EXPERIMENTAL STUDIES OF THE PROCESS OF LOOSE MATERIAL TRANSPORTATION BY A PNEUMATIC-SCREW CONVEYOR
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ЕКСПЕРИМЕНТАЛЬНІ ДОСЛІДЖЕННЯ ПРОЦЕСУ ПЕРЕМІЩЕННЯ СИПКИХ МАТЕРІАЛІВ ПНЕВМО-ШНЕКОВИМ ТРАНСПОРТЕРОМ

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ABSTRACT
The article presents the developed design of the pneumatic-screw conveyor, as well as its experimental installation. The method of conducting experimental researches to determine force indicators at movement of different types of loose materials under the influence of air pressure and their volume of various types of bulk materials. Based on the conducted experimental studies, the response surfaces and two-dimensional cross-sections of the pneumatic-screw conveyor productivity when the material passes from the whole area in the hopper transition zone to the screw feeder, its rotation frequency and the working air pressure in the process line have been constructed.

РЕЗЮМЕ
У статті представлено розроблену конструкцію пнемо-шнекового транспортера, а також його експериментальну установку. Наведено методику проведення експериментальних досліджень для визначення силових показників при переміщенні різних типів сипких матеріалів від впливу тиску повітря та їх об'єму різних видів сипучих матеріалів. На основі проведених експериментальних досліджень побудовані поверхні відгуку та двомірні перерізи продуктивності пнемо-шнекового транспортера від зміни площі отвору в зоні переходу бункера на шнековий живильник, частоти його обертання та величини робочого тиску повітря в технологічній магістралі.

INTRODUCTION
Based on the analysis of the patent literature, well-known theoretical and experimental studies, it has been established that mechanical screw conveyors are characterized by low productivity and energy consumption for the process of loose materials transportation. At the same time, pneumatic conveyors, unlike screw ones, have much higher productivity, but also the energy to perform the same manufacturing process is significantly higher.

The modeling of loose materials movement processes in vertical and horizontal mechanical conveyors with definition of their rational parameters and operating modes has been outlined in several studies (*Pylypaka S.F., et al., 2019; Qi J., Meng H., et al., 2017*). Filling the technological route of the conveyor with loose materials heavily depends on design perfection and selection of screw feeder parameters, and the research to substantiate the structural and kinematic parameters which have been given in the articles (*Lyashuk O.L., et al., 2018; Mondal D., 2018*).

Improving the quality indicators during transportation of agricultural production materials, particularly seeds, can be provided by screw conveyors, the working surfaces of which are made elastic. The results of such studies have been presented in the works (*Tian Y., et al., 2018; Hevko R.B., et al., 2019*).

Screw conveyors can also move loose materials along curved paths in elastic casings. Theoretical and experimental studies of these types of conveyors have been discussed in the researches (*Trokhaniak O.M., et al., 2020*).

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The choice of optimal parameters of screw and scraper conveyors with a general assessment of the efficiency of their operation has been given in the articles (*Yao Y.P., et al., 2014, Roberts Alan W., Bulk Solids, 2015, Wang D.-X., 2012*).

The current study presents the design and the evaluation of a laboratory device, which combines mechanical motion of wheat grain and turbulent air streaming inside a positive pneumatic conveyor system *(Buteler M. et.al., 2020)*. Our experimental results, which were conducted under laboratory conditions, show that the recovery efficiency of the prototype was equal to 98.0% (±1.4) on average.

The work written by *de Freitas A.G. et.al., (2020),* presents the experimental characterization of industrial bulk solids feeder, named Batchpump, and validates the performance in terms of transport capacity and compressed gas consumption of an unconventional compact pressure vessel, used as a feeding device for dense phase pneumatic conveying. The developed device was shown to have similar performance parameters (transport rate and gas consumption) when compared to conventional versions of blow tanks operating at 4 bar pressure and conveying powder material at about 9 t/h rate, albeit the smaller dimensions and simplification in operation, resulting in significant advantages in retrofits and in the implement of a new conveyor line.

The paper of *Gao X.M. et.al., (2020),* covers critical speed of pneumatic transport for conveying materials and measuring the angle of friction and the coefficient of restitution of materials on a variety of material surfaces. With the help of a machine verification test it was proved that the optimal parameters for the pneumatic transportation of Baisha peanut pods with a moisture content of 7.24% was a fan speed of 2700 r/min and a cushioning/anti-obstruction layer thickness of 6 mm.

