INFLUENCE OF THE DESIGN PARAMETERS OF A SCREW FEEDER LOADING MECHANISM ON THE TORQUE VALUE OF THE DRIVE SHAFT

Vasyl Vasylkiv*, Dmytro Radyk, Mykola Stashkiv, Larysa Danylchenko

Ternopil Ivan Puluj National Technical University, Ternopl, Ukraine

*E-mail of corresponding author: VasylkivV@gmail.com

Vasyl Vasylkiv 0000-0001-8517-3223,
Dmytro Radyk 0000-0003-4345-9770,
Mykola Stashkiv 0000-0002-7325-8016,
Larysa Danylchenko 0000-0002-4089-207X

Resume

The processes of material capture and movement in a screw feeder are characterized by significant loads due to the pressure of a vertical load column, which creates additional resistance to the movement of the material, overcoming which leads to unproductive energy consumption. The paper aims to study the influence of the design parameters of the loading mechanism on the torque on the drive shaft of a screw feeder. The results of experimental studies and computer simulation of the design parameters of the loading mechanism relation (the length of the loading zone, the inclination angle of the rotating wall of the loading nozzle, its displacement value relative to the vertical axis of the auger operating part, and the height of the material in the loading nozzle), to the torque value on the drive shaft of the screw feeder for transportation of bulk cargo, are presented in this paper.

Available online: https://doi.org/10.26552/com.C.2023.068

Article info

Received 6 April 2023
Accepted 28 July 2023
Online 5 September 2023

Keywords:

screw feeder
bulk material
torque
loading mechanism
the length of the loading zone
displacement of the loading nozzle

ISSN 1335-4205 (print version)
ISSN 2585-7878 (online version)

1 Introduction

Screw transport and technological mechanisms are widely used in various industrial sectors. This is evidenced by a noticeable upward trend in their use in the construction, food, processing, metallurgy, and agricultural industries. The specific weight of such screw mechanisms in loading and unloading operations and transportation of bulk cargo reaches 40-45%. Screw feeders are the most commonly used units for transport and technological operations and uniform feeding of various receiving devices. They provide efficient loading, unloading, transportation and technological processing (dosing, cleaning and pressing) of fine-dispersed building materials, chemicals, grain and other bulk materials that are required for the further extension of the technological cycle.

It is known that the screw feeders differ from conveyors of the same type by shorter transportation length, as a result, the hanger bearings are not available, which improves their design and improves transportation conditions, as well as increases the filling factor of the feeder. They are characterized by relatively increased productivity, engine power, and structural strength, since they are subjected to significant overloads that occur due to the action of the cargo pressure under the hopper opening or the loading nozzle on the auger operating parts. They are also able to overcome the higher resistance of material movement in the operating mode, which is caused by the weight of the material in the hopper above the outlet. Screw feeders are more energy-intensive since they change the direction of the cargo flow movement, coming from the hopper into the longitudinal movement of transportation. In this way, there is a change and transformation of the energy of the material coming in a continuous flow from the hopper, and the material captured by the flights of the auger operating part in the process of longitudinal transportation. At the same time, the screw feeders can perform the function of conveyors of the same type, moving the cargo to a short distance from the hopper opening.

Most types of screw feeders do not require separate hopper shutters, since when the feeder is stopped, it keeps the cargo from spontaneously spilling out. At the same time, the bulk cargo unloading from the hopper using feeders is characterized by the main function of their operating device on the cargo, which is especially important in the case of poorly flowing cargo, the flow of which through the hopper opening, only due to the action of its weight, is insufficient. In this regard, there are three types of such feeders: open, semi-open and closed.

The object of the presented research is a screw feeder, containing a semi-open loading hopper with free movement of the bulk cargo, and equipped with a single-threaded horizontal screw with a constant pitch of turns. The operating part can be partially displaced in the horizontal direction, relative to the outlet opening and the vertical axis of the hopper, and the material in the capture zone is fed tangentially to the rotation surface of the operating part. The movement of the bulk cargo flow is carried out under the action of the cargo gravity forces.

2 Analysis of the past research and publications

Many analytical, research and experimental studies, along with various patented studies, have been conducted to analyze the characteristics of screw feeders. The works [1-3] analyzed the mechanics of the screw feeder in connection with the characteristics of the bulk material in the feeder hopper, behavior of the material and flow control during its loading and transportation. The papers [4-5] propose a methodology for calculating the structural and power parameters and consider factors affecting the performance of the screw feeders and their optimization based on the results of experimental studies. Formalized descriptions and synthesis of schemes for shaping auger spirals of screw feeders were presented by the authors in [6-7].

Important, from the point of view of further improvement of the screw feeder designs, are the issues of predicting the torque and loading characteristics of bulk cargo transportation processes presented in [8-9], as well as the study of the conditions for formation of a “dead zone” during the loading of a screw feeder, considered by the authors in [10-11].

A significant number of publications are devoted to the study of the design principles of screw feeders: a non-proper design and selection of this device, which is present in large part of industrial processes, could mean poor performances, excessive power, severe wear of plant and degradation of the feeding material [12-13]. The design of a screw feeder is a highly complex procedure: for a correct and successful installation, it is essential to have a proper understanding of influences of all the parameters of the transport process [14-15].

The construction and exploitation parameters of screw feeders must meet the defined requirements concerning their efficiency, the filling rate of the trough, or providing the necessary power to the drive [16-17]. The behavior of bulk materials during transportation by a screw conveyor is very complicated. It depends on many factors, such as the type and shape of the screw flights, the rotational speed of the shaft, the way of proportioning the material, or the physical properties of the material. The study of these factors in the processes of loading and transportation of bulk cargo, their mutual influence and modeling were presented by the authors in [18-19]. The use of the Discrete Element Method (DEM) for simulation and validation of the screw feeders allows for optimizing their design, taking into account the conditions of use [20-23].

Theoretical methods for designing the screw conveyors do not consider all the factors mentioned above, or oversimplify them. In the case of typical bulk materials of uniform granulation and standard constructions of the screws (constant pitch, constant internal and external diameters) and fed by one source, e.g., a hopper, theoretical methods allow reasonable estimation of the exploitation parameters of the screw feeders [24-25].

In the case of materials of specific properties (cohesive or strongly aerated materials) or for unusual shapes of screws or multiple feeding points, these methods do not provide reliable results of efficiency and power [26-27]. For this reason, the external diameters of the screws and power demands are very often chosen to be safely larger. Such an approach is unfavorable because of the excessive use of materials, ineffective use of the drive unit, and high exploitation costs. On the other hand, the difficulties in making decisions on the design of screw feeders are often caused by insufficient exploitation data on the peculiarities of the process of transporting the bulk materials.

In the conditions of energy resource shortage in the world, the important directions of creation and design of the screw feeders are implementation of technical solutions characterized by the low energy consumption and high productivity. This is achieved by improving their layout schemes, auger operating parts and cargo-loading devices based on experimental studies and computer simulation [25, 28]. It is known that the geometric parameters of the loading mechanism and the features of its location relative to the vertical plane passing through the longitudinal axis of the operating part have an impact on the energy consumption of the bulk cargo transportation process [27].

That is why the issue of developing and researching the semi-open screw feeders with shifted loading nozzle, relative to its vertical axis 6, i.e., from the vertical plane passing through the longitudinal axis of the auger (Figure 1), is of scientific and practical interest. The main advantage of such a feeder design is that the material is fed into the capture zone not vertically, but along the inclined wall, the plane of which is tangential to the surface of rotation of the auger operating part.

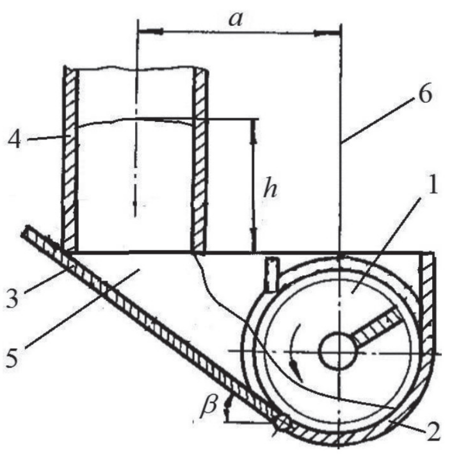


Figure 1 *Cross-sectional diagram of the screw feeder in the loading mechanism location area: 1 - auger operating part; 2 - housing casing; 3 - a rotating wall of the loading nozzle; 4 - loading nozzle; 5 - bulk cargo; 6 - the vertical axis of the auger operating part*

In this design, the torque value on the drive shaft, and therefore energy consumption, is affected by the inclination angle of the rotary wall of the loading nozzle β, the length of the loading zone L, the displacement value of the loading nozzle relative to the vertical plane a, passing through the longitudinal axis of the transporting auger, and the height of bulk cargo in the loading nozzle h.

