Вісник Тернопільського національного технічного університету
https://doi.org/10.33108/visnyk_tntu
Scientific Journal of the Ternopil National Technical University
2025, № 2 (118) https://doi.org/10.33108/visnyk_tntu2025.02
ISSN 2522-4433. Web: ***visnyk.tntu.edu.ua***

UDC 631.361.8

THE PROCESS OF MOVING GRAIN MATERIAL IN THE PNEUMATIC LINE OF A PNEUMATIC SCREW CONVEYOR

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Abstract. *Pneumatic conveyors are used to move diverse cargoes of various industries. To ensure the performance of such work in large specialized agricultural companies that grow grain crops, powerful pneumatic conveyors are used, and the use of such mechanisms is cost-effective provided that grain crops are grown on significant areas or, accordingly, significant gross grain production. In the conditions of operation of multi-branch farms that harvest grain crops on insignificant areas, the topical task is the issue of payback of such transport mechanisms due to their insignificant seasonal workload of the performed works. Solving this important task is possible by developing and using small-sized and mobile pneumatic screw conveyors, which are designed to move grain materials or perform transport work on the currents of multi-branch farms. The purpose of the work is to increase the functional indicators of the operation of screw transport mechanisms by means of constructive improvement and substantiation of rational parameters of the pneumatic screw conveyor. The article describes an improved pneumatic screw conveyor (design and operating principle) and presents the results of a theoretical analysis of the contact interaction of elementary particles of grain material during their movement in the air flow of the pneumatic duct of the pneumatic screw conveyor based on the study of the total elementary kinetic energy.*

Key words: *screw feeder, pneumatic pipeline, grain flow, elementary mass, contact interaction, model, kinetic energy, speed, vector, recovery coefficient, fluctuation rate.*

https://doi.org/10.33108/visnyk_tntu2025.02.079 *Received 10.03.2025*

1. INTRODUCTION

Pneumatic conveyors or pneumatic transport are used to move various cargoes in various industries. A specific feature of such transport mechanisms is that the transportation of materials can take place along routes of various configurations, which facilitates the ways of their delivery to the destination [1, 2].

To ensure the performance of such work in large specialized agricultural companies that grow grain crops, powerful pneumatic conveyors with a capacity of up to 200...250 t/h are used and which move cargoes in the horizontal direction to a distance of up to 100 m or more, or in the vertical direction – to a lifting height of up to 30 m [3, 4]. The use of such pneumatic conveyors is cost-effective if grain crops are grown on significant areas or significant gross grain production [5].

In the conditions of operation of multi-branch farms that harvest grain crops on small areas (30…100 hectares), the current task is the issue of payback of such powerful transport mechanisms due to their insignificant seasonal workload of the performed works [6].

The ways to solve this important technical and economic problem are the development and use of small-sized and mobile pneumatic screw conveyors, which are designed to move grain materials during their post-harvest processing or perform transport work on small streams of multi-branch farms of the agrarian sector of the industry of Ukraine [7].

The use of such pneumatic screw conveyors for performing transport work on grain streams of multi-branch farms will significantly increase the technical and economic indicators of growing grain crops [8].

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The study of the process of transporting or moving materials by air flow in a pneumatic pipeline is one of the important steps in ensuring the rational functioning of the process of transport mechanisms or the manufacturability of the process of operation of a pneumatic screw conveyor [9, 10].

2. MATERIALS AND METHODS

The proposed small-sized mobile pneumatic screw conveyor (Fig. 1) consists of a main frame (not shown in the figure), on which a cylindrical casing 1 is installed, which is made in the form of a guide pipe, inside which a screw 2 with a variable pitch is mounted, which decreases towards its output end. A hopper 3 is fixed on the outer side of the casing from its input end. A flange 4 is fixed on the output end of the casing, to which a cylindrical housing 5 is fixed by means of a bolted connection. Pneumatic nozzles 6 are installed inside the casing, and fittings 7 and 8 are mounted in the walls of the casing to which the hoses of the pneumatic system are connected. A flexible hose 9 of the pneumatic line is connected to the output end of the cylindrical housing. The pneumatic screw conveyor has a pneumatic distribution system, a control panel, a screw drive mechanism 10 [11].