The use of pneumatic conveyors and selection of options when moving various loose materials for rectilinear and curvilinear process routes has been described in the works (*Manjula E.V.P.J., et al., 2017; Naveen Tripathi, et al., 2015*).

In general, the disadvantage of pneumatic screw mechanisms is that screw conveyor flights provide not only translational axial material movement, but also its rotary motion, which results in both material damage and decrease in mechanism efficiency (*Hevko R.B., et al., 2014; Baranovsky V.M. et al., 2018*). As a result, it is not possible to reach the highest economic effectiveness and the maximum efficiency of a pneumatic screw conveyor in general.

When optimizing the parameters of transportation-technical systems equipped with the operating elements of screw mechanisms and at the stage of their development, it is to the point to build a mathematical technological model of a screw feeder of a pneumatic screw conveyor (*Hevko R.B. et al., 2014*) in order to obtain the performance pattern of a screw feeder, which is cantilevered on its support depending on its main design and kinematic parameters.

The aim of experimental studies of these types of conveyors is to select the optimal parameters and modes of their operation for efficient movement of loose materials on technological routes of different spatial configuration using mechanical material feed by a screw feeder and further enhance the flow of loose material with compressed air.

MATERIALS AND METHODS

In order to understand the process flow of a screw feeder operation when transporting loose materials and further substantiation of the rational parameters of the operating elements of a pneumatic screw conveyor, it is important to consider its functional diagram, which is presented in figure 1.

The pneumatic-screw conveyor consists of a frame *1*, inside of which there is an electric motor *2* with a speed regulator *3*. In the screw body *4* there is a screw feeder *5*. The pneumatic system is connected to a central opening *7*, which is made in the slotted shaft *8* of the screw feeder. The slotted shaft of the screw feeder has the possibility of angular deflection in bearing units *9* and is biased by a pressure spring *10*. On the left end of the slotted shaft, there is a pressure disk *11*, which is rigidly fixed and makes contact with the feeder of the pneumatic distributor *12* of the pneumatic system. Here, a slotted shaft of the screw feeder is mounted with the possibility of axial deflection with the help of a ball slotted joint *13*. The helix *14* of the screw feeder is multifillar and the pneumatic-operated valve *16* is arranged in the area of material output from hopper *15*.

During the operation, loose material moves through the hopper and gets into the screw body through the screw feeder, which rotates and executes loose material feed in the output area. When there is overload, caused by accumulation of a certain amount of loose material in the working space of the screw body, due to its spiral surface, the screw feeder deflects axially against the direction of loose material transportation by means of the ball slotted joint and compresses the spring. Here, a pressure disk contacts the pneumatic distributor, which admits high-pressure air from the pneumatic system. The air enters the central opening in the slotted shaft, which causes softening of pressed loose material mass and its further transportation.

The pneumatic-operated valve, which blocks the outlet of the hopper and seals the working space of the screw body, is automatically disengaged.

