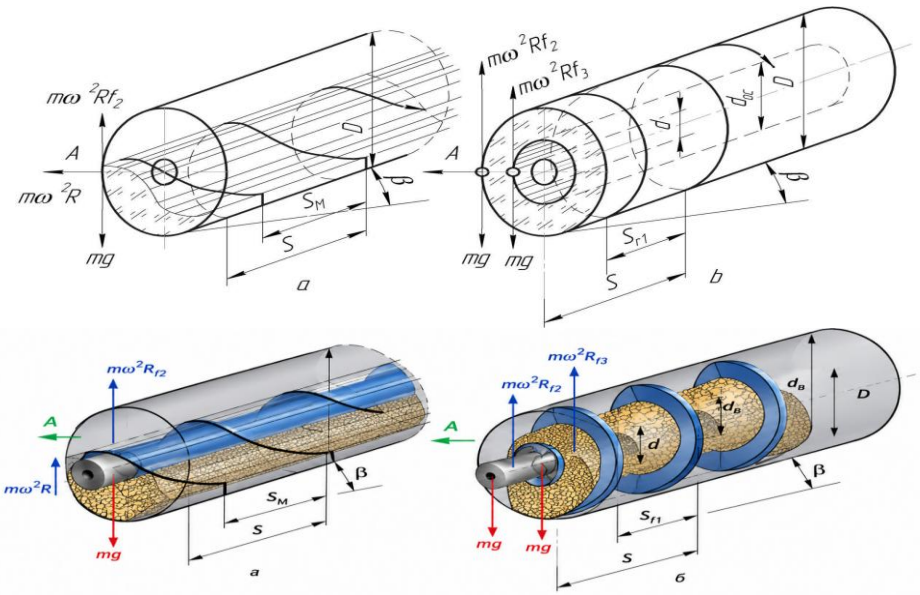


Fig. 1. Schematic diagrams of screw conveyors: (a) low-speed screw conveyor; (b) high-speed screw conveyor