Despite the considerable number of papers devoted to improving the designs of screw feeders, the problem of the above-mentioned design parameters of the screw feeder loading mechanism influence on the energy consumption of the bulk cargo transportation process has not been sufficiently investigated.

As it is known, the drive power of the screw feeders is consumed to overcome the following resistance forces: frictional forces of the load against the bunker walls; force along the screw, equivalent to the frictional torque of the screw against the cargo; force equivalent to the frictional torque in the bearing unit; the force equivalent to the internal friction in the material caused by the movement and grinding of the bulk cargo in the feeder bunker, which can only be determined by experimental means and by computer simulation.

3 Methods of mechanical and physical research

To carry out experimental investigations, a screw feeder is designed and manufactured to investigate the process of transporting bulk cargo and the influence of the design parameters of the loading mechanism on the torque value on its drive shaft.

Its creation is based on the design and principle of operation of the screw feeder with shifted loading nozzle, relative to the vertical axis of the auger, from the vertical plane passing through the longitudinal axis of the auger operating part (Figure 1).

The scheme of the screw feeder is shown in Figure 2. It consists of a frame 1, on which the drive (asynchronous three-phase electric motor), transporting and loading mechanisms are mounted.

The torque from the engine to the drive shaft 2 of the screw feeder is transmitted using the V-belt transmission to replaceable pulley 3.

The drive shaft is mounted in bearing supports 4, consisting of two angular-contract bearings and housings, which are fixed immovably to the frame using holders 5. At one end of the drive shaft 2, replaceable pulleys are installed, and at the other end, replaceable auger operating parts of the transportation mechanism are attached. This mechanism contains housing 6, made in the form of a pipe (casing) with the notch, which is used to feed the bulk cargo into the capture zone. The replaceable auger in the form of the hollow shaft 7 and the helical spiral 8 are placed in the housing. The housing is rigidly mounted on frame 1 by means of legs 9. The replaceable screw feeder auger is a cantilever fixed to the drive shaft 2. The hollow shaft 7 is installed by its inner diameter with the sliding fit on the free end of the drive shaft and is fixed by pin 10.

The loading mechanism is located above the loading opening of the transportation mechanism, which is mounted with the possibility of cross-movement relative to the vertical axis 11 of the auger. The loading mechanism consists of loading nozzle 12, unloading hopper 13 located above the nozzle, rotary wall 14, and mechanical measuring device 15 for measuring the inclination angle of the rotary wall β and the height of the bulk cargo h in the loading nozzle. The loading nozzle contains the horizontal slide valve 16 and insertable vertical plate 17, made along the width of the loading nozzle. They are installed with the possibility of changing their position relative to the vertical side wall of the nozzle. This makes it possible to adjust the length of loading zone L.

In the loading mechanism, longitudinal wall 18 and one of the cross walls 19 are made of transparent

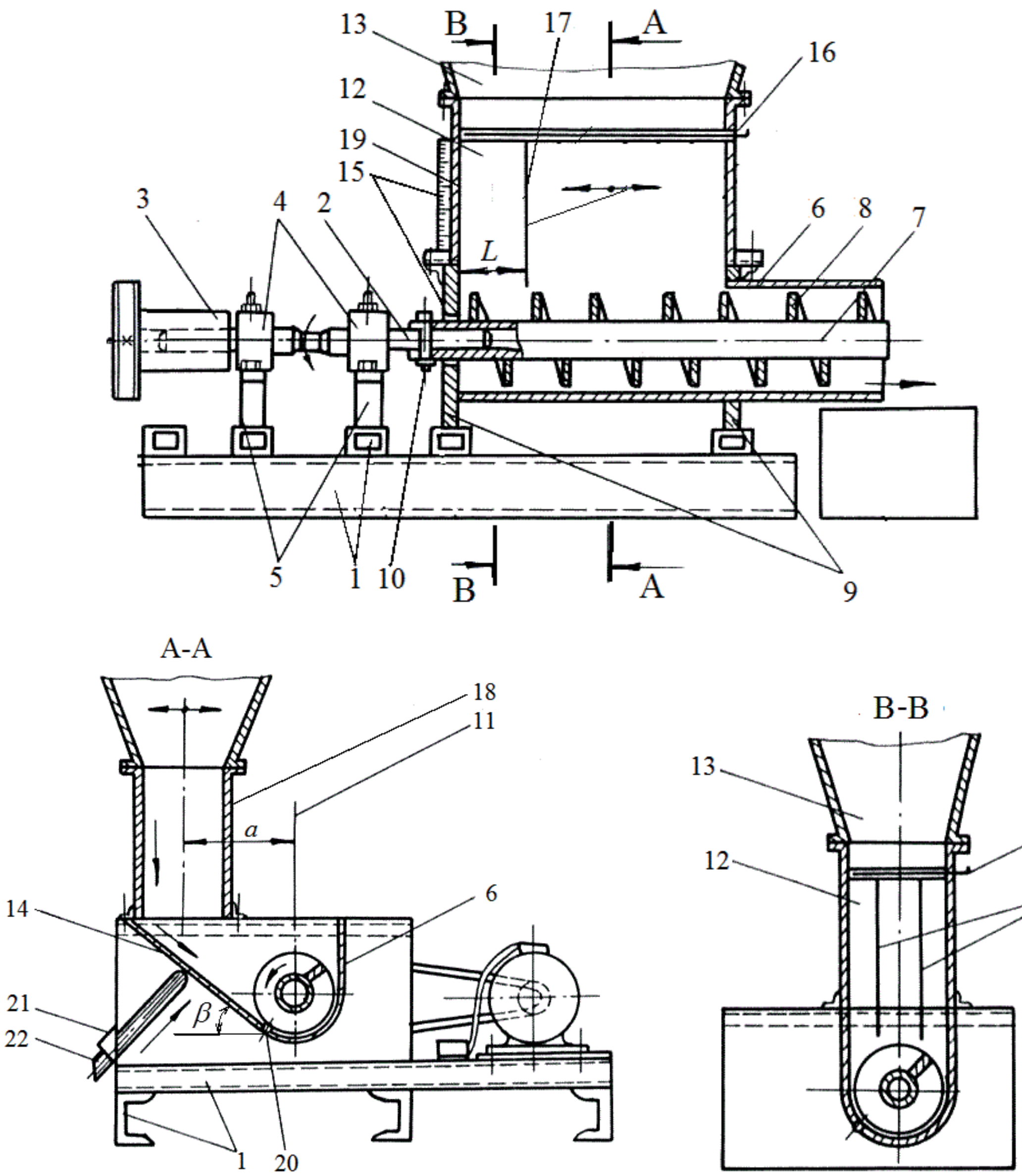


Figure 2 *Scheme of the screw feeder for conducting experimental investigations*

material to control the bulk cargo height in the loading nozzle.

The screw feeder is equipped with elements of movement with a certain step along the guides, which are installed on the legs 9 to fix the loading mechanism.

The rotary wall 14 is used to feed the bulk cargo coming from the loading nozzle 12 when it is displaced relative to axis 11 into the capture zone. The rotary wall is attached to the housing 6 by means of axis 20. The inclination angle of the wall is set using the mechanism that provides step-less control. It consists of a nut 21, which is firmly attached to legs 9, and screw 22, which is kinematically connected to the nut at one end, and is in contact with the rotary wall at the other end, and the axis of screw 22 is placed at an angle approximately 45° to the horizontal plane.

The screw feeder operates in the following way. The bulk cargo flows from the unloading hopper 13, through loading nozzle 12, enters rotary wall 14, sliding along which it is captured by the flights of helical spiral 8, and transported in housing casing 6 to the unloading area. The auger operating part is set in motion by the drive-through shaft 2. To adjust the displacement value a of the loading nozzle relative to vertical axis 11 of the transporting auger, loading nozzle 12 and unloading hopper 13 are moved along special guides to the predetermined value. The inclination angle β of the rotary wall 14 is adjusted using the screw 22.