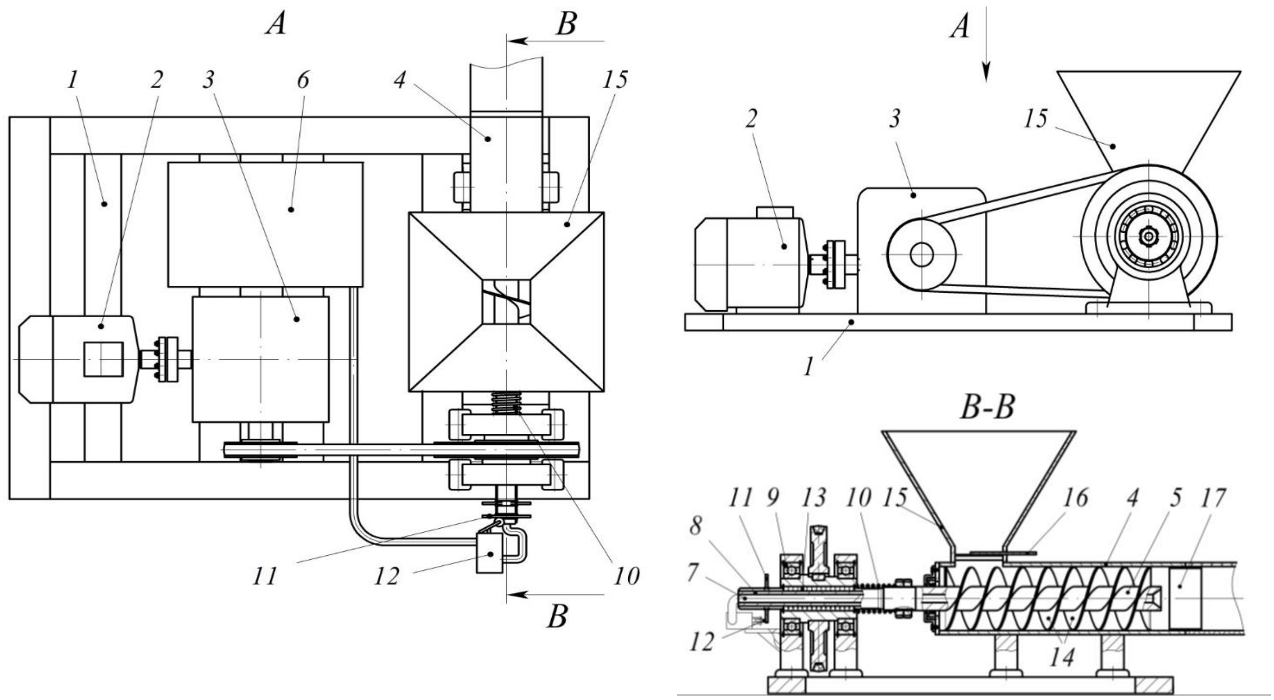


Fig. 1 – Design concept of the pneumatic-screw conveyor

1 – frame; 2 – electric motor; 3 – speed regulator; 4 – screw body; 5 – screw feeder; 6 – pneumatic system; 7 – central opening; 8 – slotted shaft; 9 – bearing units; 10 – pressure spring; 11 – pressure disk; 12 – pneumatic distributor; 13 – ball slotted joint; 14 – screw helix; 15 – hopper; 16 – pneumatic-operated valve, 17 – air circuit.

When the material is transported, axial pressure on the screw feeder is reducing and it is drawn toward the direction of loose material transportation by pressure spring force and this causes shifting of the pressure disk, which engages the pneumatic distributor that, in its turn, shuts off air feeding from the pneumatic system.

In the course of implementing loose material transportation performed by the screw, the value of the coefficient of pressure screw space filling was non-constant and depended mostly on the uniformity of loose grain material that was fed from the loading hopper as well as on other factors such as material size specifications, its moisture, material particle compacting capability in the process of their transportation by the screw etc.

The efficiency of the pneumatic screw conveyor Q was determined according to the known equation, which characterizes calculation of the necessary diameter of the pressure screw of pneumatic screw conveyor, taking into account the volumetric efficiency of the last pressure flight of the pneumatic screw conveyor feeder (*Hevko R.B. et al., 2018*), thus:

$$D = 0.29\sqrt[3]{\frac{Q}{\left(1-a_1^2\right)a_2\rho k_k \eta_t n}} \tag{1}$$

where Q – pneumatic screw conveyor efficiency, t/h; $a_1 = d/D$; $a_2 = \pi a_1 f_1 = \pi f_1 d/D$;

η_t - volumetric efficiency of the last pressure flight of the pneumatic screw conveyor feeder.

The efficiency Q (t/h) of the pneumatic screw conveyor was determined according to the formula:

$$Q = \frac{\left(D^2 - d^2\right)}{0.024}\pi d f_1 \rho k_k \eta_t n \tag{2}$$

According to *Hevko R.B. et al., (2018)*, the coefficient of sliding k_k was determined from the following formula:

$$k_k = k_\beta k_y \left(10 p_k\right)^{\lambda_D} \tag{3}$$

where p_k – excess pressure in the mixing chamber of the screw feeder, MPa; λ_D – the coefficient that shows the degree of impact of the coefficient of screw compacting capability k_y and screw diameter D on k_k.

Power dependence of the excess pressure in the mixing chamber and the coefficient λ_D $\left(10 p_k\right)^{\lambda_D}$ represent the degree of the influence of the reverse pressure and the diameter of the screw D on the value of the sliding coefficient k_k, taking into account material compacting in the screw space due to the excess pressure. The volumetric efficiency was determined according to the dependence (*Baranovsky V.M., et al., 2018*):

$$\eta_t = 1 - \frac{0.6\sqrt{10 p_k}}{n\sqrt{\rho k_y}} \sqrt{\frac{D_{cm} f_1}{f_2\left(D - d f_1\right)} 10^3} \tag{4}$$

where D_{cm} – average diameter of loose material friction along the screw flight, m; f_1 – internal friction coefficient $f_1 = tg^2\left(45^0 - 0.5\alpha_k\right) = tg^2\beta$