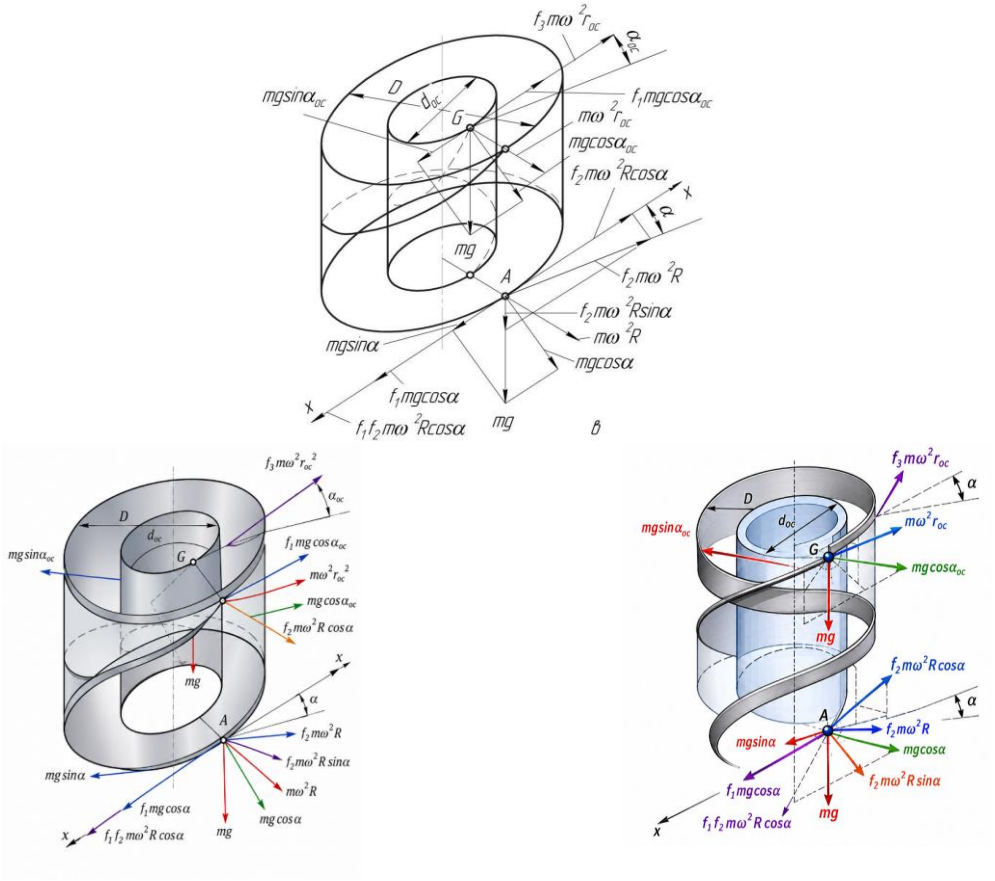


Fig. 2. Schematic diagram of a vertical screw conveyor

The operating principle of screw and spiral screw conveyors is based on the continuous movement of bulk material along the conveying channel under the action of a rotating working element. The performance of the conveyor largely depends on the method of material feeding, the flow characteristics within the loading zone, and the interaction between the conveyed material and the screw surface. Therefore, the proper selection of the loading device design and the material feeding arrangement is of primary importance in the design of conveying systems.

Two principal loading methods are employed in screw conveyors: gravity feeding and forced feeding. In gravity feeding, the material enters the conveying section under the action of its own weight through a hopper or an inlet chute. This method is characterized by its simple design and is commonly used in conveyors intended for transporting grain, compound feed, and fine bulk materials. However, the efficiency of gravity feeding depends on the flowability of the material, its angle of repose, and the uniformity of material supply to the working element.

Forced feeding is applied when a stable and controlled material supply is required regardless of the physical and mechanical properties of the conveyed material. In such systems, the material is delivered to the conveying section by auxiliary feeders, metering devices, or specialized feeding mechanisms. This loading method is primarily used for materials with high moisture content, a tendency to compact, or a non-uniform structure.

Depending on the kinematics of material flow, gravity loading and discharge processes can be classified into several principal types. One of the most common is axial loading, in which the material moves predominantly along the screw axis. This configuration ensures a uniform supply of material into the conveying channel and provides favorable conditions for stable transportation of bulk solids. Axial loading is characterized by relatively low energy losses and reduced mechanical impact on the conveyed material.

Angular loading involves feeding the material at a certain angle relative to the conveyor axis. In this case, the material flow becomes more complex because additional interaction forces arise between the particles and the screw surface. This loading method is employed where installation space is limited or when the conveyor must be integrated into complex technological production lines. However, angular loading may result

in a non-uniform distribution of material within the conveying channel and increased local loads acting on the screw.

Peripheral (circumferential) loading is achieved by enlarging the loading chamber or by partially immersing the screw working element directly into the bulk material. Under these conditions, the screw flights capture the material more intensively, thereby increasing the conveying capacity of the system. This loading arrangement is frequently employed in spiral screw conveyors designed for transporting bulk, fibrous, or heterogeneous materials. Nevertheless, the efficiency of peripheral loading depends on the geometric parameters of the loading chamber and the operating conditions of the conveyor.

An important component of the conveying system is the loading hopper, whose geometry directly influences the uniformity of material supply, the filling ratio of the conveying channel, and the stability of screw conveyor operation. An improperly designed hopper may lead to the formation of stagnant zones, irregular material flow, or conveyor overloading. Therefore, when designing spiral screw conveyors, it is essential to consider the geometry of the loading device, the characteristics of the bulk material, and the specific requirements of the technological process.

To evaluate the effectiveness of different loading device designs, it is advisable to perform a comparative analysis of hopper configurations in order to determine the most suitable design for specific operating conditions. Table 1 presents a comparative evaluation of loading hopper configurations, providing an assessment of their influence on material feeding stability, conveyor capacity, and the overall performance of the conveying system.

Table 1.

Comparative evaluation of loading hopper configurations.

Parameter	Configuration 1	Configuration 2	Configuration 3	Configuration 4	Configuration 5
Hopper geometry	Straight walls	Partially rounded walls	Inclined guide surfaces	Smooth curved walls	Optimized streamlined shape
Material feeding conditions	Non-uniform material feeding	Improved material inflow	Stable material flow	Reduced stagnant zones	Maximum feeding uniformity
Performance coefficient	0,62	0,73	0,78	0,94	1,00

To improve material intake and reduce the initial resistance encountered during conveying, screw conveyors are often designed with a progressively increasing screw pitch. The highest discharge capacity is achieved with axial and peripheral (circumferential) discharge configurations. In contrast, angular discharge arrangements reduce conveyor capacity by approximately 6–12%, while the required drive power may increase by 50% or more compared with axial discharge configurations.

