

THE INFLUENCE OF BULK MATERIAL FLOW ON TECHNICAL AND ECONOMICAL PERFORMANCE OF A SCREW CONVEYOR

ВПЛИВ ПОТОКУ СИПКОГО МАТЕРІАЛУ НА ТЕХНІКО-ЕКОНОМІЧНІ ПОКАЗНИКИ РОБОТИ ГВИНТОВОГО КОНВЕЄРА

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Keywords: flow movement, bulk material, impact of material particles, rational parameters, changes in energy consumption

ABSTRACT

The paper covers theoretical investigations of the movement of bulk material flow when it is fed by a pneumatic screw conveyor. Process calculation of the impact of bulk material particles during their transportation in guiding covers has been conducted. A mathematical model, which characterizes the overall energy spent on the impact of two particles, depending on impact velocity, physical and mechanical properties of bodies and impact conditions, has been developed. The limits of design and kinematic parameters that provide the effective application of pneumatic screw conveyors for transporting bulk materials have been defined.

РЕЗЮМЕ

В статті наведено теоретичні дослідження руху потоку сипких матеріалів при їх подачі пневмо-шнековими транспортерами. Проведено розрахунок процесу співудару частинок сипкого матеріалу під час його транспортування в направляючих кожухах. Побудовано математичну модель, яка характеризує загальну енергію, втрачену під час співудару двох частинок, залежно від швидкостей співудару, фізичко-механічних властивостей тіл та умов середовища удару. Встановлено межі конструктивно-кінематичних параметрів, які забезпечують ефективне застосування пневмо-шнекових транспортерів для переміщення сипких матеріалів

INTRODUCTION

There is a number of scientific works, which deal with the problems of material transportation in airflow (Ackerman N.I. and Shen H.H., 1982; Haydl H.M., 1986; Hewko B.M. et al., 2015; Hevko R. Et al., 2018; Hevko R.B. et al., 2017; Hevko R.B. et al., 2018; Li Y. and Li Y.Z. , 2008; Loveikin V. and Rogatynska L., 2011; Owen Philip J. and Cleary Paul W., 2010; Tian Y. Et. Al., 2018; Lyashuk O.L. et al., 2015; Lyashuk O.L. et al., 2018; Rogatynska O. et al., 2015; Rohatynskiy R.M. et al, 2016; Lech M., 2001; Roberts Alan W. and Bulk Solids, 2015; Yao Y.P. et al., 2014; Yoshihama S. et al., 2016). These works are aimed at solving the problems that are connected with the improvement of technical production performance of screw conveyors. The improvement of the process of bulk material transportation can be achieved by means of using the combination or the integration of their pneumatic and mechanical movement, taking into consideration material flow properties, which is covered in the papers (Humatylin R.I., 1987; Hychin B.M., 2000; Manjula E.V.P.J. and Hiromi W.K., 2017; Naveen Tripathi, 2015). In the process of conducting theoretical investigations, basic developments that are presented in the papers (Baranovsky V.M. et al., 2018; Hychin B.M., 2000; Loveikin V. and Rogatynska L., 2011; Rogatynska O. et al., 2015) were used. However, these problematic issues are not solved to the full extent. That is why, this paper is the continuation of our investigations, which are partially presented in the papers (Baranovsky V.M. et al., 2018; Hevko R.B. et al., 2018).

MATERIALS AND METHODS

In order to provide bulk material transportation in airflow in case it is fed by a screw feeder, pneumatic screw conveyors have been developed and their detailed design description is presented in the papers (Baranovsky V.M. et al., 2018; Hevko R.B. et al., 2018).

The movement of single particles or their separate groups in a pneumatic pipeline takes place under the action of the forces of a carrying air flow in the form of an air-fuel mixture. A distinction is made between two main kinds of pneumatic transport: general pneumatic transport (material parts are conveyed by an air flow along a pneumatic pipeline by means of "jumps") and pneumatic transport with a continuous flow.

Let us consider the investigation of the process of bulk material transportation in case of its transportation in the form of a continuous flow.