The efficiency of the pneumatic screw conveyor Q was determined according to the know equation:

$$Q = \frac{\pi d\left(D^2 - d^2\right)}{0.024}\left(1 - \frac{\delta_n z_n}{D tg\beta}\cos arctg\frac{2\pi D tg\beta}{D+d}\right) \times \rho\varphi_k k_\beta k_y^2 \left(n - 0.6 tg\beta\sqrt{\frac{10 p_k D_{cm}}{\rho k_y f_2\left(D - d tg^2\beta\right)} 10^3}\right) \tag{5}$$

Based on (5), graphic representation of the dependency of the change in pneumatic screw conveyor efficiency Q on diameter D and the frequency of screw rotation n as a functional $Q = f(D,n)$ at the following values φ_k = 1.0 (*Wang D.X., 2012)*, k_β=0.8; k_y=1.3 (*Yao Y.P., et.al., 2014*); d= 0.5D, p_k=0.15 MPa (*Trokhaniak O.M. et.al., 2020*), β= 20.0 deg, f_2=0.7 (*Buteler M., et.al., 2020*), z=1, δ=0.02 m, ρ=1.3 t/m^3 and on the bulk material weight ρ and the frequency of screw rotation n as a functional $Q = f(\rho, n)$ at D =0.15m in the form of surfaces and their two-dimensional sections presented in figure 2 and figure 3, respectively, were built.

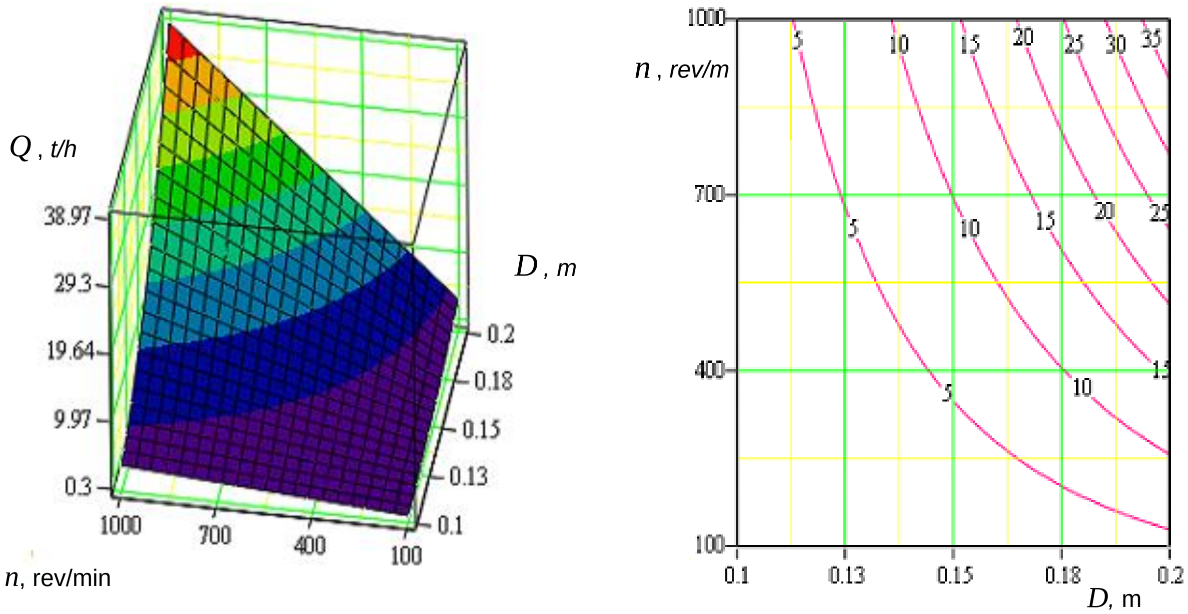


Fig. 2 – **Change dependency of pneumatic screw conveyor efficiency Q on the diameter D and the frequency of screw rotation n as a functional $Q = f(D,n)$**

The analysis of the presented surfaces shows that the pneumatic screw conveyor efficiency Q changes within the range of 0.3…39 t/h, depending on the change of screw design-kinematic and technological parameters and the properties of loose material within the following ranges: screw diameter D=0.1…0.2 m; frequency of screw rotation n = 100…1000 rev/min volumetric loose material weight

ρ=0.9…1.5 t/m^3 and characterizes the increase in the efficiency Q compared to the efficiency of the feeding screw approximately by 1.3 times.