The conveying capacity of vertical screw conveyors is approximately 30–40% of that of horizontal screw conveyors. The use of a peripheral (circumferential) loading chamber can increase conveying capacity by 6–23%, whereas the application of auxiliary feeding devices can improve capacity by a factor of 1.7–3.0.

The conveying section of a screw conveyor consists of a screw and a trough. In horizontal screw conveyors, the trough may have an open configuration, whereas steeply inclined and vertical screw conveyors typically employ a tubular casing. In open troughs, the screw may be completely submerged beneath a passive layer of material when the filling coefficient exceeds unity. The maximum conveying length of screw conveyors can reach 60 m, while the maximum vertical conveying height may be up to 20 m.

The principal parameters of a screw conveyor are classified into three groups:

- Geometric parameters: screw diameter (D), screw pitch (s), the pitch-to-diameter ratio ($\psi = s/D$), and shaft diameter (d);
- Kinematic parameters: rotational speed (n) and angular velocity (ω);
- Operating parameters: the capacity coefficient (k_n) and the coefficient of friction (f), the increase of which results in a reduction in conveyor capacity.

The pitch-to-diameter ratio is typically within the range $\psi = 0.6–1.25$. Selecting values outside this range generally leads to a decrease in conveying performance. The screw diameter usually varies from 50 to 600 mm.

Depending on the characteristics of the conveyed material, the capacity coefficient of vertical screw

conveyors is typically 2–3 times lower than that of horizontal conveyors. The screw rotational speed generally ranges from 5 to 1300 rpm (min^{-1}).

During the motion of a material particle within a screw conveyor, several forces act simultaneously on the particle: the gravitational force mg; the friction force between the particle and the screw surface f_1 mg, which promotes particle entrainment by the rotating screw; the pressure exerted by adjacent particles kf_1 mg where **k** is a proportionality coefficient; the centrifugal force $m\omega^2$ r, which presses the particle against the casing; the friction force between the particle and the casing f_2 $m\omega^2$ r, which opposes the rotational motion of the particle together with the screw; and the internal friction forces within the bulk material. The combined action of these forces causes the particle to slip along the screw flight ($\omega_m<\omega$) while simultaneously undergoing axial displacement, thereby producing the conveying effect.

The reliable operation of a vertical screw conveyor is ensured when the screw angular velocity exceeds the critical value, i.e., $\omega>\omega_k$ Under this condition, the centrifugal force is sufficient to maintain continuous contact between the material particles and the inner surface of the casing. The critical angular velocities (see Figure 2) for particles located at points A and B are determined from the force equilibrium equations projected onto the *x–x* axis:

$$mgsinsin\alpha + f_1 mgcoscos\alpha + f_1 f_2 m\omega^2 Rsinsin\alpha - f_2 m\omega^2 Rcoscos\alpha = 0$$
$$mgsinsin\alpha_{oc} + f_1 mgcoscos\alpha_{oc} + f_3 m\omega^2 r_{oc} = 0 \quad (1)$$

Where $f_1 f_2 f_3$- are the coefficients of friction between the conveyed material and the screw, the casing, and the bulk material itself; $r_{oc} = 0{,}5d_{oc}$, where r_{oc} and d_{oc} are the radius and diameter of the material heap, respectively, and a_{oc}-is the angle of repose at which conveying becomes impossible.

After mathematical transformation, the corresponding expressions for the outer point A and the inner point B (Figure 2) can be obtained as follows:

$$\omega_{kA} = \sqrt{\frac{2gtg(\alpha+\varphi_1)}{Df_2}};\ \omega_{кB} = \sqrt{\frac{2gsinsin(\alpha_{oc}-\varphi_1)}{d_{oc}f_3 coscos\varphi_1}}. \quad (2)$$

For a horizontal screw conveyor (see Figure 1), the critical angular velocities corresponding to the outer point A and the inner point B are given by:

$$\omega_{kA} = \sqrt{\frac{2g}{Df_2}};\ \omega_{kB} = \sqrt{\frac{2g}{d_{oc}f_3}}. \quad (3)$$

The operating rotational speed of the screw in high-speed conveyors is generally several times greater than the critical rotational speed and satisfies the condition: $n > n_k = 30\,\omega_k/\pi$. For low-speed screw conveyors, the recommended operating speed is determined from the empirical relationship $n < A/\sqrt{D}$. Where A = 65-50 - for light materials (e.g., grain, chopped forage, and semi-solid manure) and A = 50-30 for heavy materials (e.g., coal, salt, root crops, and mineral fertilizers).