The length of loading zone L is adjusted by moving the horizontal slide valve 16 and inserting vertical plate 17 relative to the vertical side wall of the nozzle. The torque value on shaft 2 varies depending on the displacement value a of the loading nozzle 12, the length of the loading zone L, and the inclination angle of the rotary wall 14.

The experimental screw feeder is designed with the

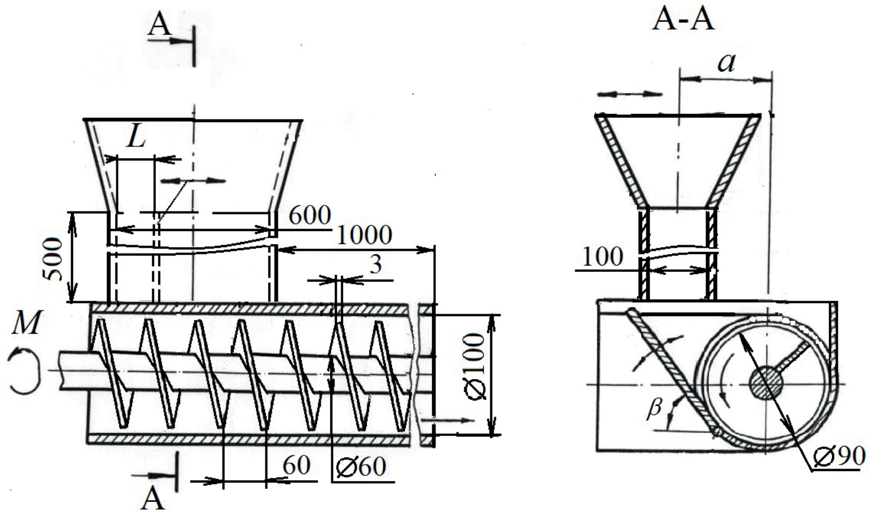


***Figure 3** Scheme of the screw feeder with dimensions of its structural elements*

following geometric parameters: height of the loading nozzle - 500 mm, length - 600 mm, width - 100 mm; helical spiral pitch T = 60 mm, the external diameter of the spiral D = 90 mm, the internal diameter of the spiral d = 60 mm, the thickness of the flights - 3 mm, the internal diameter of the housing - 100 mm. The electric drive ensured the rotation frequency of the auger operating part n = 380 rpm.

To establish the influence of the design parameters of the screw feeder's loading elements on energy consumption during the transportation of the bulk cargo, the dependence of torque value on its drive shaft on the geometric parameters of the loading mechanism and its displacement value a, relative to the vertical axis of auger operating part, is investigated.

The transportation process and torque on the drive shaft are investigated for three different materials: sand (bulk weight γ = 1400 kg/m^3, external friction ratio on steel f_1 = 0.32, internal friction ratio f_2 = 0.57, angle of natural slope φ = 30°, minimum angle of wall inclination β_g = 35°), wheat grains (γ = 650 kg/m^3, f_1 = 0.41, f_2 = 0.46, φ = 23°, β_g = 26°), and corn grains (γ = 750 kg/m^3, f_1 = 0.37, f_2 = 0.52, φ = 27°, β_g = 24°).

In investigation of the torque dependence on the displacement value of the loading nozzle a, relative to the auger operating part of the screw feeder, the inclination angle of the rotary wall is constant and equal β = 45° at the bulk cargo height in the loading nozzle h = 500 mm and the loading zone length L = 300 mm. The range of variation of displacement value is chosen in the range from 0 to 120 mm, which is approximately a = (0 - 1.3) D with the interval of 20 mm.

The torque dependence on the inclination angle of the rotary wall β is investigated within the range of values from 0° to 90° at h = 500 mm, L = 600 mm, a = 1.1 D = 100 mm. This displacement value, is chosen in such a way as the entire bulk cargo column, entering from the loading nozzle, would act on the inclined wall. The movement of cargo along the inclined wall depends on many factors. The main condition for this movement occurrence is that the inclination angle of the wall is greater than the friction angle of the bulk cargo to the wall surface (Figure 1), taking into account its granulometric composition and rheological properties.

To establish the geometric parameter of the screw feeder, which characterizes the height of the loading nozzle, the dependence of the torque value on the height of the bulk cargo in the loading nozzle is investigated. Therefore, the influence of the height h of such cargo in the loading nozzle on the torque value is determined within the range of h = 150-600 mm for L = 600 mm, in the absence of the displacement value of the loading nozzle relative to the auger operating part of the screw feeder. The inclination angle of the rotary wall equals β = 90°, that is, the wall occupies a vertical position and the loading nozzle is placed directly above the auger operating part. In this case, parameter β does not affect the parameters of the cargo transportation process.

The influence of the loading zone length L on the drive shaft torque is carried out under the conditions h = 500 mm, β = 90°, a = 0 mm, with the change in the loading zone length within 100-600 mm, using the vertical plate inserted into the loading pipe. By changing the location of this plate, relative to the front wall of the nozzle, the required size of the loading zone is set.

The scheme of the investigated screw feeder, with the marked main dimensions of its structural elements, is shown in Figure 3.

The Altivar 71 multisystem drive and the standard PowerSuite V.2.5.0 software from Schneider Electric were used to measure the torque and speed control of the screw feeder drive shaft (Figure 4).

This drive is a frequency converter and was designed for the control of the three-phase asynchronous and synchronous motors in constant-torque applications.

The Power Suite V2.5.0 software is designed to control the Altivar 71 drive and coordinate its multisystem multichannel frequency converters,

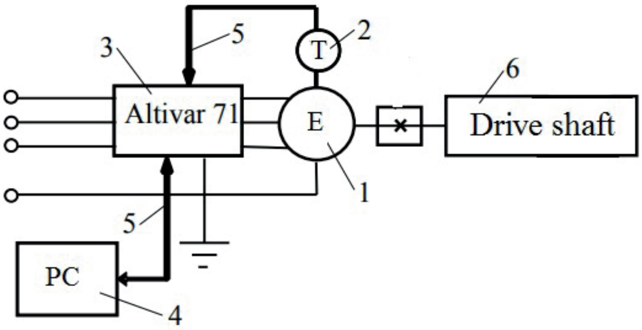
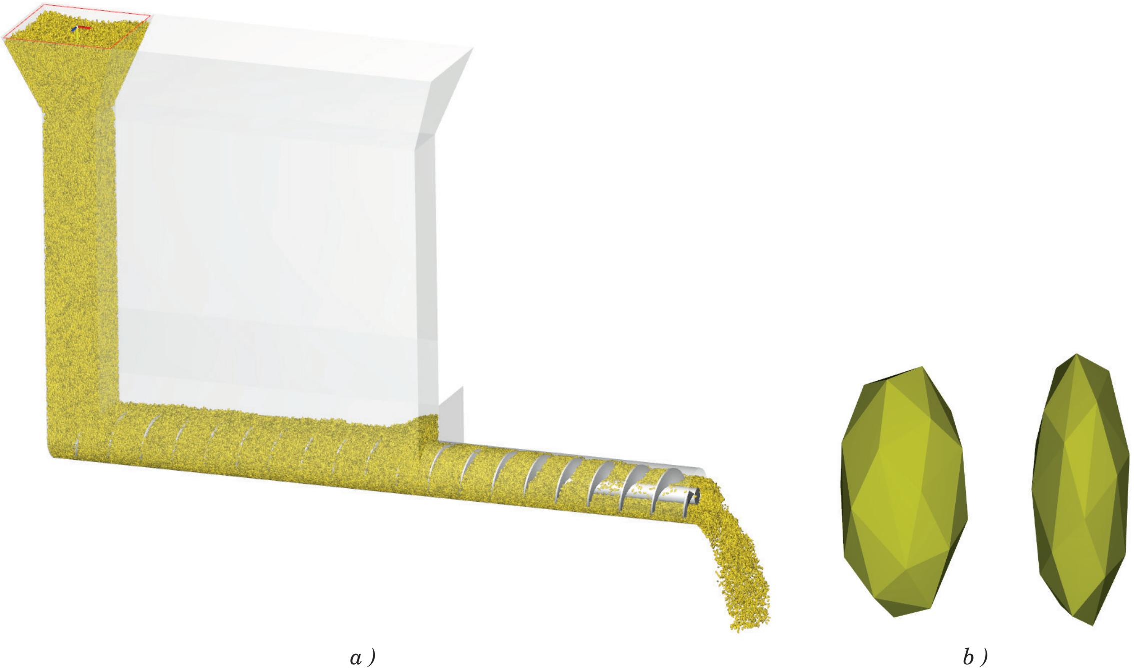


***Figure 4** Electrical circuit for the torque measurement and speed control of the screw feeder drive shaft: 1 - asynchronous electric motor, 2 - frequency transmitter E40S6-10Z4- 6L-5 for motor shaft rotation, 3 - multisystem control drive (frequency converter) Altivar 71, 4 - personal computer, 5 - communication cables*



a) *b)*

***Figure 5** Computer simulation of the grain material transportation process by the discrete elements method and elementary particles in the form of a polyhedron*

Altistart 48 soft starters, Lexium 05 servo drives and TeSysU intelligent starters, as well as to read data from the multisystem drive and display them on a computer monitor in the form of numerical values or their graphical representation.