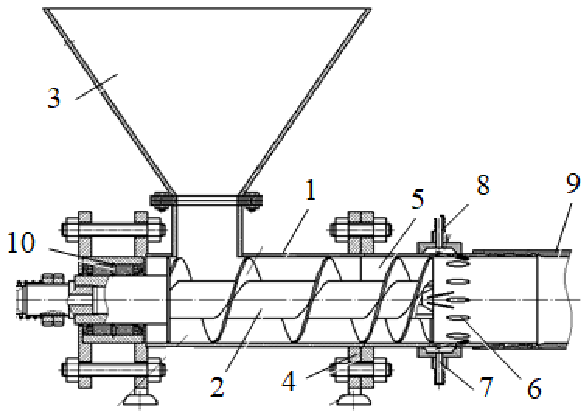

Figure 1. Structural diagram of a pneumatic screw conveyor:
1 – casing (guide pipe); 2 – screw; 3 – hopper; 4 – flange; 5 – housing; 6 – nozzle;
7, 8 – fitting; 9 – pneumatic hose; 10 – screw drive

Loaded into the hopper 3 (Fig. 1) grain material enters the space of the casing 1 and to the screw 2, which due to its rotation moves the grain material along its horizontal axis of rotation to the output end of the casing. Subsequently, after the grain material has descended from the last pressure spiral turn of the screw, the grain material is moved by the compressed air flow in the housing 5 to the nozzles 6, and then along the pneumatic line to its destination.

The movement of cargo in a compressed air flow from a mechanical point of view is a complex and chaotic process and is characterized by the presence of many objective and subjective factors that have a significant impact on the kinematic and dynamic processes occurring in it [12].

One of the methods for studying such flows is the theoretical analysis of the expenditure of kinetic energy on the movement of materials and the contact interaction of material particles during movement in the pneumatic pipeline of a pneumatic screw conveyor using the basic laws of theoretical mechanics and methods for the movement of solid media [13, 14].

3. RESULTS AND DISCUSSION

At the first stage, we will consider the process of moving an elementary particle of grain material in the pneumatic pipeline of a pneumatic screw conveyor.

It is known that in the process of moving flows of granular materials or the movement of elementary mass particles in the air pipeline, their chaotic movement occurs, which is relatively complex in nature [15, 16]:

– depending on the unequal values of the translational velocities of movement, elementary particles acquire relative shear velocities;

– depending on the nature of the contact interaction of elementary particles or by co-impact with each other, they acquire additional components of the translational velocities, which accompanies their spatial chaotic movement in the space of the pipeline.To analyze the kinematic process of moving grain material in the air flow of the pneumatic duct of a pneumatic screw conveyor, a diagram was drawn up, Fig. 2. It characterizes the process of moving the flow of particles 2 (Fig. 2) of grain material in the pneumatic duct 1 of the pneumatic screw conveyor, while we assume the shape of the grain material in the form of an ellipsoid.

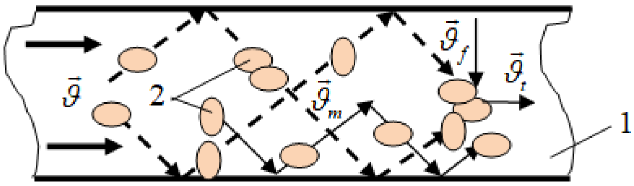

Figure 2. Scheme of the movement of grain material particles in a pneumatic pipe: 1 – pneumatic pipe; 2 – grain material particle

As a basis for considering and analyzing the kinematic process of contact interaction of two particles of elementary mass dm_1 and dm_2, we take the known dependence that describes the behavior of the state of movement of a loose grain medium [17]

$$p(x)\bar{\xi}(x) = \chi\left(\frac{d\vartheta}{dx}\right)^2, \tag{1}$$

where $p(x)$ is the analogue of hydrostatic pressure in the pneumatic pipeline, Pa; $\bar{\xi}(x)$ is the porosity or dilatation of the granular medium; χ is the coefficient of the physical constant; ϑ is the speed of movement of grain material in the air flow of the pneumatic pipeline, m/s.

In equation (1), the product of the components $p(x)$ and $\bar{\xi}(x)$ of the left-hand side is identical to the physical concept of the elementary kinetic energy of the chaotic movement of a particle of the grain medium of elementary mass dm, and the product of the coefficient of the physical constant χ by the square of the velocity ϑ^2 is identical to the elementary value of the work spent on the movement of an elementary particle.

It is known that the basis for the movement or motion of a granular medium, which is the medium of grain material, is the displacement of the flow of particles of elementary mass dm, where the instantaneous speed of movement of particles in the air space of the pneumatic pipeline is the sum of three interrelated components of speeds – the fluctuation speed, the indirect translational speed of movement of the particle, the angular speed of rotation of the particle.