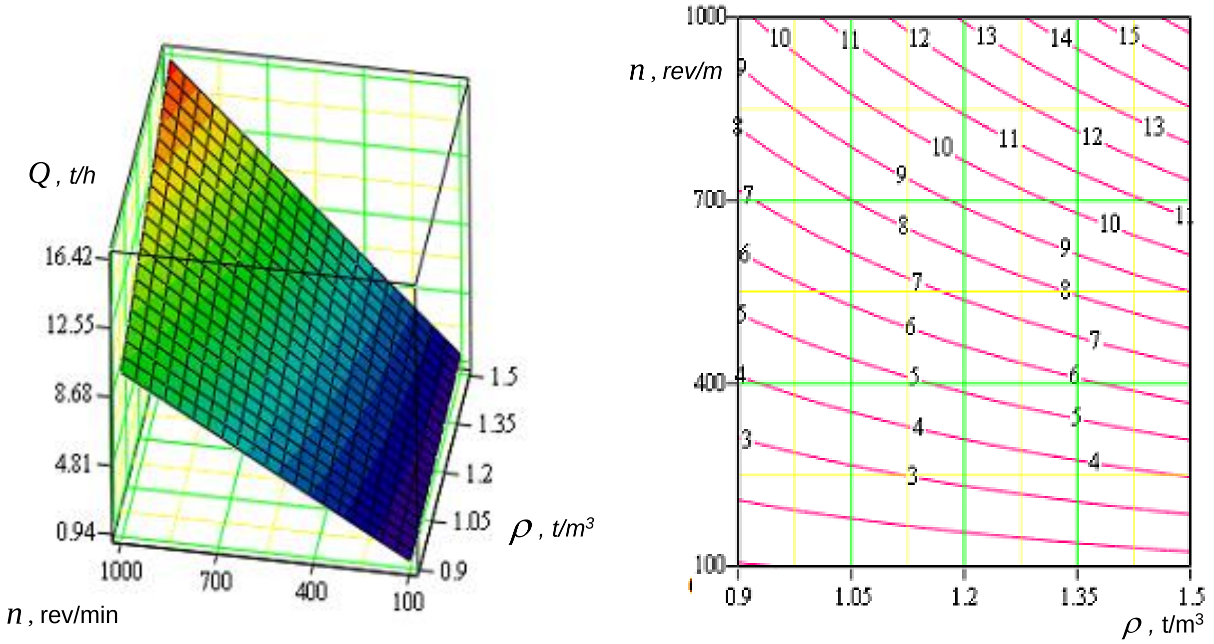


Fig. 3 – Change dependency of pneumatic screw conveyor efficiency Q on bulk material weight ρ and the frequency of screw rotation n as a functional $Q = f(\rho, n)$

Based on the design concept of the pneumatic-screw conveyor, a laboratory-scale plant (Fig.4) has been developed. Its main units are: compressor *1* with electric drive *2*, drive motor of the screw operating element *3*, control unit *4*.

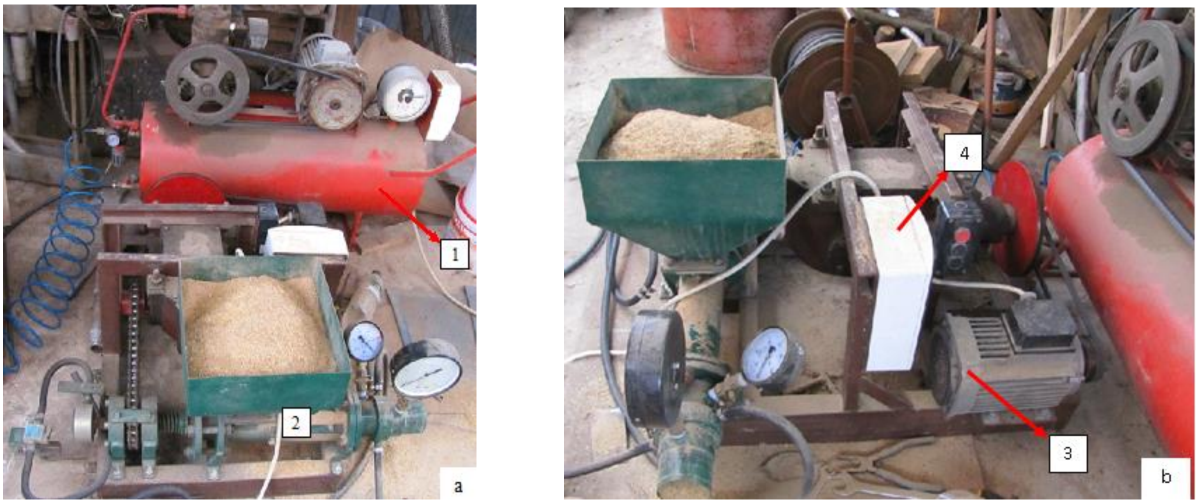


Fig. 4 – Overall view of the laboratory-scale plant
a – side view; b – front view; 1 – electrically driven compressor; 2 – pneumatic-screw conveyor;
3 – drive motor of operating elements; 4 – control unit.