The axial conveying velocity of the material v_s (Figure 3 a) depends on the peripheral velocity of the screw v and the theoretical axial conveying velocity v_{sr}, corresponding to the motion of particle A without rotational slip. Considering the relationships. $v = \frac{\pi Dn}{60}; v_{ST} = vtga; v_{ST} = Sn/60$ and based on the velocity diagram, the following relationship can be obtained: $vs = k_v$,

$$v_{ST} = \frac{k_v Sn}{60}, \text{де} k_v = \frac{coscos\alpha coscos(\alpha+\varphi_1)}{coscos\varphi_1} = \frac{v-v_M}{v} = 1 - \frac{n_M}{n} \quad (4)$$

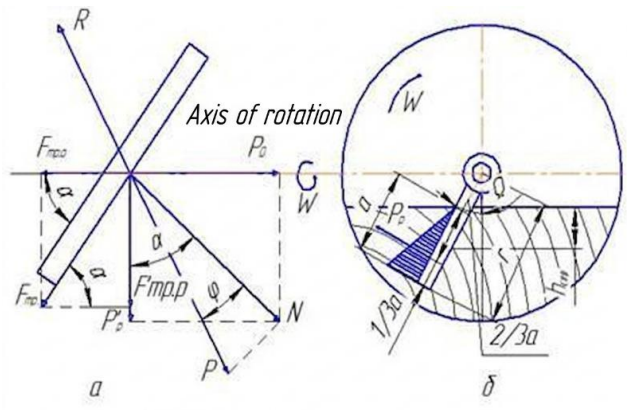


Fig. 3. Calculation schemes: (a) axial conveying velocity; (b) spiral screw

Theoretical calculations and experimental studies show that, depending on the type of conveyed material, the velocity coefficient k_v ranges from 0.6 to 0.9, with higher values typically adopted for high-speed screw conveyors.

The theoretical conveying capacity can be expressed in the general form as: $Q_t = 3600\rho F_T v_s$

Where F_T – is the cross-sectional area of the material flow, v_s is the axial conveying velocity of the material, and $\rho -$ is the bulk density of the conveyed material.

The conveying process in a screw conveyor is highly complex and is influenced by several factors. One of the most significant is the screw rotational speed *n* (see Figure 1 b), As the rotational speed increases, the conveying capacity initially rises, reaches a maximum, and subsequently decreases. Another important factor is the conveyor inclination angle, β (see Table 1), as the inclination angle increases, the conveying capacity decreases. This effect is taken into account by the inclination coefficient $k_\beta = 1{,}0 \dots 0{,}3$; Furthermore, the design of the loading and discharge devices influences conveyor performance and can be incorporated into the calculation through the loading coefficient $k_z = 1{,}0 \dots 0{,}5$i $k_r = 1{,}0 \dots 0{,}94$.

Expressing the actual volume of material conveyed over one screw pitch as $V_g = F_c S = k_V V$, where V = 0,785 ($D^2 - d^2$) s and k_v= 0,2 ... 0,9 – is the inter-flight volume utilization coefficient, while substituting the expression for the axial conveying velocity, $v_s = k_v v_{ST} = k_v\, sn/60$ together with the corresponding correction coefficients, the following equation is obtained:

$$Q = 47 k_Q \psi D^3 n \rho, \tag{5}$$

from which:

$$D = \sqrt[3]{\frac{Q}{47 k_Q \psi n \rho}}. \tag{6}$$

The calculated screw diameter is then rounded to the nearest standard value in accordance with the applicable national standard (DSTU) and verified using the design criterion $D \geq (4 \dots 10)A$, where (A) is the maximum particle size of the conveyed material. For vertical screw conveyors, lower values of the pitch-to-diameter ratio Ψ and should satisfy the condition $\alpha < \varphi$ angle of repose of the bulk material.

The improvement of screw conveyor performance is primarily associated with increasing the screw rotational speed, the use of lightweight structural materials, and the optimization of loading and discharge devices.