Then the elementary total kinetic energy $d\sum_{i=1}^{n} E_i$ (J) of the particle movement is defined as the sum of the kinetic energies of the three available movements – the elementary kinetic energy of the particle of relative translational motion dE_t (J) during shear, the elementary kinetic energy of the chaotic random deviation of the particle or fluctuation dE_f (J) and the elementary kinetic energy of transverse mass transfer dE_m (J) during particle rotation, i.e.

$$d\sum_{i=1}^{3} E_i = dE_t + dE_f + dE_m \,. \tag{2}$$

In this case, the corresponding kinetic energies of the three available displacements of a particle of elementary mass dm_e are determined by the formula [18]:

$$dE_t = \frac{dm_e\left(\Delta x\right)^2}{2}\left(\frac{d\vartheta_t}{dx}\right)^2; \tag{3}$$

$$dE_f = \frac{dm_e\left(\vartheta_f\right)^2}{2}; \tag{4}$$

$$dE_m = \frac{dm_e l_e \vartheta_m}{2}\frac{d\vartheta_t}{dx}, \tag{5}$$

where Δx is the difference in the particle displacement relative to its centers of gravity of the initial and final coordinates, m; ϑ_f is the fluctuation velocity, m/s; ϑ_m is the velocity of transverse mass transfer of the particle, m/s.

Accordingly, the difference in the particle displacement $\Delta x = x_2 - x_1$ relative to its centers of gravity of the initial and final coordinates, the elementary mass dm_e of the ellipsoidal particle, the fluctuation velocity ϑ_f and the velocity of transverse mass transfer of the particle ϑ_m are determined by the dependencies

$$\left.\begin{aligned} dm_e &= V_e\rho_q = \frac{4}{3}\pi abc; \\ \vartheta_f &= \vartheta_m = 2\upsilon_k l_m \end{aligned}\right\}, \tag{6}$$

where $V_e = 4\pi abc/3$ is the volume of the ellipsoid, m^3; a, b, c is the corresponding axes of the ellipsoid, m; ρ_q is the specific gravity of the grain material, kg/m^3; υ_k is the average frequency of particle contacts, 1/s; l_m is the average distance between the reduced centers of mass of the particle, m.

Then equations (3)–(5) will take the form:

$$dE_t = \frac{2\pi abc\left(x_2 - x_1\right)^2}{3}\left(\frac{d\vartheta_t}{dx}\right)^2; \tag{7}$$

$$dE_f = \frac{4\pi abc\rho_q \left(\upsilon_k l_m\right)^2}{3}; \tag{8}$$

$$dE_m = \frac{4\pi abc\rho_q \upsilon_k l_m^2}{3}\frac{d\vartheta_t}{dx}, \tag{9}$$

and the elementary total kinetic energy $\sum_{i=1}^{n} dE_i$ (J) of the movement of a particle of grain material in the pneumatic line of the pneumatic screw conveyor according to (2) and (7)–(9) is determined by the formula

$$\sum_{i=1}^{3} dE_i = \frac{2\pi abc\left(x_2 - x_1\right)^2}{3}\left(\frac{d\vartheta_t}{dx}\right)^2 + \frac{4\pi abc\rho_q\left(\upsilon_k l_m\right)^2}{3} + \frac{4\pi abc\rho_q \upsilon_k l_m^2}{3}\frac{d\vartheta_t}{dx}. \tag{10}$$

After transformation and simplification, dependence (10) will have the form

$$\sum_{i=1}^{3} dE_i = \frac{2\pi abc\rho_q}{3}\left[\left(x_2 - x_1\right)^2\left(\frac{d\vartheta_t}{dx}\right)^2 + 2\upsilon_k l_m^2\left(\upsilon_k + \frac{d\vartheta_t}{dx}\right)\right], \tag{11}$$

and equation (1), which describes the behavior at this stage of the analysis of the state of movement of the loose grain medium in the pneumatic line of the pneumatic screw conveyor according to (11), can be written in the form

$$p\left(\bar{\xi}\right) = \chi' \frac{2\pi abc\rho_q}{3}\left[\left(x_2 - x_1\right)^2\left(\frac{d\vartheta_t}{dx}\right)^2 + 2\upsilon_k l_m^2\left(\upsilon_k + \frac{d\vartheta_t}{dx}\right)\right]\left(\frac{d\vartheta_t}{dx}\right)^2, \tag{12}$$

where $\bar{\xi}$ is the average porosity of the grain medium; χ' is the coefficient of the physical constant, which is adequate to the specific work spent on moving the particle layer over an area equal to 1 m2.