The energy spent during the process of transportation in case of a pneumatic way of bulk material conveyance generally depends on the motion modes of the flow of bulk material parts. Motion modes of a particle flow are connected with physical and mechanical properties of the transported bulk materials, the design of a pneumatic transport unit, the geometry of a pipeline and its routing, the operation pressure and the travelling speed of a carrying flow motion, the consistency of bulk material feeding to a pipeline etc.

The main factors of physical and mechanical properties, which influence the motion modes of the flow of bulk material particles, are the following: density, particle size, coefficients of internal and external friction etc. The speed of flow motion is the dominant factor of the energy spent in the process of transportation. Energy spending during such a process is the minimum at wave and batch material movement in an aerated condition that is achieved due to the creation of an airflow, which is fed to a pipeline through inlet nozzles. It is typical of the process that is presented in Fig.1.

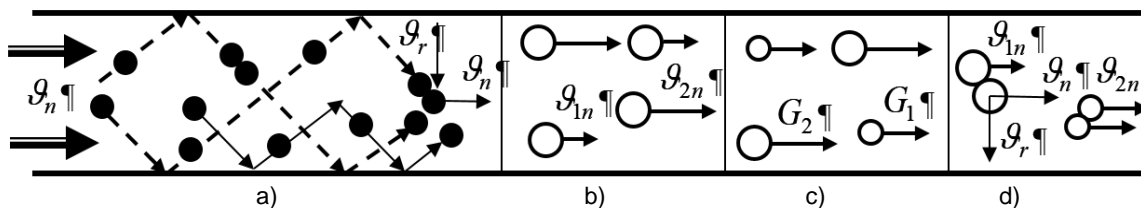


Fig. 1 - Motion patterns of the particles, which move in a pipeline
a – particle movement types; b, c, d – cases of the impact of particles

The main envelopes of the available motion modes of bulk material particle motion for the horizontal segments of a pipeline are presented in the form of the operation field of the three ways of conveying bulk materials in a pneumatic transport: continuous mass displacement, pneumatic conveyance while in flight of separate particles or groups of material particles in suspension, intermediate motion modes.

Formal characterization of the transportation process lies in the following – let us assume that, while in flight along a pipeline, particles of bulk material move only alongside forward and their form and mass remain.

In this case, there are three main characteristic movement types of particles or particle groups in the horizontal direction in the air flow of a pipeline relative to the contact with its internal surface (Fig. 1 a): along a lower wall, having impacts with a lower wall, having impacts with both walls.

The analysis of the motion modes of the flows of bulk material particles shows that they are followed by the relative motion of particles that have a very complex nature. On one side, due to various velocities of the translational motion of particles in a pipeline, they have relative displacement velocity and, on the other side, due to relative contacts (impacts) of particles, they acquire additional components of the travelling velocity of their random motion.

Material particles, which fly in a transport medium, collide only if their travelling velocities are different in value $v_{1n} \neq v_{2n}$ (Fig. 1 b) or in direction. The difference between the velocities of particles is particularly important, if particles differ significantly in their weight $G_1 \neq G_2$ (Fig. 1 c) or in air flow resistance force. However, particles of equal size can collide as well, if there are radial (normal) and tangential speeds (Fig. 1 a, d), besides axial (instantaneous) speeds that are equal for all the material parts.

Let us consider the impact process of the two spherical particles of bulk material, which move in the air flow of a pipeline following the pattern of contacting with the external surface of a pipeline (Fig. 1 a), here, let us consider the material of particles to be elastic.

The analytic model of the impact process of two spherical parts 1, 2 of bulk material is presented in Fig. 1, here, the impact process is considered in case of the movement of the two spherical particles after their contact with the pipeline wall 3.

According to the theory of granulated medium motion, it is known that at flow displacement, the velocity of particles is the sum of three related velocity components: the velocity of fluctuation, travelling

(average) and rotational velocities, and, in case of solving the problems of displaced material flows, a kinetic theory of continuous gases is applied.