Flexible screw conveyors are particularly suitable for conveying distances of 12–15 m in the horizontal direction and 3–4 m in the vertical direction. Their conveying capacity typically reaches 10–18 $m^3\ h^{-1}$ and can be estimated using the simplified expression:

$$Q = 40\rho \frac{\pi d^2}{4} Sn, \tag{7}$$

where D = 25-200 mm – casing diameter, d - spring diameter, where d/D=0,75-0,9. Recommended operating conditions: n = 1500 ... 500$m \in$ $^{-1}$, s/d=0,75-1,4 and α = 15-30°.

The power requirement N and the specific energy consumption $N_{\text{уД}} = N/Q$ depend primarily on the conveyor inclination angle β and the screw rotational speed n. The energy required for conveying increases with both increasing rotational speed and increasing inclination angle. Nevertheless, the overall efficiency of the conveying process can be improved by increasing conveyor capacity and optimizing the screw design.

During conveyor operation, power is consumed to overcome the following resistance components.

N_1 - friction between the conveyed material and the trough (or casing);

N_2 - friction between the conveyed material and the screw flights;

N_3 - friction in the thrust bearing;

N_4 - friction in the radial bearings.

The resistance forces and the corresponding power losses are determined using the analytical methods presented previously. Accordingly, the total power requirement of the screw conveyor is expressed as follows:

$$N = K_u\,[(N_1 + N_2)k + N_3 + N_4]/\eta \tag{8}$$

where $K_u = 1{,}05 \dots 1{,}2; k = 1{,}05 \dots 1{,}4$ і η where the coefficients represent, respectively, the allowance for overcoming starting inertia, the resistance associated with material mixing, and the efficiency of the drive mechanism.

For preliminary estimation of the screw conveyor power requirement, the following empirical equation is commonly used:

$$N = kcgQ(L + H)\omega_0 \tag{9}$$

Where c=1,0-3,0 is the coefficient accounting for the influence of the conveyor inclination angle β=20, 90° – and ω_0 = 1,2-4,0 – is the coefficient of resistance to material movement. For flexible screw conveyors ω_0 = 7-21 depending on the properties of the conveyed material and the complexity of the conveying path.

The required motor power, taking into account the overload factor K_0 =1,3 ... 1,5 and the drive efficiency η= 0,7-0,9 is determined as follows;

$$N_D = K_0 \frac{N}{\eta} \quad (10)$$

Determination of Resistance Forces and Drive Power (continued). The relationships obtained in Eqs. (8)–(10) make it possible not only to determine the drive power required for a specific conveyor design but also to quantitatively evaluate the influence of the loading and discharge methods on the energy performance of the system. Thus, these relationships directly link the conveyor loading and discharge configurations with its power consumption, making it possible to assess the effect of different loading schemes on the energy efficiency of the conveying process. Consequently, the proposed analytical expressions provide a theoretical basis for optimizing the design of loading and discharge units with the aim of increasing conveying capacity while minimizing the energy consumption of spiral screw conveyors.

Relationship Between Drive Power and the Loading Configuration. The coefficients k_Z = 1.0–0.5 and k_L = 1.0–0.94, which characterize the design of the loading and discharge units, are incorporated into the calculation of the conveying capacity Q and, consequently, indirectly affect Eqs. (9) and (10), since the required drive power (N) is directly proportional to the conveying capacity. Therefore, a less efficient loading configuration (i.e., a decrease in k_Z from 1.0 to 0.5) not only reduces the conveying capacity by approximately 50% under otherwise identical operating conditions but also necessitates a compensatory increase in the screw rotational speed (n) to maintain the required conveying capacity. According to Eq. (9), this results in an additional increase in the required drive power, because N increases with increasing rotational speed at a rate greater than linear due to the dependence of the resistance to material movement on the sliding velocity of the bulk material particles.

The result established earlier in this study–namely, that the drive power increases by 50% or more for an angular discharge configuration compared with an axial discharge configuration–provides a practical illustration of this effect. A poorly designed discharge configuration forces the conveyor to operate under conditions of increased resistance, corresponding to higher values of the coefficient c in Eq. (9), which directly leads to an increase in the required drive power N_D without any changes in the screw diameter, pitch, or material. This finding further confirms that the design of the loading and discharge units is a key factor affecting not only the conveying capacity but also the overall energy efficiency of the spiral screw conveyor.