It is known that according to the Ackerman-Schen formula [19] the following are determined:

- the average contact frequency υ_k of the particle

$$\upsilon_k = \frac{\tau}{D_{1k} n_{1V}}\frac{d\vartheta_t}{dx}, \tag{13}$$

where τ is the shear stress, Pa; D_{1k} is the dissipation of kinetic energy of one particle contact, J; n_{1V} is the number of particles per unit volume of one layer, 1/m^3;

- dissipation D_{1k} of kinetic energy of one particle contact

$$D_{1k} = \frac{4}{3}\pi abc\rho_q\left(\frac{1-\kappa^2}{4} + \frac{f\left(1+\kappa\right)}{\pi} - \frac{f^2\left(1+\kappa\right)^2}{4}\right)\left(\vartheta_f\right)^2. \tag{14}$$

Substituting the value of D_{1k} from (14) into dependence (13), we obtain

$$\upsilon_k = \frac{12\pi\tau}{4\pi abc\rho_q n_{1V}\left(\vartheta_f\right)^2\left[\pi\left(1-\kappa^2\right)+4f\left(1+\kappa\right)-\pi f^2\left(1+\kappa\right)^2\right]}\frac{d\vartheta_t}{dx}. \quad (15)$$

Therefore, the final dependence for determining the elementary total kinetic energy $\sum_{i=1}^{n} dE_i$ (J) of the movement of a particle of grain material in the pneumatic line of a pneumatic screw conveyor has the form

$$\sum_{i=1}^{3} dE_i = \frac{2\pi abc\rho_q}{3}\left[\left(x_2-x_1\right)^2\left(\frac{d\vartheta_t}{dx}\right)^2+\left(\Omega l_m^2\frac{d\vartheta_t}{dx}\right)\left(\Omega\frac{d\vartheta_t}{dx}+\frac{d\vartheta_t}{dx}\right)\right], \quad (16)$$

where $\Omega = \frac{24\pi\tau}{4\pi abc\rho_q n_{1V}\left(\vartheta_f\right)^2\left[\pi\left(1-\kappa^2\right)+4f\left(1+\kappa\right)-\pi f^2\left(1+\kappa\right)^2\right]}$, and equation (12), which describes the behavior at the final stage of the analysis of the state of movement of the loose grain medium in the pneumatic line of the pneumatic screw conveyor according to (16) can be written in the form

$$p\left(\overline{\xi}\right) = \chi'\frac{2\pi abc\rho_q}{3}\left[\left(x_2-x_1\right)^2\left(\frac{d\vartheta_t}{dx}\right)^2+\left(\Omega l_m^2\frac{d\vartheta_t}{dx}\right)\left(\Omega\frac{d\vartheta_t}{dx}+\frac{d\vartheta_t}{dx}\right)\right]. \quad (17)$$

The obtained final dependence (16) describes the «temperature of the granular medium» [15] during mutual movements of particles of granular loose medium.

At the second stage, we will consider the process of collision of two elementary particles of grain material in the pneumatic pipeline of a pneumatic screw conveyor.

As a basis for consideration and analysis of the kinematic process of contact interaction of two particles, we formalize the process of movement of particles of elementary mass dm_1 and dm_2 in the air pipeline as follows:

- the material of particles of elementary mass dm_1 and dm_2 in the process of their contact interaction or collision of one particle with another particle of grain material is elastic;
- the elasticity of an elementary particle is characterized by the corresponding coefficient of recovery κ.

The contact interaction of two particles of elementary mass dm_1 and dm_2, which move in the air flow of the pneumatic pipeline, usually occurs only under the condition:

- when particles of different elementary mass $dm_1 \neq dm_2$ collide or, respectively, when the particles have different weights $dm_1 g \neq dm_2 g$, which also, respectively, leads to the consequent condition J;
- when the elementary mass particles differ significantly in their shape, or have different values of the air resistance force $F_{o1} \neq F_{o2}$.

A case of contact interaction of two identical particles is also possible, when their elementary masses are equal to each other $dm_1 = dm_2$, or their corresponding dimensional geometric parameters are equal to each other [20]. In this case, the appearance of a condition is also necessary under which, in addition to the instantaneous velocities or velocities of the axial direction of their movement (approach), there must be normal or radial and tangential components of the velocities. Let us consider the process of contact interaction of an elementary particle 1 (Fig. 3) of grain material with an elementary particle 2 of grain material, which move in the pneumatic line 3 of the pneumatic screw conveyor.

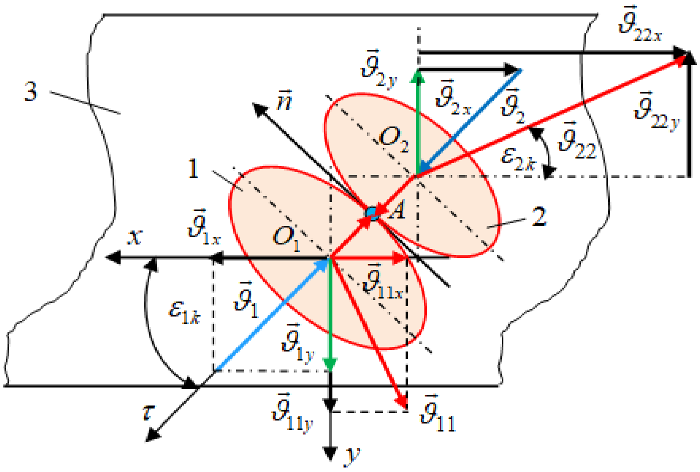

Figure 3. Scheme for calculating the process of contact interaction of two particles of elementary mass of grain material: 1 – particle of elementary mass; 2 – particle of elementary mass; 3 – transmission line