The analysis of the known state equation of bulk material during its movement $p(y)\bar{\varepsilon}(y) = \chi \left(\frac{d\vartheta}{dy} \right)^2$

shows that, on the right side, the product of the squared velocity of bulk material movement $d\vartheta/dy$ by the coefficient of the physical constant χ is identical to the specific value of the work, which is required for moving the layer of particles, calculated for 1 m^2 , and, on the left side, the product of the hydrostatic pressure analog $p(y)$ by the dilatancy (porosity) of grain medium $\bar{\varepsilon}(y)$ in the physical meaning is identical to the kinetic energy of relative random particle motion due to the complex movement of bulk grain medium.

The interaction of two particles 1 and 2 takes place mostly due to the exchange of impact pulses on an oblique impact, here, the vectors \bar{g}_1 and \bar{g}_2 , which characterize impact velocities, are directed at the angle α_c to the horizon.

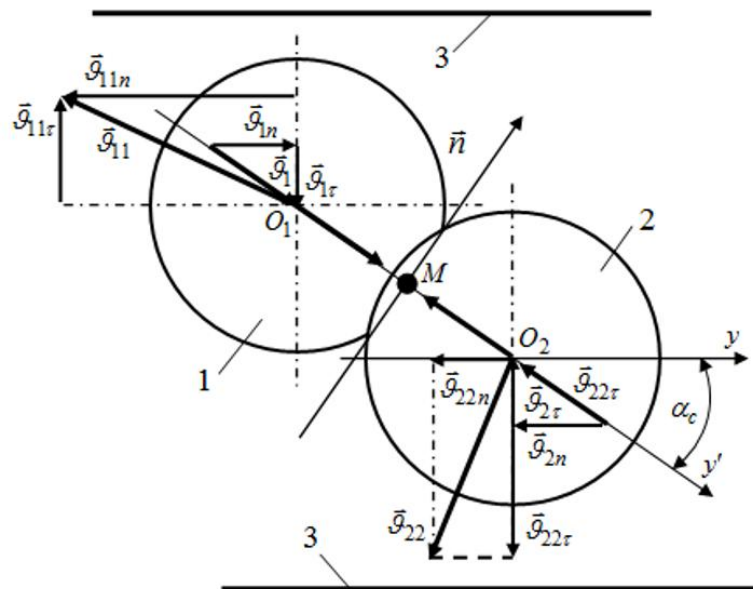


Fig. 2 - Calculation scheme of the impact process of bulk material particles

According to the law of energy conservation, the total sum energy E (J), which is spent during the impact of two particles 1 and 2 of a bulk material is the following:

$$E = \frac{1}{2} m_{1c} g_1^2 + \frac{1}{2} m_{2c} g_2^2 - \frac{1}{2} m_{1c} g_{11}^2 - \frac{1}{2} m_{2c} g_{22}^2 \tag{1}$$

where m_{1c} , m_{2c} – the reduced mass of the particles 1 and 2, kg, respectively; g_1 , g_2 – the movement velocity of the particles 1 and 2 before the impact, m/s, respectively; g_{11} , g_{22} – the movement velocity of the particles 1 and 2 after the impact, m/s, respectively.

After the reduction of (1), we obtain:

$$E = \frac{1}{2} m_{1c} (g_1^2 - g_{11}^2) + \frac{1}{2} m_{2c} (g_2^2 - g_{22}^2) \tag{2}$$

Having denoted the difference in velocities $(g_1^2 - g_{11}^2)$ and $(g_2^2 - g_{22}^2)$ by Δg_1 and Δg_2 , respectively, and having taken into consideration that $m_{ic} = V_{ic} \rho = \rho \pi d_{ic}^3 / 6$, where $V_{ic} = \pi d_{ic}^3 / 6$ – the volume of the particle i (m^3), d_{ic} – the diameter of the particle i (m), we can write down the following:

$$E = \frac{1}{12} \pi d_{1c}^3 \rho (\Delta g_1)^2 + \frac{1}{12} \pi d_{2c}^3 \rho (\Delta g_2)^2 = \frac{1}{12} \pi \rho [d_{1c}^3 (\Delta g_1)^2 + d_{2c}^3 (\Delta g_2)^2] \tag{3}$$

Let us determine the components of the difference in before-impact and after-impact velocities Δg_1 and Δg_2 from the following considerations.