One of the main mechanisms of a pneumatic screw conveyor is the mechanism of pneumatic distributor engagement (Fig.5). This mechanism allows compressed air automatically feed along hoses to nozzles (*Hevko R.B. et al., 2018*).

When there is an accumulation of loose material at the point of its feeding by the feeder, flight screw loading increases, but at first stages of transportation pressure spring *1* force is able to deal with this load. A feeder valve is connected to the slotted shaft *3*, which is fixed in the body *2* by means of balls and its axial deflection is possible when loading increases. When flight loading reaches its critical value, the axial component of which exceeds compressed spring force, the valve begins to bias in the direction opposite to material movement. Here, the rotary pneumatic junction *5* engages the pneumatic distributor *4* and ingoing compressed air begins to move along air-lines in the direction of material unloading area.

Such mechanism gives the opportunity to regulate torque value when a pneumatic distributor is engaged for various loose materials transportation and to control the distance of their movement.

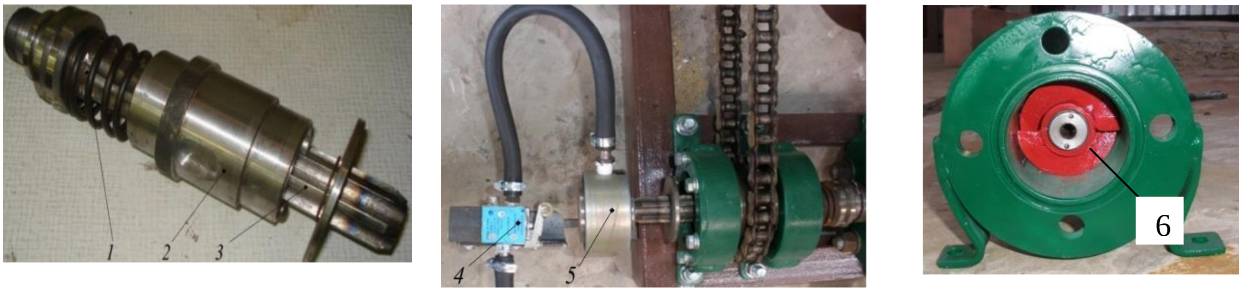


Fig. 5 – Mechanism of pneumatic distributor engagement and its connection to a tri-linear switch
1 – *spring; 2– body; 3 – slotted shaft with half slots; 4 – pneumatic distributor; 5 – pneumatic junction; 6 – nozzle.*

In order to conduct experimental studies, a pneumatic screw conveyor plant with air-powered transportation flow has been designed and it is presented in figure 6.

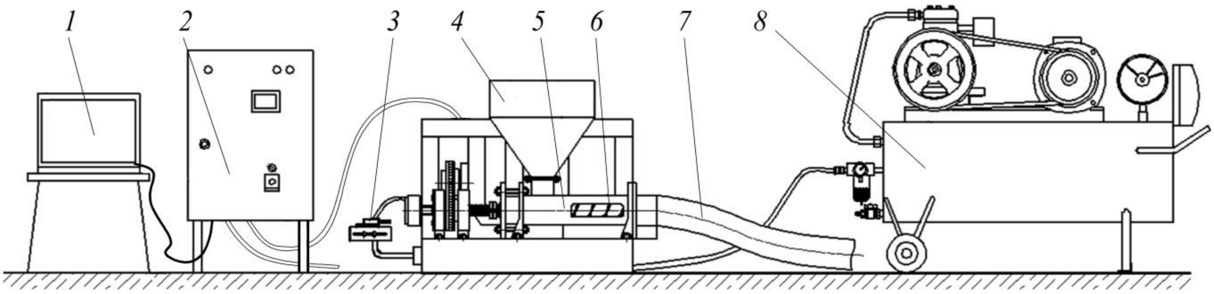


Fig. 6 – The lay-out of the pneumatic screw conveyor plant with air-powered material flow
1 – computer; 2 – «Altivar-71»; 3 – pneumatic distributor; 4 – hopper; 5 – feeder body;
6 – screw feeder; 7 – flexible transportation pipe; 8 – compressor.

