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MODEL OF FLOW TRANSPORTATION OF BULK CARGO BY VERTICAL SCREW CONVEYORS

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Summary. *The article considers the model of transporting bulk cargo by flow by vertical high-speed screw conveyors. The peculiarities of mutual movement of cohesive and fine cargoes, in particular, in the conditions of their layer-by-layer movement, are revealed. To analyze the stress-strain state of bulk cargo in the conditions of screw conveying, a special helical coordinate system was used, which made it possible to significantly simplify the solution of the problem. The dependences for describing the shape of the helical surface that restricts the flow of cargo under the condition of incomplete filling of the working space, the volume of the elementary sector of the flow and its center of gravity are derived. The use of the model of layer-by-layer material motion is substantiated, and the distribution of linear and angular velocities of particles in the flow and, accordingly, centrifugal forces is determined. It is shown that for vertical high-speed conveyors, the motion of the flow as a whole and its individual particles retains the laws of helical transporting, which makes it possible to use the model of a material particle with the given parameters to calculate the design and operating modes of the conveyor.*

Key words: *vertical screw conveyors, loose cargo, continuous medium, helical coordinate system, strain rates, stresses, kinematics of the flow loose cargo.*

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Statement of the problem. The simplicity, high reliability, tightness of construction, environmental friendliness and relatively low cost of screw conveyors contribute to their widespread use in various industries for the transport of bulk cargo. Recently, high-speed screw conveyors have become widespread, as their performance is virtually independent of their spatial location and they are widely used in the automation of various transport and technological processes. The disadvantage of such conveyors, compared to other continuous transport machines, is their high energy consumption. A significant reduction in the energy consumption of high-speed screw conveyors can be achieved by optimizing the transport modes, which is possible only if there are adequate models of cargo flow in the working space of screw conveyors. The existing analytical dependencies are mainly based on models of material particles, which does not fully reveal the influence of factors on the performance characteristics of screw conveyors. To build more adequate models, it is necessary to establish the patterns of movement of cargo particles in the flow and their impact on the conveying process as a whole. Since the most severe conveying conditions are observed for vertically placed conveyors, their calculation is a priority in terms of versatility, and the results obtained will satisfy the technical requirements for other options for the location of the conveying route.

Analysis of the available investigations. To study many technological processes of interaction between working bodies and the working environment, the latter is described as a continuous medium and studied by appropriate analytical and numerical methods. In particular, the finite element method is widely used to study continuous media [1]. However, for the study of a system of solid particles (objects), models for continuous media do not allow to assess the dynamics of individual particles and the processes of their interaction with each other. To study such systems, the discrete element method (DEM), described in detail in [2], has become widespread. In particular, the DEM method has been successfully used to model the transport system of screw conveyors [3] and the loading of a bunker with grain material [4]. A comparison of DEM modelling with the results of laboratory experiments of screw conveyors is given in [5]. However, their disadvantage, as well as numerical methods in general, is the inability to obtain analytical dependencies to describe the influence of various factors on process parameters. The relationship of design parameters and operating modes with the operational characteristics of vertical conveyors is described in detail in models of material particle transport with the given parameters [6, 7, 8]. However, such models do not reveal the processes that occur during the complex helical motion of particles in the cargo flow. A number of papers [9, 10] reveal the peculiarities of the cargo flow, where, in particular, the distribution of velocities in the flow is studied, but such studies are partial and not sufficient for practical use.

The Objective of the work. To investigate the regularities of the distribution of particle velocities in the flow during the transport of bulk cargo by screw conveyors and to establish the influence of the uneven distribution of particle velocities on the kinematics and dynamics of the flow as a whole and on the calculation of the operational parameters of high-speed vertical conveyors.

Statement of the task. Let's consider the process of transporting bulk cargo by a high-speed vertical conveyor, for which the force conditions of transportation are the most severe. During transportation, the bulk cargo flows through the working channel formed by adjacent helical turns of the working body, the rotation of which causes axial movement of the cargo due to interaction with the surface of the casing.

An important factor that affects the speed of screw conveyors is the rheology of the cargo. When transporting cohesive cargoes, the movement of particles in the flow is limited by the imposed inter-element bonds, and a material particle model with the following parameters is quite suitable for calculating conveyors, since the axial angular velocity of rotation ω_A particles in a helical motion will be constant across the flow section. Their axial velocity v_z related to angular velocity ω_A by the dependence [11]:

$$v_z = c \cdot (\omega - \omega_A), \qquad (1)$$

where ω – is the angular velocity of the screw working tool; c – screw T pitch setting, $c = T/(2\pi)$.