Random particle movement results in the transverse mass transfer (of particles), which is followed by the transfer of the impulse, the carriers of which are the particles that move with various velocities depending on the coordinates, which results in the intensity of the relative movement of bulk material particles.

According to Gauss hypothesis, it is known that the connection between the values of contacting and normal impulses on impact is formed similar to Coulomb's law for friction

$$\Delta g = -f(1+k)g' \tag{4}$$

where Δg – the change of relative tangential velocity, as a result of an impact, m/s; g' – the velocity of particle fluctuation, m/s; k – the coefficient of recovery on impact.

The velocity of fluctuation g' characterizes the coefficient of transverse quasi-diffusion $D_{kd} = 0.5 g's$, where s – the average distance between the particles relative to their reduced mass (m), which, in its turn, regulates the intensity of the relative motion of bulk material particles. Here, the intensity of particle motion increases proportionally to D_{kd} and to the velocity gradient dg'/dy of relative particle motion in the direction of their displacement velocity.

However, the dependence (4) does not take into account the physical properties of the surfaces of the particles, which collide at the contact point M .

In addition, it is known that the closest relationship between the values of contacting and normal impulses on impact is described by "λ-hypothesis", according to which, the change in the relative tangential velocity Δg as a result of the impact of colliding points is proportional to the before-impact value of this velocity g

$$\Delta g = -\bar{\lambda} g \tag{5}$$

where $\bar{\lambda}$ – the average value of the coefficient that characterizes the properties of the surfaces of the particles, which collide; g – the before-impact velocity of a particle, m/s.

Having taken into account the peculiarities of the problem of the impact of two spherical bodies, let us apply these two hypotheses (4), (5) by means of their combination or considering them when determining the change in the relative tangential velocity Δg , which is the result of the collision of two bodies.

Having taken into account the scheme of the impact process (Fig. 2) and the fact that

$k = g_{ii} / g_i = \frac{dS_{ii}}{dt} / \frac{dS_i}{dt} = \frac{dS_{ii}}{dS_i}$, where g_{ii} , g_i – the velocity of the i particle before and after the impact,

respectively, m/s; dS_{ii} , dS_i – the distance covered by the i particle before and after the impact, respectively, (m); t – particle movement time, (s), let us combine these two borderline cases (4), (5) by a continuous function in the form of:

$$\left. \begin{aligned} \Delta g_1 &= -f \left(1 + \frac{dS_{11}}{dS_1} \right) g'_1 \sin^2 \alpha_1 - \bar{\lambda} \frac{dS_1}{dt} \cos^2 \alpha_1; \\ \Delta g_2 &= -f \left(1 + \frac{dS_{22}}{dS_2} \right) g'_2 \sin^2 \alpha_2 - \bar{\lambda} \frac{dS_2}{dt} \cos^2 \alpha_2 \end{aligned} \right\} \tag{6}$$

where α_1 , α_2 – the angle between the velocity vector of the impact of the particles 1 and 2 and the impact line y' , respectively (deg.).

Having substituted the values of the corresponding velocity components from (6) into the dependence (3), we obtain:

$$E = \frac{1}{2} \pi \rho f^2 \left\{ \begin{aligned} & d_{1c}^3 \left[\left(1 + \frac{dS_{11}}{dS_1} \right) g'_1 \sin^2 \alpha_1 - \bar{\lambda} \frac{dS_1}{dt} \cos^2 \alpha_1 \right]^2 + \\ & d_{2c}^3 \left[\left(1 + \frac{dS_{22}}{dS_2} \right) g'_2 \sin^2 \alpha_2 - \bar{\lambda} \frac{dS_2}{dt} \cos^2 \alpha_2 \right]^2 \end{aligned} \right\} \tag{7}$$

In order to simplify the solution of the problem, let us assume that the particles 1 and 2 of bulk material are of the same mass, that is to say $m_{1c} = m_{2c} = m_c$, here, the correct identities are the following: $d_{1c} = d_{2c} = d_c$, $\mathcal{G}'_1 = \mathcal{G}'_2 = \overline{\mathcal{G}'}$, $\alpha_1 = \alpha_2 = \alpha$, respectively, where d_{1c} , d_{2c} , d_c – the diameter of the particles 1 and 2 and the average particle diameter, respectively, (m).