In order to determine real power parameters of the process of loose material transportation, a frequency control drive Altivar-71 with Power Suite v.2.5.0 software has been used in the process of experimental studies. Altivar-71 system is connected to the network and to a computer. While setting the required rotation frequency with the help of a computer, there is a command transfer to the electric motor by means of Altivar-71 system and it begins to rotate the screw feeder valve with pre-set parameters.

By changing certain parameters, it is possible to determine the influence of torque value T and engine power N depending on the rotation frequency of the operating element n at its overload and the beginning of reverse movement of the slotted shaft with the screw feeder in order to feed the air from the pneumatic system. In addition, the obtained data are the initial ones in order to choose spring stiffness.

RESULTS

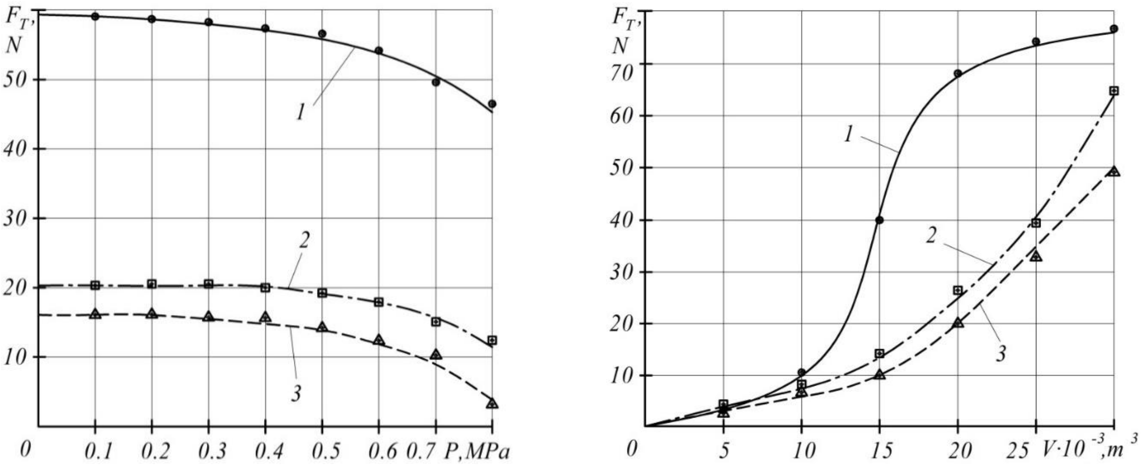
Based on the results of experimental studies, graphical dependences of the force F_T of load transportation on the air pressure P are constructed (Fig.7a) and the displacement forces of different loose materials from their volume V at a constant air supply pressure P = 0.6 MPa (Fig.7b).

The bulk density of loose material also has a significant effect on the magnitude of the F_T force. Thus, for wheat with a bulk density of 720 kg/m^3 and bran with a bulk density of 250 kg/m^3, the F_T force is significantly higher for a material with a higher bulk density.

Experimental research on the efficiency of the pilot pneumatic screw conveyor unit at high-pressure air feeding was conducted based on implementing a multifactorial experiment of FFE 3^3 type. The efficiency of the pilot pneumatic screw conveyor unit Q at high-pressure air feeding, which was experimentally observed, was found in the form of a mathematical model:

$$Q = -4.33 + 7.34\ln(S_c - 24) + 2.26\ln(n - 300) + 2.97\ln(20P - 5) \quad (6)$$

The conducted experimental research on the pilot unit resulted in obtaining the dependencies of pneumatic screw efficiency on the change in the area of the hopper discharge hole $12.10^{-4} \le S_c \le 36.10^{-4}$ m^2, the frequency of feeder rotation $150 \le n \le 450$ rev/min and the value of operating air pressure $0.2 \le P \le 0.3$ MPa in a technological line, which are presented in the form of response surfaces (a) and their two-dimensional sections (b), as a functional $Q = f(S_c, P)$ at n = 300 rev/min (Fig.8a) and $Q = f(n, P)$ at $S_c = 24\ 10^{-4}$ m^2 (Fig.8b).