The Altivar 71 drive is tethered to the computer using cable 5 VW3-A8106, which connects the plug on the front panel of the Altivar 71 to the computer's COM port.

Thus, the torque on the drive shaft of the screw feeder is measured using a frequency converter ALTIVAR 71, and its data are sent to the PC. The resulting changes in torque and engine power over time are obtained in the form of graphical and tabular dependencies in the display window of the computer. Experimental research is carried out to define the dependence of the torque on the magnitude of displacement of the loading pipe relative to the operating part of the screw feeder, the angle of the rotary wall, the material height in the loading pipe and the length of the loading zone.

To identify the peculiarities of the bulk cargo stagnation zone location, a computer simulation of the grain material transportation process is carried out (Figure 5, *a*).

The discrete element method is used to model the bulk cargo, a numerical method is designed to calculate the motion of a large number of particles, such as molecules, grains of sand, gravel, and other granular media. The grain of wheat is modeled as the elementary particle in the shape of a polyhedron (Figure 5, *b*) with 25 faces. The dimensions of the polyhedron are as follows: height 7.2 mm, width 3.8 mm, thickness 2.6 mm (volume 71.2 mm^3). The following physical and mechanical parameters of the material are set for the grain model: density 650 kg/m^3, modulus of elasticity 108 MPa, Poisson's ratio 0.3.

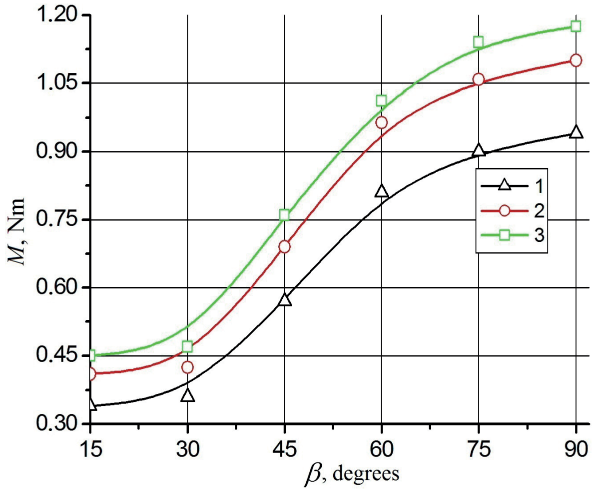


Figure 6 *Graph of the torque dependence on the inclination angle of rotating wall* β

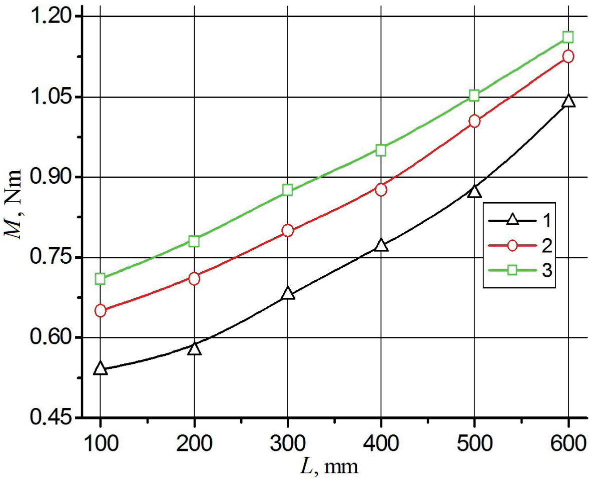


Figure 7 *Graph of the torque dependence on the length of loading zone L*

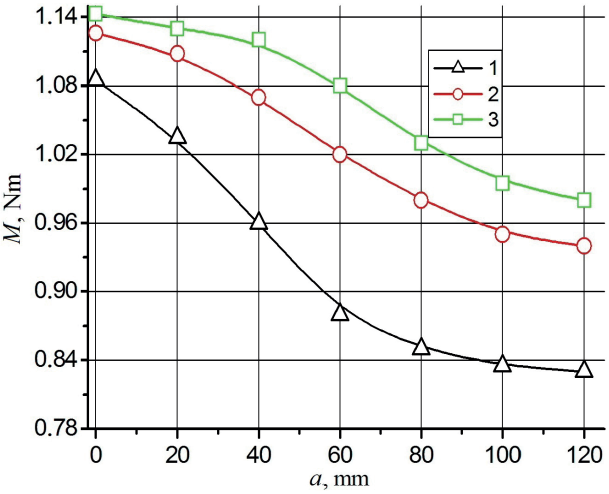


Figure 8 *Graph of the torque dependence on the displacement value of the loading nozzle a relative to the auger operating part of the screw feeder*

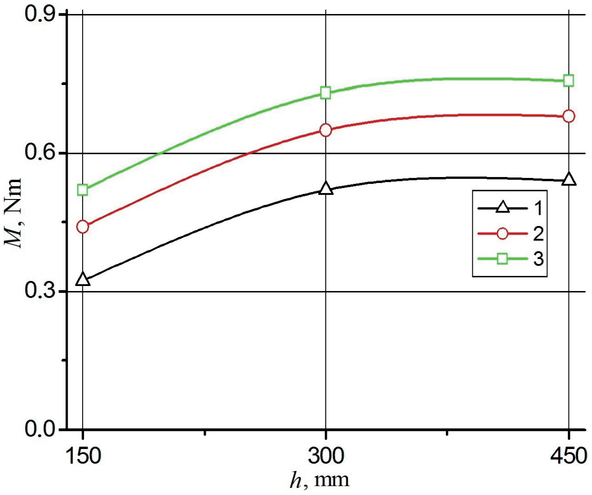


Figure 9 *Graph of the torque dependence on the bulk cargo height h in the loading nozzle*

The model of Hysteretic Linear Spring is used to simulate the normal interaction forces of bulk cargo particles. Linear Spring Coulomb Limit model is used to simulate the tangential forces. Linear Spring Rolling Limit model is used to simulate the sliding friction. The Numerical softening factor is 0.1. Thermal modeling and coarse-grained modeling are not used. During the computer simulation, the auger rotation frequency was 380 rpm, and the grain feed is 2000 kg/h. The type of bulk cargo feeding is continuous.

4 Results and discussion of experimental findings

The results of experimental research of the torque dependence on the inclination angle of a rotary wall β, loading zone length L, displacement of the loading nozzle relative to the operating part of screw feeder a, and the bulk cargo height h in the loading nozzle, for such materials as sand (1), wheat grain (2), and corn grain (3), are shown in Figures 6 to 9.

The graphs show that the inclination angle of the rotary wall of the loading nozzle significantly affects the energy consumption during the cargo transportation (Figure 6). At small inclination angle values (up to 20°-30°), the torque does not change intensively. Only when the wall inclination reaches the natural slope angle value of the transported bulk cargo, the torque starts to increase sharply. This is explained by the fact that with the increase in the angle, the normal component of the bulk cargo weight, acting on the wall, decreases, and the normal force, acting on the auger operating part, increases, resulting in an increased torque.

Thus, the experimental method has confirmed the statement that the inclined wall takes a significant part of the cargo weight and thereby reduces the load on the auger operating part of the screw feeder, which significantly reduces the torque value.