Thus, having taken into account this assumption, let us write the dependences (3) and (6) in a simplified form:

$$E = \frac{1}{12} \pi d_c^3 \rho \left[(\Delta \mathcal{G}'_1)^2 + (\Delta \mathcal{G}'_2)^2 \right] \tag{8}$$

$$\left. \begin{aligned} \Delta \mathcal{G}'_1 &= -f \left(1 + \frac{dS_{11}}{dS_1} \right) \overline{\mathcal{G}'} \sin^2 \alpha_c - \bar{\lambda} \frac{dS_1}{dt} \cos^2 \alpha_c; \\ \Delta \mathcal{G}'_2 &= -f \left(1 + \frac{dS_{22}}{dS_2} \right) \overline{\mathcal{G}'} \sin^2 \alpha_c - \bar{\lambda} \frac{dS_2}{dt} \cos^2 \alpha_c \end{aligned} \right\} \tag{9}$$

where $\overline{\mathcal{G}'}$ – the average value of the velocity of particle fluctuation, m/s.

Having substituted the values of the corresponding velocity components from (9) into the dependence (8) and after the transformation and the simplification of the expression, we obtain:

$$E = \frac{1}{2} \pi d_c^3 \rho \left\{ \begin{aligned} & f^2 (\mathcal{G}')^2 \cos^4 \alpha_c \left[\left(1 + \frac{dS_{11}}{dS_1} \right)^2 + \left(1 + \frac{dS_{22}}{dS_2} \right)^2 \right] - \\ & - 2f \bar{\lambda} \mathcal{G}' \sin^2 \alpha_c \cos^2 \alpha_c \left[\left(1 + \frac{dS_{11}}{dS_1} \right) \frac{dS_1}{dt} + \left(1 + \frac{dS_{22}}{dS_2} \right) \frac{dS_2}{dt} \right] + \\ & + \bar{\lambda}^2 \cos^4 \alpha_c \left[\left(\frac{dS_1}{dt} \right)^2 + \left(\frac{dS_2}{dt} \right)^2 \right] \end{aligned} \right\} \tag{10}$$

The dependence (10) is a mathematical model, which characterizes the general energy that is spent during one impact of two spherical particles of bulk grain material, depending on the velocity components of the impact process, physical and mechanical properties of colliding bodies and the conditions of impact medium. This model can be used in order to analyse the accepted expression of the “temperature of grain medium” and, further, bulk material state during particle movement in a pipeline.

If the assumption is made that the coefficients of the recovery of the particles 1 and 2 on their impact are maximally adequate or even equal in their value, then the dependence (10) can be written in the following form:

$$E = \pi d_c^3 \rho \left\{ \begin{aligned} & f^2 (\mathcal{G}')^2 (1+k)^2 \cos^4 \alpha_c - \\ & - (1+k) f \bar{\lambda} \mathcal{G}' \sin^2 \alpha_c \cos^2 \alpha_c \left(\frac{dS_1}{dt} + \frac{dS_2}{dt} \right) + \\ & + 0,5 \bar{\lambda}^2 \cos^4 \alpha_c \left[\left(\frac{dS_1}{dt} \right)^2 + \left(\frac{dS_2}{dt} \right)^2 \right] \end{aligned} \right\}. \tag{11}$$

RESULTS

Fig. 3 presents the characteristic curve of the change in the general energy E spent during one impact of two spherical particles of bulk material depending on: a – the coefficient of recovery k and the coefficient of the internal friction f ; b – the diameter of the particles d_c and the angle between the vector of impact velocity and the line of collision α_c ; c – the diameter of particles d_c and the bulk weight of material ρ .