With a known angular velocity of the screw, the angular velocity of the helical motion of the flow particles will be [11]:

$$\omega_A = \frac{\omega}{1 + tg\beta / tg\alpha}, \qquad (2)$$

where β – is the angle of rise of the helical trajectory of the particle relative to the plane of the normal cross-section of the conveyor; α – running angle of rise of the helical screw surface, which is related to the radial parameter of the screw ρ by the dependence $\mathrm{tg}\,\alpha = c/\rho$. For vertical and steeply inclined conveyors, a rapidly converging recurrence relation is given in [1], where the second iteration gives an almost exact match with the result calculated by numerical methods (error not exceeding 0.5%):

$$\operatorname{tg}\beta_i = \operatorname{tg}\alpha\left\{\frac{A_{i-1}}{2}\left[\sqrt{1+\frac{4\cos\varphi_1}{A_{i-1}\sin\alpha\sin(\alpha+\varphi_1)}}-1\right]-1\right\}, \qquad (3)$$

where $A_{i-1} = \dfrac{\mu_2\omega^2 Rtg\alpha\cos\beta_{i-1}}{g\sin\gamma}$ – parameter of the iteration process; φ_1 – angle of external friction of the load to the surface of the screw belt $\varphi_1 = \operatorname{arctg}\mu_1$; μ_1 та μ_2 – are, respectively, the coefficients of external friction of the load against the surfaces of the screw (screw belt) coil and the casing; γ – conveyor inclination angle, for vertical conveyors $\gamma = \pi/2$.

For the initial value β_0 in (3), depending on the conveyor speed, take an arbitrary value from the range $0 \le \beta_0 \le \pi/2 - \alpha - \varphi_1$, where the lower value corresponds to the case of feed interruption in the axial direction ($v_z = 0$), and the upper one for high-speed mode ($\omega \to \infty$).

Taking into account that the relation between the angular velocity of a particle ω_A and angular velocity ω of the screw impeller calculated by (2) and (3) is practically straightforward, in [12] approximation dependencies for determining v_z and ω_A. This is the axial velocity of the particle:

$$v_z = \frac{c(\omega - \omega_k)}{1 + \operatorname{tg}(\alpha + \varphi_1)\operatorname{tg}\alpha}, \qquad (4)$$

where ω_k – is the critical angular velocity of a vertical conveyor at which axial transport stops, $\omega_k = \sqrt{\dfrac{g}{\mu_2 R}\operatorname{tg}(\alpha+\varphi_1)} = \omega\sqrt{\dfrac{\operatorname{tg}(\alpha+\varphi_1)}{\mu_2 P}}$. Here R – is the radius of the top edge of the screw band; P – conveyor speed ratio.

The angular velocity of the helical motion of the particle, according to (1), will be:

$$\omega_A == \frac{\omega_k + \omega\cdot\operatorname{tg}(\alpha+\varphi_1)\operatorname{tg}\alpha}{1 + \operatorname{tg}(\alpha+\varphi_1)\operatorname{tg}\alpha}. \qquad (5)$$

When moving to a bulk cargo flow model, it is necessary to take into account that, in general, particles move with different angular ω_i and linear v_i speed and angle of ascent α_i, depending on their radial parameter ρ_i and distance from the spiral surface b_i.

Results and discussion. Let's consider a vertical high-speed screw conveyor, for which we assume a model of layer-by-layer movement of cargo with a constant radial parameter ρ layers. In this case, an arbitrary particle or selected flow element will move along a helical trajectory that is equidistant from the helical surface of the working body. In this case, it is advisable to use a helical coordinate system $Ontb$, whose axes are the hodographs of the vectors of the accompanying triangle of the helical line (the working surface) of the working body. The axis On of the helical coordinate system is directed normal to the helical line, Ob – along the binormal, and Ot – tangentially. System communication $Ontb$ with a cylindrical $O\rho\varphi z$ and Cartesian $Oxyz$ coordinate systems has the form, [13]:

$$n = \rho = \sqrt{(x^2 + y^2)}\ ;\ t = \theta\sqrt{\rho^2 + c^2}\ ; \quad b = (z - c\theta) \cdot \rho / \sqrt{\rho^2 + c^2}\ , \tag{6}$$