Example of Practical Evaluation. Assuming constant operating conditions for the conveyor (Q = const, L = const, H = const) and adopting, ω_0 = 2,0 which is a representative value for bulk agricultural materials, the transition from an axial to an angular discharge configuration approximately doubles the coefficient c owing to the increased sliding distance and friction angle. According to Eq. (9), this results in a proportional increase in the calculated drive power N, When the overload factor K_0 = 1,3-1,5 is taken into account, the required electric motor power N_D. increases accordingly. These results demonstrate that optimizing the design of the loading and discharge units is an economically justified approach to reducing the specific energy consumption N_D = N/Q, This approach represents an effective alternative to the conventional strategy of increasing the screw diameter or pitch, which requires substantially more extensive design modifications.

Practical Implications for Conveyor Design. The minimization of the specific energy consumption of a screw conveyor should be achieved through an integrated design approach. In addition to selecting an appropriate pitch-to-diameter ratio (ψ = s/D) and screw rotational speed (n), as traditionally recommended, the geometry of the loading hopper and the discharge configuration should be explicitly considered during the preliminary drive power calculations using Eqs. (8)–(10). Neglecting these design factors may lead to a systematic overestimation of the required drive power and, consequently, to the unnecessary oversizing and increased cost of the drive system.

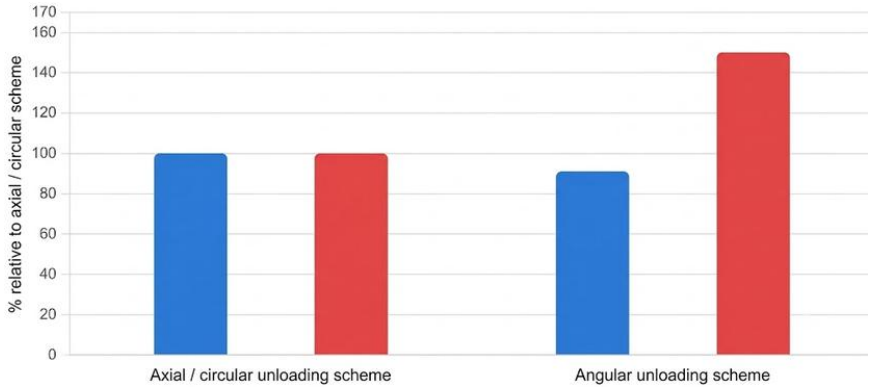


Fig. 4. The graph clearly illustrates the asymmetric effect of the angular discharge configuration

A relatively small reduction in conveying capacity (up to approximately 9%) is accompanied by a disproportionately large increase in the required drive power (up to 50% or more). This imbalance constitutes the principal finding of Section 6, demonstrating that the selection of the discharge configuration is not a secondary design consideration but a critical factor affecting the energy efficiency of the conveyor. Therefore, the discharge configuration should be explicitly taken into account during the preliminary drive power calculations based on Eqs. (8)–(10).

The established patterns of changes in productivity depending on the loading scheme have a direct electromechanical continuation: since the power N is directly proportional to the product $Q\cdot(L+H)\cdot\omega_0$ (formula 9), and the resistance coefficient to movement ω_0 increases when switching from an axial to an angular loading or unloading scheme, the conveyor electric drive is forced to operate in a mode of increased load without changing the rotation frequency n.

This has two practical consequences for the electromechanical system:

1. Increase in the starting current of the motor. With an angular unloading scheme, which is accompanied by an increase in the drive power by 50% or more (compared to the axial scheme), the rated current of the stator of the asynchronous motor also increases in proportion to the load on the shaft, which, with an unchanged rated power of the motor, can lead to its systematic overload and accelerated thermal wear of the winding insulation.

2. The need for a power reserve when selecting a motor. The overload coefficient $K_0 = 1.3…1.5$, included in formula (10), should be chosen taking into account the worst-case scenario – that is, the structurally least efficient loading/unloading scheme that is actually implemented in a particular conveyor. Ignoring this factor at the design stage of the electric drive leads either to systematic underloading of the engine (with an overestimated power reserve – and, accordingly, to a reduced power factor $\cos\varphi$ and efficiency of the electric motor at partial loads), or to its chronic overload (with an underestimated reserve). Thus, a rational choice of the structural scheme of the loading unit is not only a mechanical, but also an electrical reserve for increasing the efficiency of the conveyor: reducing the resistance to material movement (optimized hopper shape, circular loading scheme) allows you to reduce the installed power of the drive electric motor by 15–30% without losing system productivity, which directly affects the capital costs and operational energy consumption of the electromechanical complex as a whole.