The analysis of the graphical plotting shows that if the coefficient of recovery k increases within the limits of $0 \leq k \leq 1$ and the coefficient of internal friction f increases within the limits of $0 \leq f \leq 1$, the general energy E spent on the impact of two spherical particles of bulk material increases on average from 0.1 to 0.3 J (Fig. 3, a), here, the dominant factor of the change in E is the coefficient of recovery k .

The increase of the energy E (Fig. 3, b, c) spent on the impact of two particles with the diameter of $d \leq 0.002$ (s) is not significant and its average value is 0.01 J, if there is a change in the angle between the vector of impact velocity and the line of collision α_c within the limits of $0 \leq \alpha_c \leq 0.5$ (rad) and the change in bulk weight within the limits of $900 \leq \rho \leq 1500$ (kg/m³), and with further increase of α_c the increase in energy spending E is practically near zero (Fig. 3, b). Significant energy E spending takes place during the transportation of particles with the diameter of more than 2 mm, here, there is a sharp increase of E from 0.02 to 0.14 J for $\rho = 1300$ kg/m³ (Fig. 3, b) or from 0.05 to 0.3 J (Fig. 3 c).

In order to provide a contact (impact) of the particles 1 and 2, the angle α_c (Fig. 2) must be within the limits of the interval $(0, \pi/2)$.

Having taken into account that particle movement in a flow of a pipeline has a complex nature, let us write the kinetic energy of relative bulk medium movement in the form of the sum of particle kinetic energies in their relative translational motion during their displacement and during their random motion in the process of transverse mass transfer, that is to say:

$$E_c = E_g + E_{g'} + E_n \quad (12)$$

where:

E_c – the kinetic energy of particle relative motion;

(J); E_g , $E_{g'}$, E_n – the kinetic energy of translational motion, random motion (fluctuation) and transverse mass transfer of bulk medium particles, respectively, (J).

Correspondingly, the kinetic energy of the particles in their relative translational motion in the direction of their displacement E_g , in their random motion (fluctuation) $E_{g'}$ and in the process of transverse mass transfer E_n of the particles of a bulk medium, is determined from the following expressions

$$\left. \begin{aligned} E_g &= \frac{1}{12} \pi d_c^3 \rho (\Delta y)^2 \left(\frac{d\mathcal{G}}{dy} \right)^2; \\ E_{g'} &= \frac{1}{2} \frac{\pi d_c^3}{6} \rho (\mathcal{G}')^2 = \frac{2\pi d_c^3}{3} \rho v_c^2 s^2; \\ E_n &= \frac{1}{4} \frac{\pi d_c^3}{6} \rho s \mathcal{G}' \frac{d\mathcal{G}}{dy} = \frac{1}{12} \pi d_c^3 \rho v_c s^2 \frac{d\mathcal{G}}{dy} \end{aligned} \right\} \quad (13)$$

where:

Δy – the difference in the coordinates of the particles' centres of the adjacent layers of a bulk medium, (m);

v_c – the average frequency of the impact of bulk medium particles, (1/s).

Here,

$$\Delta y = c_1 - c_2; \quad \mathcal{G}' = 2s v_c \quad (14)$$

where:

c_1 , c_2 – the centre coordinates of the adjacent layers, respectively, and the average frequency of an impact v_c is determined by means of Ackerman-Shen method:

$$v_c = \frac{\tau}{K_d N} \frac{d\mathcal{G}}{dy}, \quad (15)$$

Where:

τ – displacement potential, (Pa); K_d – the dissipation of the kinetic energy of particle impact on one contact, (J); N_c – the number of particles per unit layer volume, (1/m³).