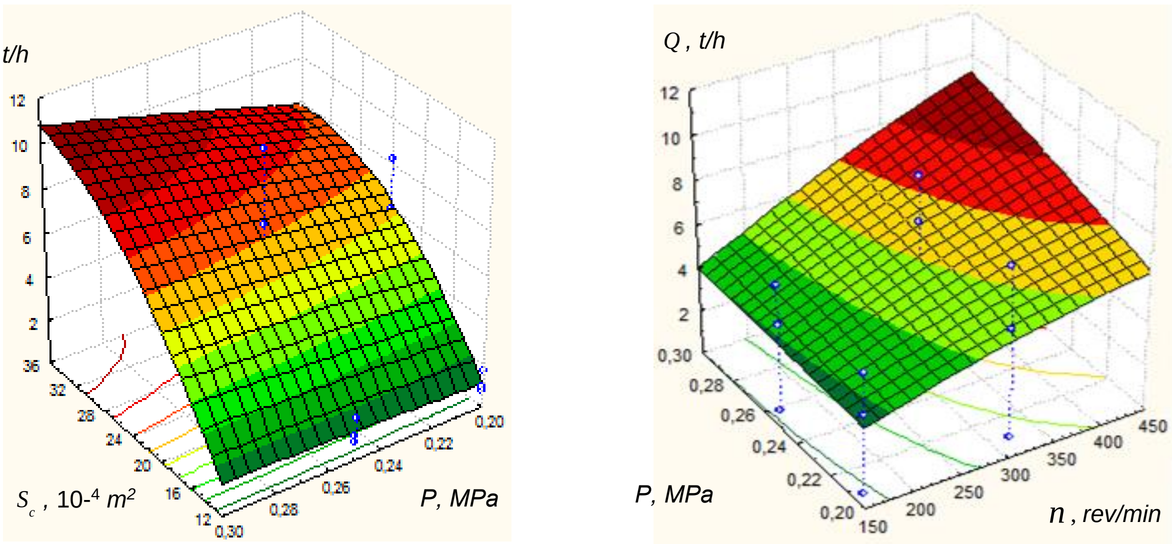


a) b)

Fig. 7 – Graphic dependencies: effort of load transportation on one running meter F_T

a – on air pressure P; b – on the volume V of different loose materials; 1 – wheat; 2 – saw dust; 3 – bran.

The graphs show that the effort F_T of transporting loose materials decreases with increasing air pressure P in the pneumatic system and increases with increasing volume V of loose material.



a) b)

Fig. 8 – Response surfaces of pneumatic screw conveyor efficiency as a functional

a – Q = f(S$_c$, P) at n = 300 rev/min; b – Q = f(n, P) at S$_c$ = 24 10-4 m^2.

The obtained regression dependence (6) can be used for determining the efficiency of the pilot pneumatic screw conveyor unit with high-pressure air feed depending on the change in the area of a hopper discharge hole S_C, the frequency of screw rotation n and the value of the operating air pressure P within the following limits: $12.\ 10^{-4} \le S_C \le 36.\ 10^{-4}$ m^2; $150 \le n \le 450$ rev/min; $0.2 \le P \le 0.3$ MPa.

The analysis of graphical dependences shows that the productivity Q of the pneumatic screw conveyor increases with increasing magnitude of the active factors. The most significant influence on the value Q has the value S_c, then the value n. It should be noted that increasing the area of the discharge hole of the hopper S_c over $36 \cdot 10^{-4}$ m^2 does not increase the productivity of Q, because the excess loose material is not included in the housing of the screw feeder, and is thrown back into the hopper.

The minimum influence on productivity Q, in the given range of variable values of factors, has the size of air pressure P in the technological line.

CONCLUSIONS

The article presents the developed design of the pneumatic screw conveyor as well as experimental installations and research methods for determining the force indicators for the movement of loose load under the influence of air pressure and the volume of different types of loose materials. It is established that transportation efforts F_T of bulk materials decreases with increasing air pressure in the pneumatic system. The bulk density of loose material has a significant effect on the amount of the effort F_T. Thus, for wheat with a bulk density of 720 kg/m^3 and bran with a bulk density of 250 kg/m^3, the effort F_T at a pressure P of up to 0.8 MPa and V = (20…25) 10^{-3} m^3 is by 3.5…5 times larger for a material with a larger bulk density.

Based on the manufactured installation of pneumatic-screw conveyor with feeding the flow of material by air jets, the dependences of productivity Q of pneumatic-screw conveyor on the change of the area of the eastern opening of the hopper, the speed of the screw feeder and the working air pressure in the process line have been established. The value S_c, then the value n has the most significant influence on the value Q. Increasing the area of the discharge hole of the hopper S_c over 36·10^{-4} m^2 does not increase the productivity Q, because the excess material does not enter the housing of the screw feeder, and is thrown back into the hopper.

The minimum influence on the productivity Q of the pneumatic-screw conveyor, in this range of variable values of factors, has the value of air pressure P in the process line.

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