Computer simulation of this process (Figure 5) has confirmed the tendency to increase the torque and the duration of the stabilizing process of its value with

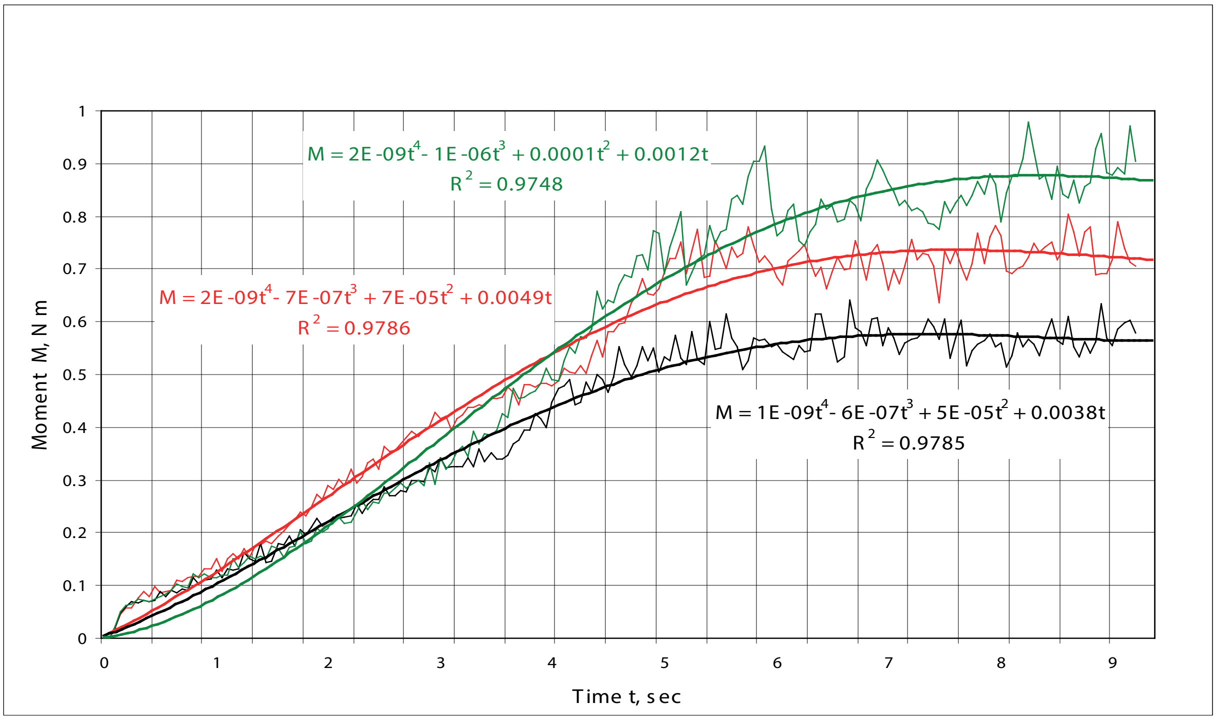


Figure 10 *Graphs of the torque dependence on time at loading zone length L = 100 mm for different inclination angles of the rotary wall based on the results of computer simulation of the bulk cargo transportation process*

▬ - β = 45°, ▬ - β = 67.5°; ▬ - β = 90°

the increase in the inclination angle of rotary wall β.

In the graph (Figure 10), the simulation results are approximated by the fourth-degree polynomials.

The equations shown in Figure 10 mathematically describe the general upward trend, i.e., the trend of changes in the torque on the drive of the screw feeder operating part. These equations are obtained by approximating the results of a virtual experiment with the standard deviation R^2, i.e., the scattering of the values of a random variable relative to its mathematical expectation.

In Figure 10, as well as in Figures 11, 13, and 16 below, the zero second is taken as the starting point. The "Zero second" is the moment when the screw drive of the operating part is switched on. In the time period, from 0 to 0.5 seconds, the rotary wall takes up the working position (the required angle β is set). The bulk material starts to flow into the loading nozzle 0.5 seconds after the auger drive has been started.

The torque values for different inclination angles of the rotary wall β, obtained by the computer simulation are, 25% lower than the values obtained experimentally. This is explained by the fact that computer simulation does not take into account the power losses due to the rotation of the screw feeder drive elements.

An important factor, affecting the energy consumption value when transporting the cargo in the screw feeder, is the length of the loading zone *L* (the open part of the auger operating part under the loading nozzle in the direction of transportation) (Figure 7). The graph shows that the increase in the loading zone length results in a significant increase in torque. This is explained by the fact that an increase in the loading zone length contributes to the formation of a larger, so-called "dead zone", which, due to its weight and the friction force, creates resistance to the movement of bulk cargo in the loading zone of the screw feeder.

This also confirms that the dimensions of the loading nozzle should be minimal and determined on the condition that it provides the required throughput, taking into account the rheological properties of the transported cargo and, especially, dome formation.

Computer simulation of this process (Figure 10, 11) has confirmed the tendency to increase torque with the increasing length of the loading zone.

Analysis of the results of computer simulation shows that in the process of transporting the bulk cargo in the loading zone, due to the point contact of elementary particles in the form of a polyhedron, the change in the direction of their movement is observed, that is, the change in the cargo kinetic energy, which also requires additional energy consumption. In addition, such cargo accumulated in the hopper opening above the transporting operating part (Figure 5, a) not in the loading zone, thereby creating additional resistance to the movement of bulk cargo in the operating mode due to the additional pressure of the vertical cargo column. As a result, the so-called "dead zone" is formed (Figure 12). Overcoming these resistance forces causes unproductive energy consumption during the technological operations.

The results of the transportation process simulation prove that the increase in the loading zone length,

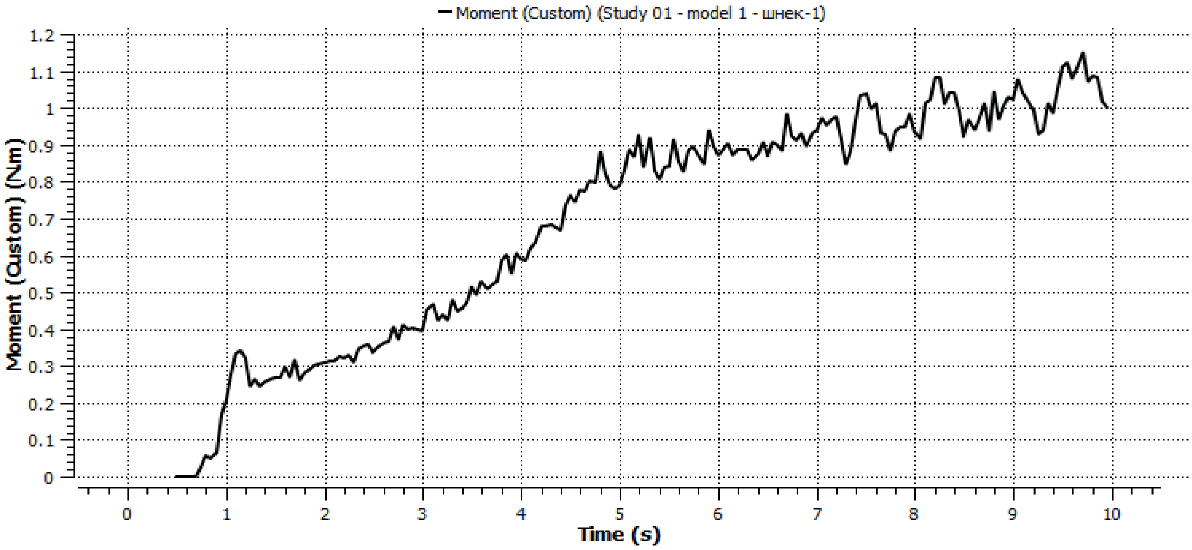


Figure 11 *Graph of the torque dependence on time for $L = 300\,mm$ and $\beta = 90°$ based on the results of computer simulation of the bulk cargo transportation process*