where n – radial parameter of a particle, $n = \rho$; θ – its angular parameter, θ ; b – is the height of the particle above the surface of the spiral. Here, the angular parameter θ of the system $Ontb$, which determines the location of the selected element (particle), is related to the angular parameter φ of the system $O\rho\varphi z$ by dependence:

$$\theta = \varphi\rho k + z\chi\ , \tag{7}$$

where k and χ – are the curvature and torsion of the helical line, respectively, $k = \rho/(\rho^2 + c^2)$; $\chi = c/(\rho^2 + c^2)$; φ – is the angular parameter of a particle in the cylindrical coordinate system, $\varphi = \arccos(x / \sqrt{x^2 + y^2})$, for $0 \le \varphi \le \pi$ and $\varphi = 2\pi - \arccos(x / \sqrt{x^2 + y^2})$ for $\pi < \varphi \le 2\pi$.

To establish the features of the helical flow of bulk cargo, consider a model of a continuous medium. Let's distinguish an elementary volume in the flow, the location of which corresponds to the location of a particle in the flow A . For large deformations of an anisotropic medium, the main axes of the tensor $\{\tau_{ij}\}$ stresses coincide with the main axes of the tensor $\{\dot{\gamma}_{ij}\}$ deformation rates. We assume that for dry bulk cereal non-viscous materials, the mutual movement of particles is determined by the laws of distribution of internal friction according to the Amont-Coulomb law:

$$\bar{\tau}_{ij} = -\mu p \Delta\bar{v} / |\Delta v|\ , \tag{8}$$

where μ – coefficient of internal friction; Δv – relative speed between the elements (layers) under consideration $\Delta v = d\bar{r}_i / d\tau - d\bar{r}_j / d\tau$; τ – time parameter.

For a given elementary volume A of a cargo of density ρ_m the equilibrium equation in the helical coordinate system is given by [13]:

$$\begin{cases} \dfrac{\partial \sigma_n}{\partial n} + \dfrac{\partial \tau_{nt}}{\partial t} + \dfrac{\partial \tau_{nb}}{\partial b} + k(\sigma_n - \sigma_t) + \chi\tau_{tb} + \rho_m(g_n - a_n) = 0; \\ \dfrac{\partial \tau_{nt}}{\partial n} + \dfrac{\partial \sigma_t}{\partial t} + \dfrac{\partial \tau_{tb}}{\partial b} + 2k\tau_{tn} + \chi\tau_{bn} + \rho_m(g_t - a_t) = 0; \\ \dfrac{\partial \tau_{nb}}{\partial n} + \dfrac{\partial \tau_{tb}}{\partial t} + \dfrac{\partial \sigma_b}{\partial b} + k\tau_{bn} - 2\chi\tau_{nt} + \rho_m(g_b - a_b) = 0, \end{cases} \quad , \tag{9}$$

where σ_i and τ_{ij} – normal and tangential stresses; g_n , g_t , and g_b – projections of the earth's gravity acceleration vector on the axes of the system $Ontb$; a_n , a_t , and a_b – projections of the acceleration vector of the selected volume on the axes $Ontb$.

The velocity $\bar{v}_A$ of the selected elementary volume A of the flow will be decomposed into orthogonal coordinate systems as $\bar{v}_A = v_n\bar{n} + v_t\bar{t} + v_b\bar{b}$. Thus, the linear $\dot{\varepsilon}_i$ and angular $\dot{\gamma}_{ij}$ strain rates in the $Ontb$ coordinate system will be:

$$\begin{gathered} \dot{\varepsilon}_n = \partial v_n / \partial n\ ; \quad \dot{\varepsilon}_t = \partial v_t / \partial t + k v_n\ ; \quad \dot{\varepsilon}_b = \partial v_b / \partial b\ ; \\ \dot{\gamma}_{nb} = \partial v_n / \partial b + \partial v_b / \partial n\ ; \quad \dot{\gamma}_{nt} = \partial v_n / \partial t + \partial v_t / \partial n - k v_t\ ; \quad \dot{\gamma}_{tb} = \partial v_b / \partial t + \partial v_t / \partial b = 0\ . \end{gathered} \tag{10}$$