We assume that the collision or kinematic contact of two elementary particles of mass dm_1 and dm_2 occurs after their collision with the inner wall of the pneumatic pipe 3, while the collision of two particles with each other occurs in the air space of the pneumatic pipe after their contact with its inner wall, and the angle ε_{1k} should vary in the range from 0 to 90 degrees, or $0 \le \varepsilon_{1k} \le \pi/2$ rad.

In this case, the process of contact interaction of two particles of elementary mass dm_1 and dm_2 can be considered in terms of oblique collision, in which the direction of the initial impact vectors of the particle velocities $\vec{\vartheta}_1$ and $\vec{\vartheta}_2$ are directed at an angle ε_{1k} and ε_{2k} to the direction of movement of compressed air, and the contact process is accompanied by the resulting shock pulses of two particles $dm_1\vartheta_1$ and $dm_2\vartheta_2$.

According to the law of conservation of energy in the process of contact impact of two elementary particles of grain material of mass dm_1 and dm_2, their total elementary kinetic energy $\sum_{i=1}^{2} dE_i$ (J) is determined by the formula

$$\sum_{i=1}^{2} dE_i = \frac{1}{2}dm_1\vartheta_1^2 + \frac{1}{2}dm_2\vartheta_2^2 - \frac{1}{2}dm_1\vartheta_{11}^2 - \frac{1}{2}dm_2\vartheta_{22}^2 =$$
$$= \frac{1}{2}\left(dm_1\vartheta_1^2 - dm_1\vartheta_{11}^2\right) + \frac{1}{2}\left(dm_2\vartheta_2^2 - dm_2\vartheta_{22}^2\right) = \frac{dm_1\left(\vartheta_1^2 - \vartheta_{11}^2\right) + dm_2\left(\vartheta_2^2 - \vartheta_{22}^2\right)}{2}, \tag{18}$$

where ϑ_1, ϑ_2 – the speed of movement of the centers of the 1st and 2nd particles of grain material before contact between them, m/s;

ϑ_{11}, ϑ_{22} – the speed of movement of the centers of the 1st and 2nd particles of grain material after contact with each other, m/s.

The difference in the components of the velocities $\vartheta_1 - \vartheta_{11} = \Delta\vartheta_1$ and $\vartheta_2 - \vartheta_{22} = \Delta\vartheta_2$ according to the Gauss hypothesis [21] about the existence of a connection between the tangential and normal momenta of two elementary particles, which is formed similarly to Coulomb's law of friction of two bodies, is determined by the formula

$$\left.\begin{aligned}\vartheta_1 - \vartheta_{11} = \Delta\vartheta_1 = -\vartheta_{1f} f\left(1+\kappa_1\right);\\ \vartheta_2 - \vartheta_{22} = \Delta\vartheta_2 = -\vartheta_{2f} f\left(1+\kappa_2\right)\end{aligned}\right\}, \tag{19}$$

where κ_1, κ_2 – recovery coefficient of the 1st and 2nd particles of grain material; ϑ_{1f}, ϑ_{2f} – fluctuation speed of the 1st and 2nd particles of grain material, m/s; f – friction coefficient between particles.

Substituting the value of the difference of the velocity components $\vartheta_1 - \vartheta_{11} = \Delta\vartheta_1$ and $\vartheta_2 - \vartheta_{22} = \Delta\vartheta_2$ from (19) into dependence (18), we obtain:

$$\sum_{i=1}^{2} dE_i = \frac{dm_1\left(\vartheta_1 - \vartheta_{11}\right)\left(\vartheta_1 + \vartheta_{11}\right) + dm_2\left(\vartheta_2 - \vartheta_{22}\right)\left(\vartheta_2 + \vartheta_{22}\right)}{2} = \frac{dm_1\left(\Delta\vartheta_1\right)^2 + dm_2\left(\Delta\vartheta_2\right)^2}{2}; \tag{20}$$

$$\sum_{i=1}^{2} dE_i = \frac{dm_1\left[\vartheta_{1f} f\left(1+\kappa_1\right)\right]^2 + dm_2\left[\vartheta_{2f} f\left(1+\kappa_2\right)\right]^2}{2} \tag{21}$$