5. Conclusion

The conducted analysis of the influence of the loading method on the performance of a spiral screw conveyor demonstrated that the design of the loading unit is one of the primary determinants, rather than a secondary factor, of the overall efficiency of the conveying system. Replacing a straight-walled loading hopper with an optimized streamlined configuration increases the conveyor performance coefficient from 0.62 to 1.00. The use of a circumferential loading chamber improves conveying capacity by 6–23%, while the application of dedicated feeding devices under forced loading conditions increases conveying capacity by a factor of 1.7–3 compared with conventional gravity-fed axial loading. In contrast, an angular discharge configuration reduces conveying capacity by 6–12% while simultaneously increasing the required drive power by 50% or more. The study also established that the conveying capacity of vertical screw conveyors is only 30–40% of that of equivalent horizontal conveyors, owing to the requirement that the operating rotational speed exceeds the critical angular velocity and to the additional retarding effect of gravity on the axial movement of bulk material particles. Furthermore, the theoretical analysis of the coordination between the capacities of the

loading, conveying, and discharge units confirmed that stable and reliable conveyor operation can be achieved only when the condition $P_z < P_t <; P_r$ is satisfied. Violation of this condition leads to excessive particle degradation and an increased risk of conveyor blockage. The obtained results indicate that the rational selection of the loading hopper geometry and the material feeding configuration can increase the conveying capacity of a spiral screw conveyor by 60–200% without modifying the geometric parameters of the screw itself. Consequently, the loading unit should be regarded as a priority target for optimization in the design and modernization of spiral screw conveyor systems. Future research should focus on the experimental validation of the proposed theoretical relationships using a physical conveyor model and real bulk materials, as well as on the application of the Discrete Element Method (DEM) to further investigate the influence of loading device geometry on particle trajectories and conveying performance.

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ДОСЛІДЖЕННЯ ЗАКОНОМІРНОСТЕЙ ЗМІНИ ПРОДУКТИВНОСТІ СПІРАЛЬНО-ГВИНТОВОГО КОНВЕЄРА ЗАЛЕЖНО ВІД СПОСОБУ ЗАВАНТАЖЕННЯ

Стаття присвячена дослідженню впливу способу завантаження на продуктивність спірально-гвинтового транспортера – одного з найпоширеніших типів обладнання для переміщення сипких матеріалів у сільськогосподарському виробництві, харчовій та переробній промисловості. Розглянуто принцип роботи гвинтових транспортерів, що ґрунтується на переміщенні вантажу вздовж транспортного каналу під дією обертового робочого органу за рахунок волочіння матеріалу по внутрішній поверхні кожуха незалежно від фізико-механічних властивостей вантажу. Проаналізовано особливості функціонування тихохідних та швидкохідних шнеків, встановлено вплив частоти обертання гвинта, кроку навивки, діаметра робочого органу та кута нахилу транспортера на характер руху частинок матеріалу і продуктивність системи загалом. Показано, що в тихохідних шнеках частинки рухаються переважно поступально, тоді як у швидкохідних траєкторія їх руху ускладнюється під дією відцентрових сил.

Особливу увагу приділено порівняльному аналізу способів завантаження – гравітаційного та примусового, а також кінематичних схем подачі матеріалу: осьової, кутової та кругової. Показано, що форма завантажувального бункера суттєво впливає на рівномірність подачі вантажу та коефіцієнт продуктивності транспортера, значення якого може коливатися від 0,62 до 1,00 залежно від конструктивного виконання бункера. Встановлено, що використання кругової камери завантаження підвищує продуктивність транспортера на 6–23 %, а застосування живильників – у 1,7–3 рази. Наведено теоретичні залежності для визначення критичної кутової швидкості, продуктивності та потужності приводу шнекового транспортера з урахуванням конструктивно-режимних параметрів гвинта.

Розглянуто електромеханічну систему транспортера як єдиний комплекс "завантажувальний пристрій–гвинт–електропривід", у якому зміна опору переміщенню матеріалу залежно від схеми завантаження безпосередньо відображається на навантажувальних характеристиках приводного асинхронного електродвигуна та режимах його роботи.

Ключові слова: *спірально-гвинтовий транспортер, шнек, продуктивність, спосіб завантаження, завантажувальний бункер, частота обертання, критична кутова швидкість, сипкі матеріали, енергоємність, коефіцієнт продуктивності.*

Ф. 10. Рис. 4. Табл. 1. Літ. 18.

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