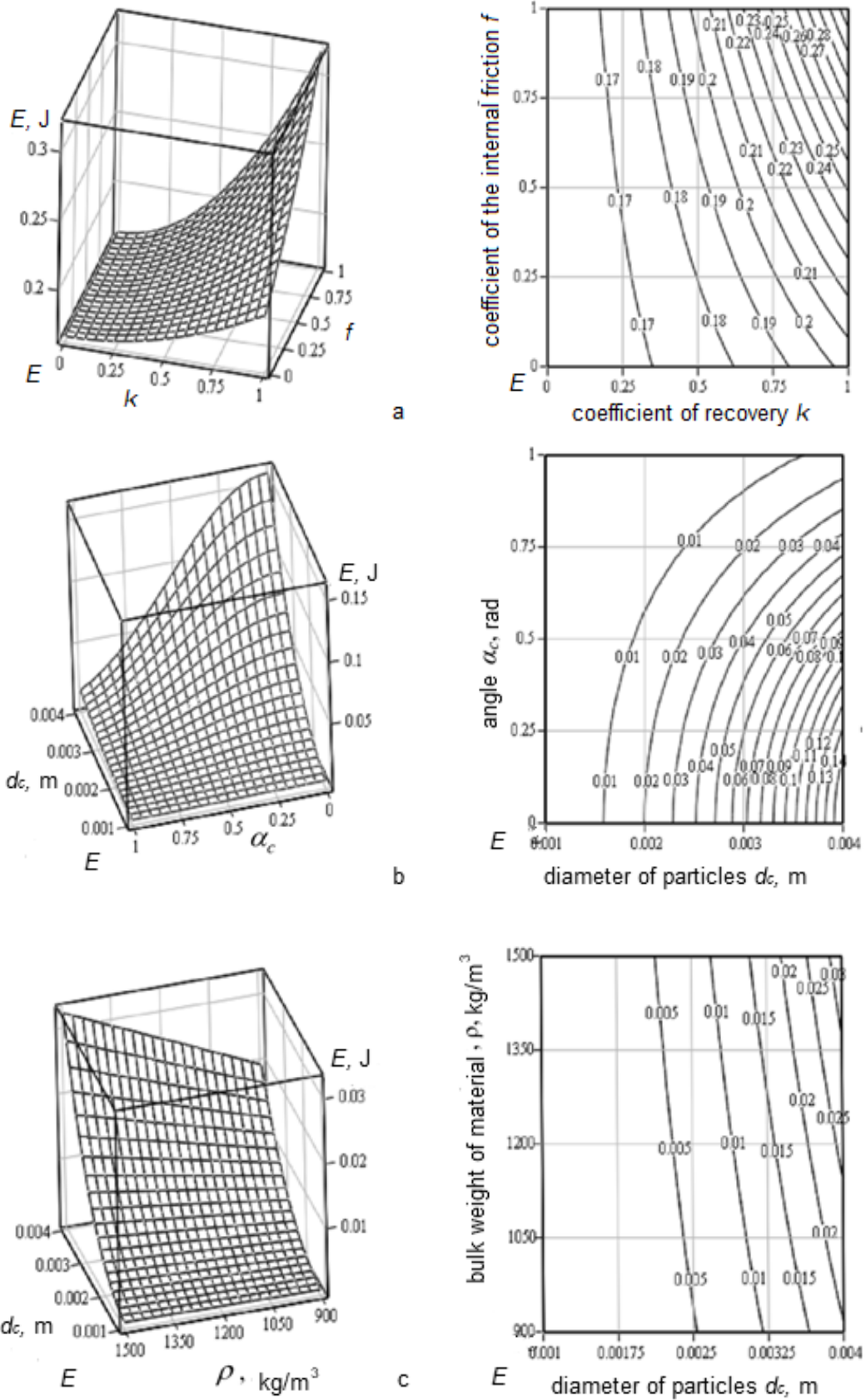


Fig. 3 - Energy change dependence as a function:
 a - $E = f(f, k)$, b - $E = f(d_c, \alpha_c)$, c - $E = f(d_c, \rho)$

The dissipation of the kinetic energy K_d of the impact of particles on one contact is determined from Ackerman-Shen formula:

$$K_d = \frac{1}{12} \pi d_c^3 \rho \left(\frac{1-k^2}{4} + \frac{f(1+k)}{\pi} - \frac{f^2(1+k)^2}{4} \right) (\mathcal{G}')^2 \quad (16)$$