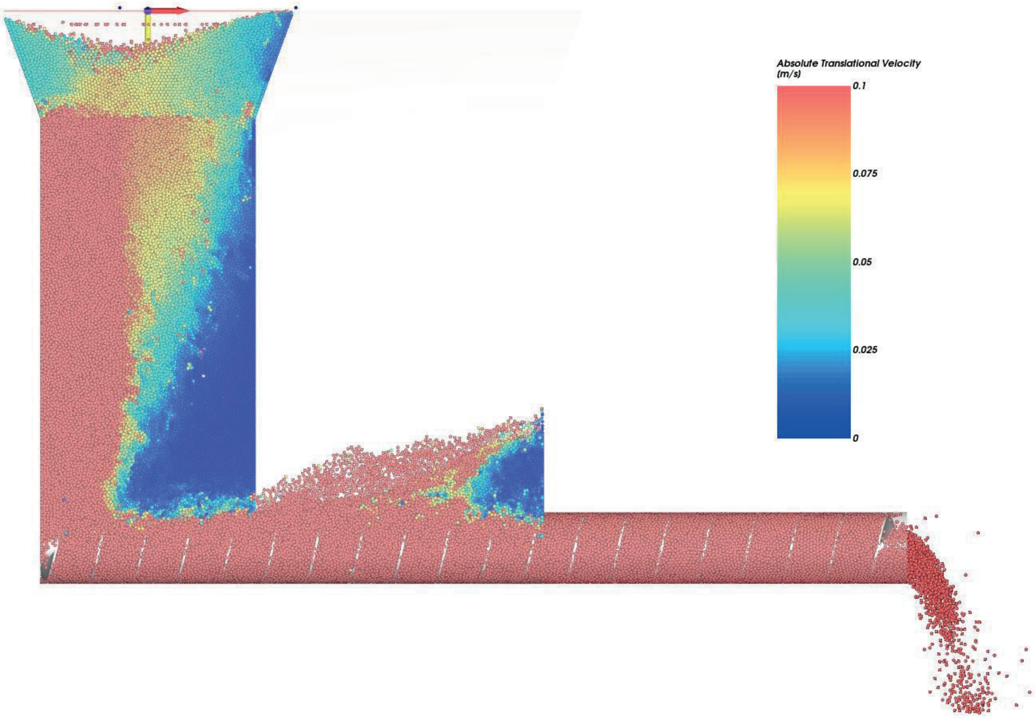


Figure 12 *Location of the stagnation zone ("dead" zone) of the bulk cargo (blue) according to the results of computer simulation of its transportation process at $L = 300\,mm$, $\beta = 90°$*

without shifting the loading nozzle relative to the auger operating part of the screw feeder, results in formation of a significant bulk cargo stagnation zone (blue color in Figure 12). Figure 8 shows the torque dependence on the drive shaft M of the experimental screw feeder on the displacement value of the loading nozzle relative to the auger operating part. The graphs show that the increase in the displacement value causes the decrease in torque, and, consequently, in energy consumption for the process of capturing and transporting the bulk cargo.

The analysis of the results of experimental investigations of torque dependence on the displacement of the loading nozzle, relative to the operating part of the screw feeder shows that within the range of displacement values $a = (0 - 0.2)\ D$ there is a slight change in the torque value. Then, there is a sharp decrease in torque values with increasing displacement until its value reaches $a = 0.9D$. Subsequently, the change in torque becomes slower again and at values of $a > 1.2\ D$ practically does not change. In the future, the moment change becomes slower again and practically does not change at values of $a > 1.2\ D$. The relative

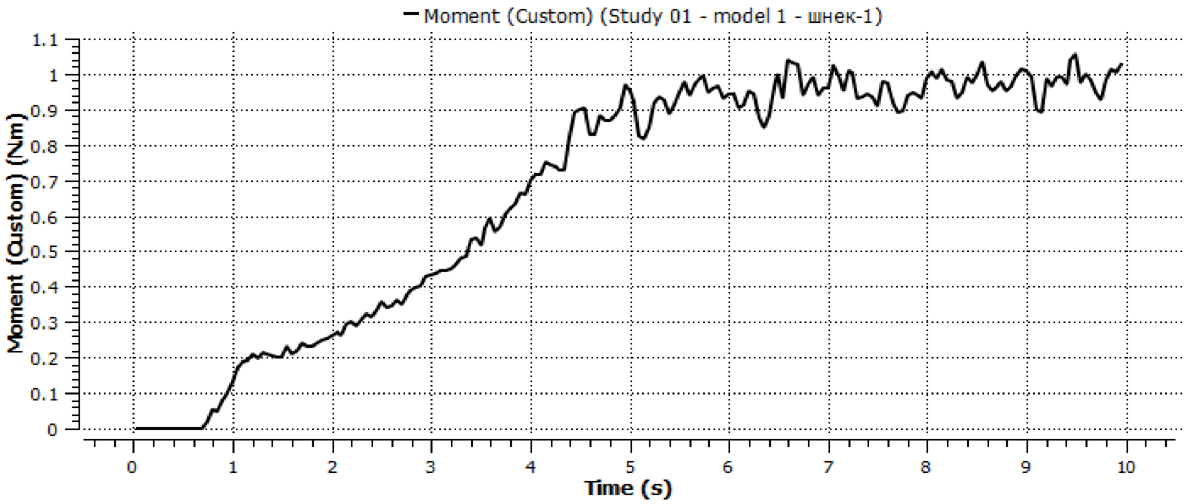


Figure 13 *Graph of the torque dependence on time for L = 300 mm, a = 100 mm; β = 90° based on the results of computer simulation of the bulk cargo transportation process*

difference of the torque values between the displacement limit value is 14 - 22 % for different bulk cargoes.

Thus, it is confirmed that the vertical bulk cargo column, above the auger operating part in the loading zone, significantly affects the energy consumption, increasing its value, which causes unproductive energy losses for the performance of technological operations to capture and move such cargo in screw feeders.

Computer simulation of the bulk cargo transportation process (Figure 13) shows the duration of the process of torque stabilization due to filling with bulk cargo a part of the unloading hopper 13 (Figure 2), placed above the auger operating part and separated from loading nozzle filled with the bulk cargo, using an inserted vertical plate 17, made along the width of loading nozzle. At the same time, in this zone, intensive formation of the so-called "dead zones" is observed near the right wall-hand of the loading nozzle and in the upper part of the bulk cargo column (Figure 14).

Such bulk cargo accumulation over the part of auger operating part in the loading nozzle of the unloading hopper results in additional energy costs caused by the presence of additional resistance to the movement of such material in the operating mode due to the pressure of vertical bulk cargo column in this zone and the costs of overcoming the frictional forces between the cargo layers.

Figure 9 shows the graph of the torque dependence on the bulk cargo height in the loading nozzle. From the graph, one can see that the increase in the cargo height in the loading nozzle results in an increase in torque, which is caused by the increase in the cargo value, and as a result, an increase in its weight acting on the operating part of the screw feeder. However, a significant increase in the torque occurs up to a certain value, despite the further increase in the bulk cargo height in the loading nozzle. This is explained by the fact that at a lower height, the conditional plane of failure intersects with the free surface of the cargo in the loading nozzle. When the bulk cargo height increases and the level of the free plane of the cargo rises, the plane of failure intersects with the opposite vertical wall of the loading nozzle, which leads to the fact that a significant proportion of the bulk cargo weight is transferred to the sides of its side walls its side walls due to the friction forces between the bulk cargo and the walls of the loading nozzle.

This is also confirmed by results of the computer simulation of the transporting process of the fixed volume of bulk cargo (Figures 15 and 16). From Figure 15, one see that at the final stage of transportation, there is a cargo accumulation (in the direction of transportation) close to the right-hand wall of the loading nozzle and its movement in the direction opposite to the direction of transportation, creating conditions for a temporary increase in torque (Figure 16) due to the mixing of the material and appearance of additional resistance to its movement in the operating mode, using the vertical bulk cargo column pressure.

Displacement of the loading nozzle, relative to the auger operating part of the screw feeder with the same length of the loading zone, avoids the appearance of a bulk cargo stagnation zone (Figure 12) and reduces the torque value by approximately 5.5 % (according to experimental data, this torque reduction is about 19 %).

Thus, it can be concluded that it is not reasonable to place the operating part of the screw feeders directly in the hoppers (except when it is technologically necessary), where they will be subjected to heavy loads from the weight of the material stored in these hoppers, and place them under the loading nozzle located between the hole in the bottom of the hopper and the operating part of the screw feeder. In this case, the dimensions of the loading nozzle are much smaller than the dimensions of the hopper, and this will contribute to reducing the impact of the bulk cargo weight on the auger operating part.