If we assume that $\kappa_1 = \kappa_2 = \kappa$, then the recovery coefficient κ is determined by the formula

$$\kappa = \frac{\vartheta_{11} - \vartheta_{22}}{\vartheta_1 \cos\varepsilon_{1k} - \vartheta_2 \cos\varepsilon_{2k}}, \tag{22}$$

where ε_{1k}, ε_{2k} is the angle between the vector of the direction of motion of the centers of the 1st and 2nd particles of grain material and the horizontal axis *Ox*, degrees, and dependence (22) can be written as:

$$\sum_{i=1}^{2} dE_i = \frac{dm_1\left[\vartheta_{1f} f\left(1+\kappa\right)\right]^2 + dm_2\left[\vartheta_{2f} f\left(1+\kappa\right)\right]^2}{2}; \tag{23}$$

$$\sum_{i=1}^{2} dE_i = 0,5 f^2 \left(1 + \frac{\vartheta_{11} - \vartheta_{22}}{\vartheta_1 \cos\varepsilon_{1k} - \vartheta_2 \cos\varepsilon_{2k}}\right)^2 \left(dm_1\vartheta_{1f}^2 + dm_1\vartheta_{2f}^2\right). \tag{24}$$

If we also assume that $dm_1 = dm_2 = dm$ and $\vartheta_{1f} = \vartheta_{2f} = \bar{\vartheta}_f$, then the dependence (23) can be written as

$$\sum_{i=1}^{2} dE_i = 0,5 f^2 dm\left(1+\kappa\right)^2 \bar{\vartheta}_f^2. \tag{25}$$

The fluctuation rate of grain material particles ϑ_{1f} and ϑ_{2f} largely depends on the value of the transverse quasi-diffusion coefficient D_{kd}, which, according to [22], is determined by the formula $D_{kd} = 0,5\vartheta_f l_m$ and which in turn regulates the intensity of mutual particle movement, while the intensity of particle movement increases proportionally to D_{kd} and the gradient of the velocity of translational motion of particles in the direction of the shear velocity $d\vartheta_t / dx$.

In addition, the dependences (19) do not take into account the physical properties of the surfaces of particles that collide at the points of collision, and the relationship between the tangential and normal momentum during contact impact is described by the «λ-hypothesis» [23], which states that the difference $\Delta\vartheta_1$ and $\Delta\vartheta_2$ of the tangential relative velocities is proportional to the pre-impact values of the velocities ϑ_1 and ϑ_2:

$$\Delta\vartheta_1 = -\bar{\lambda}\vartheta_1; \;\; \Delta\vartheta_2 = -\bar{\lambda}\vartheta_2, \tag{26}$$

where $\bar{\lambda}$ is the average coefficient, the value of which depends on the characteristics of the particles.

When further determining the difference $\Delta\vartheta_1$ and $\Delta\vartheta_2$, we take the combined hypotheses (19) and (26) as the basis of the analysis and write their limiting cases in the form of a continuous function, while we assume that $\kappa_1 = \vartheta_{11} / \vartheta_1 = \frac{dl_{11}}{dt} / \frac{dl_1}{dt} = \frac{dl_{11}dt}{dtdl_1} / \frac{dl_1 dt}{dtdl_1} = \frac{dl_{11}}{dl_1}$, and the coefficient κ_2 by analogy with κ_1 is defined as $\kappa_2 = \vartheta_{22} / \vartheta_2 = \frac{dl_{22}}{dl_2}$ [25], where dl_{11}, dl_1 are, respectively, the path traveled by the 1st particle after contact and before contact, m; t is the time of particle motion, s; dl_{22}, dl_2 are, respectively, the path traveled by the 2nd particle after contact and before contact, m.

Then, according to (19), we obtain

$$\left.\begin{aligned} \Delta\vartheta_1 &= -f\left(1+\frac{dl_{11}}{dl_1}\right)\vartheta_{1f}\sin^2\varepsilon_{1k} - \bar{\lambda}\frac{dl_1}{dt}\cos^2\varepsilon_{1k}; \\ \Delta\vartheta_2 &= -f\left(1+\frac{dl_{22}}{dl_2}\right)\vartheta_{2f}\sin^2\varepsilon_{2k} - \bar{\lambda}\frac{dl_2}{dt}\cos^2\varepsilon_{2k} \end{aligned}\right\}. \tag{27}$$

After substituting the corresponding components from (27) into dependence (20), we obtain

$$\begin{aligned} \sum_{i=1}^{2} dE_i = 0,5f^2 dm_1\left[\left(1+\frac{dl_{11}}{dl_1}\right)\vartheta_{1f}\sin^2\varepsilon_{1k} - \bar{\lambda}\frac{dl_1}{dt}\cos^2\varepsilon_{1k}\right]^2 + \\ +0,5f^2 dm_2\left[\left(1+\frac{dl_{22}}{dl_2}\right)\vartheta_{2f}\sin^2\varepsilon_{2k} - \bar{\lambda}\frac{dl_2}{dt}\cos^2\varepsilon_{2k}\right]^2 \end{aligned}. \tag{28}$$