Then, according to (14), (15) and (16), the average frequency of the impact v_c of bulk medium particles is determined as follows:

$$v_c = \frac{24\tau}{d_c^3 \rho \left[\pi(1-k^2) + 4f(1+k) - \pi f^2(1+k)^2 \right] (\mathcal{G}')^2 N} \frac{d\mathcal{G}}{dy} \quad (17)$$

Having substituted the values of Δy from (14) and the values of v_c from (17) into the equation (13), we obtain:

$$\left. \begin{aligned} E_g &= \frac{1}{12} \pi d_c^3 \rho (c_1 - c_2)^2 \left(\frac{d\mathcal{G}}{dy} \right)^2; \\ E_g &= \frac{2\pi s^2}{3d_c^3 \rho} \left(\frac{24\tau}{\left[\pi(1-k^2) + 4f(1+k) - \pi f^2(1+k)^2 \right] (\mathcal{G}')^2 N} \right)^2 \left(\frac{d\mathcal{G}}{dy} \right)^2 \\ E_n &= \frac{2\pi s^2 \tau}{\left[\pi(1-k^2) + 4f(1+k) - \pi f^2(1+k)^2 \right] (\mathcal{G}')^2 N} \left(\frac{d\mathcal{G}}{dy} \right)^2 \end{aligned} \right\} \quad (18)$$

Thus, having substituted (18) into (13) and after the transformation and the simplification of the expression, the kinetic energy E_c of the relative motion of bulk material particles is determined by the following dependence

$$E_c = \frac{\pi}{12} \left[d_c^3 \rho (c_1 - c_2)^2 + s^2 \left(\frac{8\Omega^2}{d_c^3 \rho} + \Omega \right) \right] \left(\frac{d\mathcal{G}}{dy} \right)^2 \quad (19)$$

where $\Omega = \frac{24\tau}{\left[\pi(1-k^2) + 4f(1+k) - \pi f^2(1+k)^2 \right] (\mathcal{G}')^2 N}$.

The equation (19) characterizes the so called “temperature of grain medium” during the relative motion of bulk medium particles.

Having taken into consideration (19), the known equation $p(y)\bar{\varepsilon}(y) = \chi(d\mathcal{G}/dy)^2$ of a bulk material state during its motion can be written in the following form

$$p\bar{\varepsilon} = \chi' \frac{\pi}{12} \left[d_c^3 \rho (c_1 - c_2)^2 + s^2 \left(\frac{8\Omega^2}{d_c^3 \rho} + \Omega \right) \right] \left(\frac{d\mathcal{G}}{dy} \right)^2 \quad (20)$$

where χ' – the coefficient of the physical constant, which is identical to the specific value of work that is required for moving the layer of particles, calculated for 1 m²; $\bar{\varepsilon}$ – the average porosity of a grain medium.

The obtained dependence (20) can be used for further analysis and substantiation of the process flow parameters of pneumatic screw conveyors.

CONCLUSIONS

The article presents the design of a pneumatic screw conveyor, which provides bulk material transportation with less dust concentration due to impulse air feeding.

The calculation of the impact process of bulk material particles during their transportation in a pipeline has been conducted. In addition, a mathematical model, which characterizes the general energy spent on

the impact of two particles, depending on impact velocities, physical and mechanical body properties and impact medium conditions, has been developed.

It has been determined that the increase of the energy E spent on the impact of two particles with the diameter of $d \leq 0.002$ (m) is insignificant and on average it equals 0.01 (J) on the change of the angle between the vector of impact velocity and the collision line α_c within the limits of $0 \leq \alpha_c \leq 0.5$ (rad) and of the bulk weight within the limits of $900 \leq \rho \leq 1500$ (kg/m³), and with further increase of α_c , the energy E spending is practically near zero. Significant energy spending E takes place during the transportation of the particles, the diameter of which is more than 2 mm, here, there is a sharp increase of E from 0.02 to 0,14 (J) for $\rho = 1300$ (kg/m³) or from 0.05 to 0.3 (J).

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