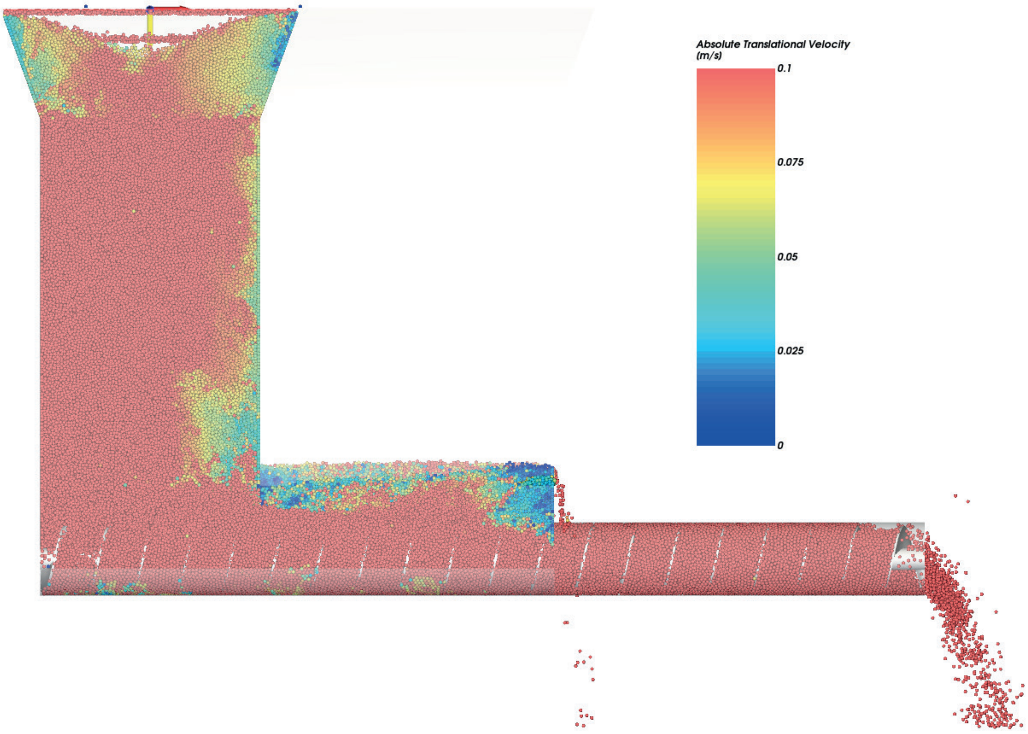
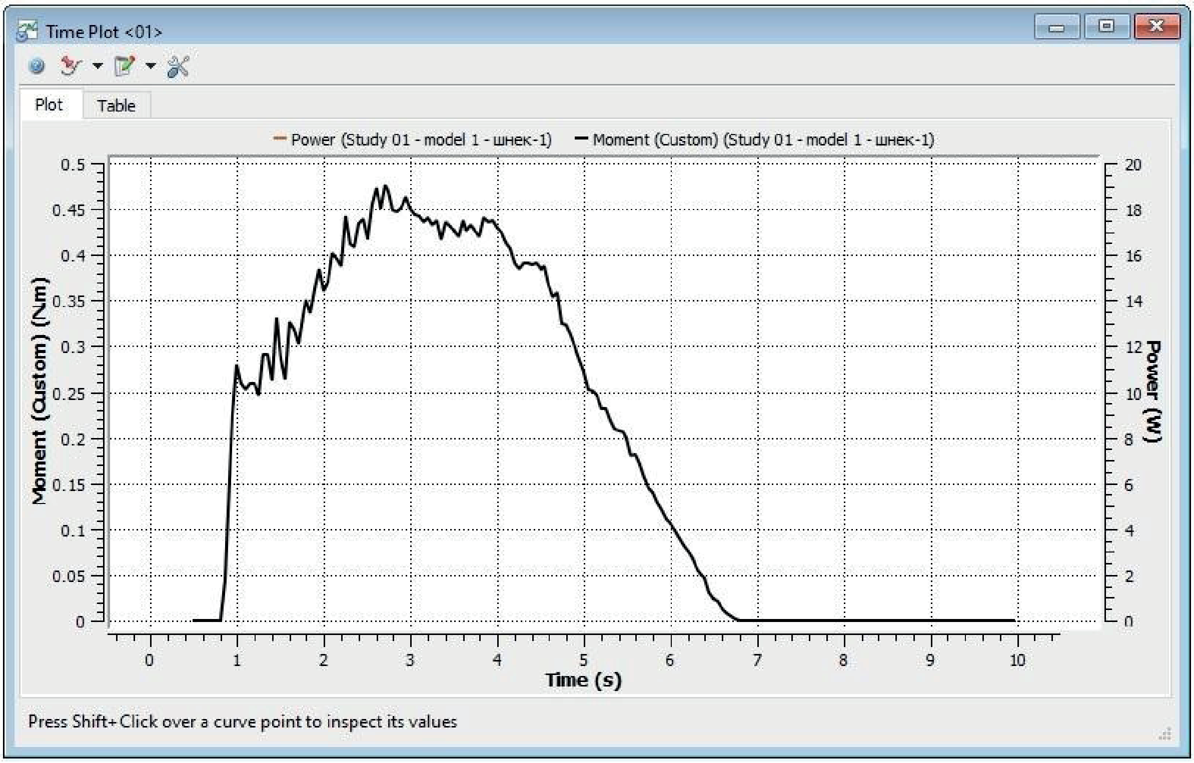


Figure 14 *Location of the stagnation zone (“dead” zone) of the bulk cargo (blue) according to the results of computer simulation of its transportation process at* $L = 300\,mm$, $\beta = 45°$ *and* $a = 100\,mm$

Figure 15 *Computer simulation of the limited volume of the bulk cargo transportation*



Press Shift+Click over a curve point to inspect its values

Figure 16 *Graph of the torque dependence on time for L = 300 mm, β = 90° based on the results of computer simulation of the limited volume of the bulk cargo transportation*

5 Conclusions

Vertical bulk cargo flow, displaced relative to the auger operating part of the screw feeder, improves its working conditions by significantly reducing the pressure of the vertical column of such cargo located in the hopper on the operating part, minimizes the internal friction force between the bulk cargo flow coming from the loading hopper and that involved in the process of longitudinal transportation, which reduces the energy costs for the process of bulk cargo capturing by the flights of the helical spiral. Feeding the bulk cargo to the working zone along a plane tangential to the cylindrical surface of the spiral rotation and inclined at an angle to the horizontal plane improves the uniformity of the capture of such cargo by the flights of the spiral and the smooth operation of the screw feeder, since the cargo, moving along the inclined plane, creates the same pressure on the auger operating part, which stabilizes the filling factor of the inter-flight volume of the screw tape.

Increasing the length of the loading zone, without shifting the loading nozzle relative to the auger operating part of the screw feeder, results in formation of a significant stagnation zone of the bulk cargo. To avoid the appearance of such a stagnation zone and reduce the torque value, it is reasonable to shift the loading nozzle relative to the operating part of the screw feeder with the same length as the loading zone.

Experimental investigations have shown that the displacement of the auger operating part of the screw feeder relative to its vertical axis reduces the energy costs of transportation for various bulk cargoes by 14 - 22%, as well as establishes the optimal inclination angle of the rotary wall for various cargo, which is in the range of 60-75° and provides the most favorable conditions for their supply to the capture zone.

The obtained results can be used for creation and effective application of the screw feeders, which are characterized by a variable length of the loading zone in the hopper, with the most favorable conditions for the supply of various bulk cargo to the capture zone by the screw at minimum energy costs for their transportation.

The next stage of research, in order to eliminate the phenomenon of formation of the so-called “dead zone” of the bulk cargo in the feeding nozzle of the screw feeder, is the development and study of screw operating parts with a variable inter-turn volume, where the increase in the inter-turn volume on each subsequent turn, corresponding to the pitch of the single-turn helical spiral of the screw operating part, should be constant. Only in that case, the bulk cargo will be captured by the turns of the helical spiral evenly along the entire length of the screw feeder’s loading nozzle. Besides that, the developed design of the screw feeder can be used for further research of the stabilization methods of cargo volumetric mass, i.e., the weight consumption during the transportation of multicomponent materials by screw feeders by studying and determining conditions of capture in the hopper by separate turns of certain materials.