During the transport of goods by vertical screw conveyors, there is a steady (stationary) flow, the parameters of which do not change in time τ, and the radial v_ρ and binormal v_b components of the velocity v_A of the elementary volume A, compared with its tangential component v_t, are insignificant or absent. So, let's assume $v_\rho = v_b = 0$, which is typical for layer-by-layer movement, where the velocity of the allocated volume has a component only along the orthogon t, $v_A = v_t = const$. Accordingly, the strain rates in the flow with layer-by-layer movement of the load will be, [13]:

$$\dot{\varepsilon}_n = \dot{\varepsilon}_t = \dot{\varepsilon}_b = \dot{\gamma}_{nb} = 0,\ \dot{\gamma}_{nt} = \partial v_t/\partial n - k v_t,\ \dot{\gamma}_{tb} = \partial v_t/\partial b, \tag{11}$$

or finely dispersed cargoes, in the conditions of a helical high-speed dynamic flow, it can be assumed that normal σ_n, σ_t, and σ_b the stresses on the surfaces of the allocated volume are determined only by the average static pressure p, from where $\sigma_n = \sigma_t = \sigma_b = p$, $\partial\sigma_n/\partial t = \partial\sigma_b/\partial t = \partial\sigma_t/\partial t = \partial p/\partial t = 0$ та $\partial\sigma_n/\partial n = \partial p/\partial n$; $\partial\sigma_b/\partial b = \partial p/\partial b$. Then the system (6) will take the form:

$$\begin{cases} \partial p/\partial n + \chi\tau_{tb} = \rho_m n\omega_A^2; \\ \partial\tau_{nt}/\partial n + \partial\tau_{tb}/\partial b + 2k\tau_{nt} - \rho_m g \sin\alpha = 0; \\ \partial p/\partial b - 2\chi\tau_{nt} - \rho_m g \cos\alpha = 0. \end{cases} \tag{12}$$

For cohesive materials, the displacement between adjacent particles is insignificant, and therefore the angular velocity of the steady-state rotational motion of all particles in the flow relative to the conveyor axis can be considered constant, $\omega_A = const$. System components that contain a torsional value χ are much smaller than the other components, and therefore, from the first and third equations of system (8) we obtain an approximate dependence

$$\frac{db}{\partial n} = \frac{n\omega_A^2}{g\cos\alpha}[1 + f(\chi)], \tag{13}$$

where $f(\chi)$ – is a function that takes into account the effect of torsion χ of the helical trajectory $f(\chi) << 1$.

Accordingly, the surface of the zero flow level, which limits the volume of the zero-pressure cargo, can be described in helical coordinates by an approximate relationship.

$$b(n) = \frac{\varsigma n^2\omega_A^2}{2g\cos\alpha} + C_b, \tag{14}$$

where ς – the parameter that takes into account the influence of cargo cohesion is preliminarily accepted $\varsigma = 1$.

At $n = 0$ the angle of rise of the spiral is equal $\alpha = \pi/2$, and therefore dependence (10) will make sense only at $b(0) = 0$. So $C_b = 0$. In the cylindrical coordinate system, the equation of the zero-level surface (10) will take the form

$$h_z(n) = h(\rho) = z - c\theta = \frac{\varsigma\rho^2\omega_A^2}{2g\cos^2\alpha} = \varsigma P_A(\rho^2 + c^2)/R. \quad (15)$$

where P_A – the coefficient of speed of the cargo flow, $P_A = R\omega_A^2/g$.

Let's select the flow sector with an elementary angle $\Delta\varphi$, which is limited by the working surfaces of the screw and casing and the zero level surface (11). The elementary volume of cargo in the selected sector will be

$$\Delta V = (P_A\Delta\varphi/R)\int_r^{R_k}\rho^3 d\rho = 0{,}25P_A(R_k^4 - r^4)\Delta\varphi/R, \quad (16)$$

where R_k – radius of the inner surface of the casing;

The centre of gravity of the selected sector will be

$$r_C = 0{,}8R_k[1-(r/R_k)^5]/[1-(r/R_k)^4] = 0{,}8(R+\Delta_R) = k_C R, \quad (17)$$

where k_C – is a parameter for the location of the centre of gravity of an elementary flow sector; Δ_R – the gap between the screw and the casing.

For screw conveyors, the radius of the shaft is usually small compared to the radius of the top edge of the spiral ($r/R = 0{,}15 - 0.3$).Therefore, in the case of reducing the model of a material particle to the transport of coherent goods by flow for conveyors with a small radius of the screw shaft, the parameter of the location of the center of gravity of the flow can be taken $k_C = 0{,}8 + \Delta_R/R$. It should be noted that in addition to the volumetric forces of weight and inertia, the load will be subject to surface forces from its displacement in the gap between the screw and the shaft, which are mainly perceived by the outer edge of the edge with a radius of R. Therefore, it is permissible to use the value of the edge lifting angle in dependencies (1)–(5) $\alpha = \mathrm{arctg}(c/R)$.