If we assume that $dm_1 = dm_2 = dm = 4\pi abc/3$, $\vartheta_{1f} = \vartheta_{2f} = \bar{\vartheta}_f$, $\varepsilon_{1k} = \varepsilon_{2k} = \varepsilon_k$, then the dependence (24), which functionally describes the change in the elementary total kinetic energy of the contact interaction of particles of the elementary mass of grain material during x-axis movement in the pneumatic pipeline of the pneumatic screw conveyor, will take on the final form

$$\sum_{i=1}^{2} dE_i = \frac{2}{3} f^2 \pi abc \left\{ \begin{array}{l} \left[\left(1 + \dfrac{dl_{11}}{dl_1} \right) \bar{\vartheta}_f \sin^2 \varepsilon_k - \bar{\lambda} \dfrac{dl_1}{dt} \cos^2 \varepsilon_k \right]^2 + \\ + \left[\left(1 + \dfrac{dl_{22}}{dl_2} \right) \bar{\vartheta}_f \sin^2 \varepsilon_k - \bar{\lambda} \dfrac{dl_2}{dt} \cos^2 \varepsilon_k \right]^2 \end{array} \right\}. \tag{29}$$

The obtained analytical dependence (29) is a mathematical model that describes the formalized process of contact interaction of particles of grain material of elementary mass during their movement in the pneumatic pipeline of the pneumatic screw conveyor and can be used to substantiate the rational parameters of its working bodies.

As a result of the analysis of the graphic models, which are built according to the dependence (25) and are shown in Fig. 4, 5, it was established that:

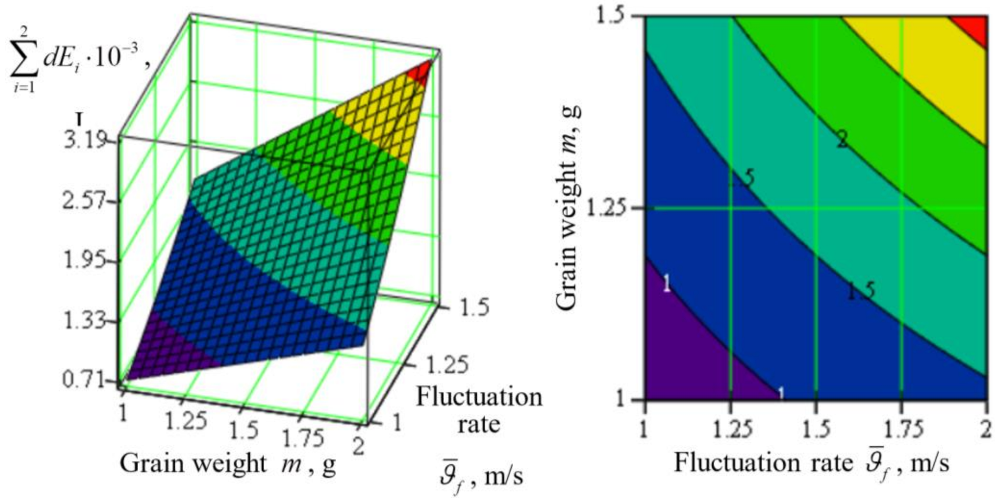

Figure 4. Dependence of the change in the elementary total kinetic energy of the contact interaction of particles of grain material of elementary mass as a function $\sum_{i=1}^{2} dE_i = (m, \bar{\vartheta}_f)$

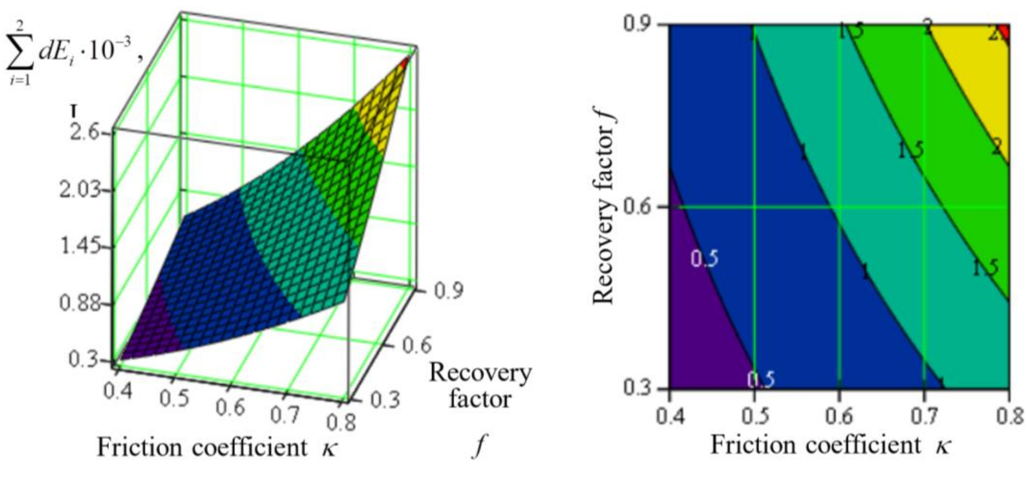

Figure 5. Dependence of the change in the elementary total kinetic energy of the contact interaction