Grants and funding

The authors received no financial support for the research, authorship and/or publication of this article.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] METCALF, J. R. The mechanics of the screw feeder. *Proceedings of the Institution of Mechanical Engineers* [online]. 1965, **180**(1), p. 131-146. ISSN 0020-3483. Available from: https://doi.org/10.1243/PIME_PROC_1965_180_015_02

[2] MINGLANI, D., SHARMA, A., PANDEY, H., DAYAL, R., JOSHI, J. B., SUBRAMANIAM, S. A review of granular flow in screw feeders and conveyors. *Powder Technology* [online]. 2020, **366**, p. 369-381. ISSN 0032-5910, eISSN 1873-328X. Available from: https://doi.org/10.1016/j.powtec.2020.02.066

[3] ROBERTS, A. W., MANJUNATH, K. S., MCBRIDE, W. The mechanics of screw feeder performance for bulk solids flow control. In: 4th International Conference on Bulk Materials, Storage, Handling and Transportation: 7th International Symposium on Freight Pipelines: proceedings [online] [accessed 2023-03-27]. Preprints of papers. Barton: ACT. 1992. ISBN 0858255545, p. 333-338. Available from: https://search.informit.org/doi/10.3316/informit.388068299607697

[4] PATINGE, S., PRASAD, K. Effect of parameters on the screw feeder performance using discrete element method. *Asian Journal of Convergence in Technology* [online]. 2016, **2**(3), p. 22-23 [accessed 2023-03-27]. ISSN 2350-1146. Available from: https://asianssr.org/index.php/ajct/article/view/157/216

[5] WANG, Y, LI, T, MUZZIO, F. J., GLASSER, B. J. Predicting feeder performance based on material flow properties. *Powder Technology* [online], 2017, **308**, p. 135-148. ISSN 1873-328X. Available from: https://doi.org/10.1016/j.powtec.2016.12.010

[6] VASYLKIV, V., PYLYPETS, M., DANYLCHENKO, L., RADYK, D. Formalized description and synthesis of schemes for shaping helical flights and auger billets based on the componentic methods. *Scientific Journal of TNTU* [online], 2021, **104**(4), p. 44-57. ISSN 2522-4433. Available from: https://doi.org/10.33108/visnyk_tntu2021.04.044

[7] VASYLKIV, V., PYLYPETS, M., DANYLCHENKO, L., RADYK, D. Investigation of deflections of winded screw flights and auger billets in the processes of their manufacture. *Scientific Journal of TNTU* [online]. 2021, **104**(4), p. 33-43. ISSN 2522-4433. Available from: https://doi.org/10.33108/visnyk_tntu2021.04.033

[8] ROBERTS, A. W. Predicting the volumetric and torque characteristics of screw feeders. *Bulk Solids Handling*. 1996, **16**(2), p. 233-244. ISSN 0173-9980.

[9] YU, Y., ARNOLD, P. C. Theoretical modelling of torque requirements for single screw feeders. *Powder Technology* [online], 1997, **93**(2), p. 151-162. ISSN 1873-328X. Available from: https://doi.org/10.1016/S0032-5910(97)03265-8

[10] PATERWITZ, M., GERLING, S., SCHEMBECKER, G. Challenges in tracing material flow passing a loss-in-weight feeder in continuous manufacturing processes. *International Journal of Pharmaceutics* [online]. 2021, **612**, 121304 [accessed 2022-01-25]. ISSN 2229-5518. Available from: https://doi.org/10.1016/j.ijpharm.2021.121304

[11] XU, X., SHEN, CH., LI, F., WANG, L. Design and experimental study of equal-area variable-pitch screw structure for wheat flour. *INMATEN Agricultural Engineering* [online]. 2021, **64**, p. 423-436. ISSN 2068-4215, eISSN 2068-2239. Available from: https://doi.org/10.35633/inmateh-64-42

[12] ANSI/CEMA Standard No. 350. Screw conveyors for bulk materials. 5th edition. 2019.

[13] BATES, L. Entrainment patterns of screw hopper dischargers, transaction of the ASME. *Journal of Engineering for Industry* [online]. 1969, **91**(2), p. 295-302. ISSN 1087-1357, eISSN 1528-8935. Available from: https://doi.org/10.1115/1.3591561

[14] BATES, L. *Guide to the design, selection, and application of screw feeders*. London: Wiley and Sons Ltd, 2008. ISBN 9781860582851.

[15] BORTOLAMASI, M., FOTTNER, J. Design and sizing of screw feeders. In: International Congress for Particle Technology PARTEC 2001: proceedings [online] [accessed 2023-03-27]. 2001. p. 27-29. Available from: https://mediatum.ub.tum.de/doc/1188322/fml_20131230_514_export.pdf

[16] KULKARNI, U. G., SHAH, H. P., SANAS, S. M., SHETE, A. P., KEKAN, G. H. Design and development of screw feeder. *International Journal of Advance Research, Ideas and Innovations in Technology* [online]. 2017, **3**(2), p. 1099-1102 [accessed 2023-03-27]. ISSN 2454-132X. Available from: https://www.ijariit.com/manuscripts/v3i2/V3I2-1547.pdf

[17] LIU, M., NING, W., XIAOMEI, C., YING, S., JIANGPENG, L. Design of feed screw conveyor. *Journal of Physics: Conference Series* [online]. 2020, **1601**, 062005. ISSN 1742-6588, eISSN 1742-6596. Available from: http://dx.doi.org/10.1088/1742-6596/1601/6/062005

[18] GRIMARD, J., DEWASME, L., WOUWER, A. V. Dynamic modeling and model-based control of a twin screw extruder. In: 25th Mediterranean Conference on Control and Automation (MED): proceedings [online]. 2017. ISSN 2473-3504, p. 316-321. Available from: https://doi.org/10.1109/MED.2017.7984137

[19] KARWAT, B., RUBACHA, P., STANCZYK, E. Simulational and experimental determination of the exploitation parameters of a screw conveyor. *Eksploatacja i Niezawodnosc / Maintenance and Reliability* [online]. 2020, **22**(4), p. 741-747. ISSN 1507-2711, eISSN 2956-3860. Available from: https://doi.org/10.17531/ein.2020.4.18

[20] CLEARY, P. W. DEM modelling of particulate flow in a screw feeder model description. *Progress in Computational Fluid Dynamics, an International Journal* [online]. 2007, **7**(2-4), p. 128-138. ISSN 1468-4349, eISSN 1741-5233. Available from: https://doi.org/10.1504/PCFD.2007.013005

[21] KRETZ, D., CALLAU-MONJE, S., HITSCHLER, M., HIEN, A., RAEDLE, M., HESSER, J. Discrete element method (DEM) simulation and validation of a screw feeder system. *Powder Technology* [online]. 2016, **287**, p. 131-138. ISSN 0032-5910, eISSN 1873-328X. Available from: https://doi.org/10.1016/j.powtec.2015.09.038

[22] LOPEZ, A., VIVACQUA, V., HAMMOND, R., GHADIRI, M. Analysis of screw feeding of faceted particles by discrete element method. *Powder Technology* [online]. 2020, **367**, p. 474-486. ISSN 0032-5910. Available from: https://doi.org/10.1016/j.powtec.2020.03.064

[23] PATINGE, S., PRASAD, K. Screw feeder performance prediction using discrete element method. *International Journal of Scientific and Engineering Research* [online]. 2017, **8**(3), p. 48-51 [accessed 2023-03-27]. ISSN 2229-5518. Available from: https://www.ijser.org/researchpaper/Screw-feeder-performance-prediction-using-Discrete-Element-Method-DEM.pdf

[24] BURKHARDT, G. J. Effect of pitch, radial clearance, hopper exposure and head on performance of screw feeders. *Transactions of the American Society of Agricultural Engineers* [online]. 1967, **10**, p. 685-690. ISSN 0001-2351, eISSN 2151-0059. Available from: https://doi.org/10.13031/2013.39761

[25] CARLETON, A. J., MILES, J. E. P., VALENTIN, F. H. H. A study of factors affecting the performance of screw conveyors and feeders. *Journal of Engineering for Industry* [online]. 1969, **91**(2), p. 329-333. ISSN 0022-0817. Available from: https://doi.org/10.1115/1.3591565

[26] CARSON, J. W. Designing efficient screw feeders. *Powder and Bulk Engineering*. 1987, **12**, p. 32-42. ISSN 0897-6627.

[27] FERNANDEZ, J. W., CLEARY, P. W., MCBRIDE, W. Effect of screw design on hopper drawdown of spherical particles in a horizontal screw feeder. *Chemical Engineering Science* [online]. 2011, **66**, p. 5585-5601. ISSN 0009-2509. Available from: https://doi.org/10.1016/j.ces.2011.07.043

[28] PATEL, J. N., PATEL, S. P., PATEL, S. S. Productivity improvement of screw conveyor by modified design. *The International Journal of Emerging Technology and Advanced Engineering* [online]. 2013, **3**(1). p. 492-496 [accessed 2023-03-27]. ISSN 2250-2459. Available from: https://www.ijetae.com/files/Volume3Issue1/IJETAE_0113_77.pdf