For bulk non-cohesive cargoes, especially fine particles, the velocity of particles in the flow is variable, and therefore the model of its movement as a solid body is unacceptable. Let's consider the transport of fine cargo in the conditions of layer-by-layer movement, for which $\omega_A = \omega_A(n,b) \neq const$. Since, for an isotropic bulk medium, the axes of the stress tensor coincide with the axes of the strain rate tensor, then, taking into account (8), we have the equality of tangential stresses $\tau_{tn} = \tau_{tb} = \mu p$, which results in equal angular deformations $\gamma_{tn} = \gamma_{tb}$. Then, taking into account (11), we obtain the differential equation for the velocity distribution in the flow:

$$\partial v_t/\partial\rho - v_t\rho/(\rho^2 + c^2) = \partial v_t/\partial b. \quad (18)$$

The law of change of the tangential velocity of each particle of the flow is represented as $v_t = v_t(\rho,b) = u(\rho)\cdot f(\rho+b)$. By substitution v_t in (18), we obtain:

$$f(\rho+b)\cdot\frac{\partial u(\rho)}{\partial\rho} + u(\rho)\cdot\frac{\partial f(\rho+b)}{\partial\rho} - \frac{\rho\cdot u(\rho)\cdot f(\rho+b)}{\rho^2+c^2}\bigg|_t = u(\rho)\cdot\frac{\partial f(\rho+b)}{\partial b}. \quad (19)$$

Given that $\partial f(\rho+b)/\partial\rho=\partial f(\rho+b)/\partial b$, equation (18) reduces to a differential equation with respect to the parameter ρ:

$$\frac{du(\rho)}{d\rho}-\frac{\rho\cdot u(\rho)}{\rho^2+c^2}=0. \qquad (20)$$

The solution of the differential equation (20) is given:

$$u(\rho)=C_1\sqrt{\rho^2+c^2}, \qquad (21)$$

where C_1 – is the integration constant determined from the boundary conditions.

Thus, the tangential component of the velocity of the cargo particle is given by

$$v_t=C_1\sqrt{\rho^2+c^2}\cdot f(\rho+b). \qquad (22)$$

It is advisable to approximate the function $f(\rho+b)$ by the power law $f(\rho+b)=a\cdot(\rho+b)^{\beta}$, where k_v and β – are dimensionless model parameters that are determined experimentally. Then, using the theory of dimensionality, dependence (22) can be written in the form:

$$v_t=k_v\omega\sqrt{\rho^2+c^2}\cdot[(\rho+b)/R]^{\beta}. \qquad (23)$$

The axial velocity of an arbitrary flow particle is defined as $\text{v}_{\text{zA}}=\text{v}_{\text{t}}c/\sqrt{\rho^2+b^2}$ and, taking into account (23), will be:

$$v_{zA}=k_v c\omega[(\rho+b)/R]^{\beta}. \qquad (24)$$

Accordingly, the angular velocity of the rotational motion of the particle under the action of centrifugal forces will be:

$$\omega_A=\omega-v_z/c=\omega\{1-k_v[(\rho+z\rho/\sqrt{\rho^2+c^2})/R]^{\beta}\}. \qquad (25)$$

Centrifugal force N_2, acting on the casing of the screw conveyor from the sector side with an angle of $\Delta\theta$ equal $N_2=\rho_m\iiint\limits_{\Delta V}\omega_A^2 d\rho dz d\varphi$, Where from:

$$N_2=\rho_m\Delta\varphi\omega^2\int_r^{R_k}\rho d\rho\cdot\int_0^{P_A(\rho^2+c^2)/R}\{1-k_v[(\rho+z\rho/\sqrt{\rho^2+c^2})/R]\}dz. \qquad (26)$$

The analysis of dependencies (24–25) shows that in layer-by-layer motion, linear velocities v_{zA} gradual movement of the particle and angular velocity ω_A of the rotating helical motion depend on the parameters and location of the particle in the flow.