Of particles of grain material of elementary mass as a function $\sum_{i=1}^{2} dE_i = (f, \kappa)$

- the elementary total kinetic energy $\sum_{i=1}^{2} dE_i$ of the contact interaction of particles of grain material of elementary mass increases: within the range from 0.71 10^{-3} to 3.19 10^{-3} J depending on the increase in the elementary mass dm of the grain from 1 to 2 g and the increase in the fluctuation speed $\bar{\vartheta}_f$ from 1.0 to 1.5 m/s;

- the elementary total kinetic energy $\sum_{i=1}^{2} dE_i$ of the contact interaction of particles of grain material of elementary mass increases within the range from 0.3 10^{-3} to 2.6 10^{-3} J depending on the increase in the friction coefficient f of the grain from 0.4 to 0.8 and the increase in the recovery coefficient κ from 0.3 to 0.9.

4. CONCLUSIONS

1. Based on the study of the process of transporting grain material by a pneumatic screw conveyor, mathematical models have been developed that characterize the process of moving elementary mass particles by compressed air and the process of contact interaction of particles during their movement in the pneumatic pipeline.
2. Analytical dependencies have been obtained that describe the change in the total kinetic energy consumption during their movement in the pneumatic pipeline of the pneumatic screw conveyor depending on the process parameters.
3. It has been established that the elementary total kinetic energy of contact interaction of elementary mass grain material particles increases: within the range from 0.71 10-3 to 3.19 10-3 J depending on the increase in the elementary mass of the grain from 1 to 2 g and the increase in the fluctuation speed from 1.0 to 1.5 m/s.
4. The results of the study are prerequisites for further improvement of the methodology and techniques for optimizing rational technological and structural-kinematic parameters of the working elements of pneumatic screw transport mechanisms

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УДК 631.361.8

ПРОЦЕС ПЕРЕМІЩЕННЯ ЗЕРНОВОГО МАТЕРІАЛУ У ПНЕВМОПРОВОДІ ПНЕВМОШНЕКОВОГО ТРАНСПОРТЕРА

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Резюме. *Пневматичні конвеєри застосовують для переміщення різнопланових вантажів різних галузей промисловості. Для забезпечення виконання таких робіт у великих спеціалізованих агрофірмах, які вирощують зернові культури, застосовують потужні пневматичні конвеєри, а застосування таких механізмів є рентабельним за умови вирощування зернових культур на значних площах або, відповідно, значного валового виробництва зерна. В умовах функціонування багатогалузевих фермерських господарств, які збирають зернові культури на незначних площах, актуальним завданням є питання окупності таких транспортних механізмів у зв'язку з їх незначною сезонною завантаженістю виконаних робіт. Вирішення цього важливого завдання можливе шляхом розроблення та застосування малогабаритних і мобільних пневмошнекових транспортерів, які призначені для переміщення зернових матеріалів або виконання транспортних робіт на токах багатогалузевих фермерських господарств. Метою роботи є підвищення функціональних показників роботи шнекових транспортних механізмів за рахунок конструктивного удосконалення та обгрунтування раціональних параметрів пневмошнекового транспортера. Наведено опис удосконаленого пневмошнекового транспортера (конструкцію та принцип роботи) й викладено результати теоретичного аналізу контактної взаємодії елементарних частинок зернового матеріалу під час їх переміщення у повітряному потоці пневмопровода пневмошнекового транспортера на основі дослідження сумарної елементарної кінетичної енергії. За результатами аналізу побудованих графічних моделей встановлено, що елементарна сумарна кінетична енергія контактної взаємодії частинок зернового матеріалу елементарної маси збільшується в межах від 0,71 10^{-3} до 3,19 10^{-3} Дж залежно від збільшення елементарної маси зернини від 1 до 2 г та збільшення швидкості флуктуації від 1,0 до 1,5 м/с.*

Ключові слова: *шнековий живильнил, пневмопровід, зерновий потік, елементарна маса, контактна взаємодія, модель, кінетична енергія, швидкість, вектор, коефіцієнт відновлення, швидкість флуктаації.*

https://doi.org/10.33108/visnyk_tntu2025.02.079 *Отримано 10.03.2025*