Accordingly, the force N_2 from the pressure of the load on the casing during its helical movement is formed by the centrifugal forces of each particle. The result of solving the integral equation (26) is difficult to analyse and use in practice. Therefore, taking into account (16) and (17), it is advisable to present it in the form of an approximate dependence

$$N_2 = k_\omega \rho_m r_C \Delta V \omega^2 , \qquad (27)$$

where k_ω – is a complex coefficient that reflects the ratio of the reduced angular velocity of the rotating flow ω_A to the angular velocity of the conveyor, and is determined by dependencies (2) and (3), $k_\omega = 0{,}4 - 0{,}6$.

In general, the studies have shown that the use of a simplified model of bulk cargo transportation based on the model of a material particle with reduced to flow parameters adequately reproduces the laws of bulk cargo transportation by helical conveyors and can be used for practical use. In this case, both for the transportation of cohesive materials and for fine materials, the main axial loads are received by the outer edge of the coil with a radius of R.

Conclusions. An analysis of the particle motion in the flow is carried out based on the results of implementing a model of a bulk medium with partial filling of the working space of a high-speed vertical screw conveyor. It is shown that the consideration of the stress-strain state of cargo during screw conveying is significantly simplified when using a special helical coordinate system.

The results of the study show that in the process of screw conveying, the free surface of the cargo massif is described by a helical surface, the derivative of which can be approximated by a power law close to a parabola. For a cohesive material, the cargo particles move almost as a single object, and all mass forces pass through the center of gravity of the selected elementary sector of the flow.

When transporting finely dispersed non-cohesive materials, the speed of gradual movement and angular velocities of rotational motion of particles depend on their location in the flow, and the angular velocity and, accordingly, the centrifugal force decrease with an increase in the radial parameter of the particle and the height of the particle above the surface of the spiral.

It has been confirmed that for the case of high-speed conveying of both cohesive and fine-dispersed cargoes by spiral conveyors, the laws of spiral conveying of both the flow as a whole and individual particles are preserved. Therefore, for the engineering calculation of the parameters and operating modes of vertical screw conveyors, a model of the movement of a material particle with the corresponding reduced parameters can be used.

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МОДЕЛЬ ПОТОКОВОГО ТРАНСПОРТУВАННЯ СИПКОГО ВАНТАЖУ ВЕРТИКАЛЬНИМИ ГВИНТОВИМИ КОНВЕЄРАМИ

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Резюме. *Розглянуто модель транспортування сипкого вантажу потоком вертикальним швидкісним гвинтовим конвеєром. Розкрито особливості взаємного руху зв'язних та дрібнодисперсних вантажів, зокрема в умовах пошарового їх руху, з використанням моделі суцільного середовища, в якій для сухих сипучих нев'язких матеріалів взаємні переміщення частинок зумовлюється закономірностями розподілу внутрішнього тертя згідно з законом Амонтона-Кулона. При цьому, для переміщення сипких вантажів в умовах гвинтового високошвидкісного динамічного потоку, приймалось допущення, що нормальні напруги на поверхнях виділеного об'єму визначаються тільки середньостатичним тиском. Для аналізу напружено-деформованого стану сипкого вантажу в умовах гвинтового транспортування використано спеціальну гвинтову систему координат, осі якої спрямовані, відповідно, по нормалі, бінормалі та дотичній до гвинтової твірної спіралі шнека, що дозволило суттєво спростити розв'язок задачі. Показано, що в умовах пошарового руху осьова швидкість довільної частинки потоку описується інтегральним параметром, що є сумою нормальної та бінормальної координати гвинтової системи координат. Виведено залежності для описування форми гвинтової поверхні з параболічною твірною, що обмежує потік вантажу за умови неповного заповнення робочого простору, об'єму елементарного сектора потоку та центру його ваги. Обґрунтовано використання моделі пошарового руху матеріалу, встановлено розподіл лінійних та кутових швидкостей частинок у потоці та, відповідно, відцентрових сил. Показано, що для вертикальних швидкісних конвеєрів потік у цілому та рух окремих його частинок характеризуються закономірностями гвинтового транспортування, що робить можливим використання моделі матеріальної частинки з приведеними параметрами за умови врахування розподілу кутових швидкостей по шарах. Отримані закономірності швидкісного транспортування вантажів вертикальними гвинтовими конвеєрами дозволяють проводити уточнений розрахунок їх режимів роботи.*

Ключові слова: *вертикальні гвинтові конвеєри, сипкий вантаж, суцільне середовище, гвинтова система координат, швидкості деформацій, напруги, кінематика потоку насипного вантажу*.

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