Проведені дослідження щодо впливу довговічності роботи стрічки на собівартість транспортування тони вантажу. Дослідження показали, що чим більша довговічність транспортної установки, тим менша собівартість транспортування вантажу, а повноцінний термін служби трубчастого конвеєра визначає термін служби стрічки. В свою чергу на термін служби стрічки впливають параметри конвеєра, а також параметри вантажу що транспортується. Виявлені значимі параметри, на які проектувальник, при розробці трубчастого конвеєра, може вплинути, а саме: радіусу стрічки згорнутою в трубу і швидкості руху стрічки. Радіус і швидкість руху стрічки можна пропорційно змінювати відносно заданої продуктивності конвеєра тим самим змінюючи термін служби стрічки і собівартість транспортування вантажу. Виявлені розрахункові залежності інтегрального економічного показника – собівартості транспортування тони вантажу в який увійшли витрати на заробітну плату, електроенергію, амортизацію, матеріали, ремонт, інші витрати, маса переміщеного вантажу за увесь термін служби роботи конвеєра. Запропонована методика визначення оптимальних радіусу і швидкості руху стрічки проектованого трубчастого конвеєра, при яких середня собівартість транспортування тони вантажу за весь час експлуатації конвеєра буде мінімальною. За отриманими залежностями побудовані графіки зміни середньої собівартості транспортування вантажу конвеєром в залежності від радіуса і швидкості руху стрічки. Аналіз графіків дозволив визначити оптимальні радіус і швидкість руху стрічки проектованого конвеєра при яких собівартість транспортування вантажу мінімальна. Для заданих умов експлуатації, наведених в якості приклада, отримані рекомендовані параметри радіусу і швидкості руху стрічки які збільшуються зі збільшенням продуктивності конвеєра

Ключові слова: трубчастий конвеєр, собівартість транспортування вантажу, методика визначення, радіус, швидкість стрічки

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DETERMINATION OF THE OPTIMAL PARAMETERS OF A TUBULAR BELT CONVEYOR DEPENDING ON SUCH AN ECONOMICAL

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1. Introduction

Belt conveyors are widely used in various industries to move various materials horizontally or at a small angle. This is predetermined by the simplicity of design and high efficiency of the processes employed to transport materials to the required location. There is a significant need in many cases to move various materials at large angles to the horizontal. Displacement of materials at angles when the component of lifting exceeds friction forces on the belt is impossible by using conventional belt conveyors. Tubular belt conveyers are proposed instead of typical belt conveyors. Such conveyors can move materials not only at angles but could be applied to the spatial configuration of the route with inflections along the horizontal and vertical planes at the same time. They can be used for the transportation of various materials under conditions of mountainous terrain, as well as when natural and artificial obstacles appear on the route. A special feature of the structure of such conveyors opens up a possibility to transport a cargo at the upper (freight) and lower branches of a conveyor. However, effective and widespread use of these conveyors is hindered by the need to improve the methods of their calculation.

2. Literature review and problem statement

Application of belt tubular conveyors is outlined in paper [1]. Work [2] investigated a tubular belt conveyor taking into consideration reverse motion of the belt and demonstrated prospects of a given class of transportation means. A confirmation of the effective application of such transportation means is given in paper [3] whose authors report results of calculation of parameters and present the design of a tubular conveyor. Meanwhile, as indicated by studies [1–3], the unresolved tasks are determining the optimum para-

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meters of a tubular belt conveyor, which would minimize the cost of capital and operating expenditures An important element of tubular conveyors is the belt whose durability affects the work of the entire installation. That explains why most studies address the work of the belt, as well as determining the forces of adhesion between a material and the belt. Paper [4] investigates the influence of lateral pressure of a material in order to establish a model of adhesion with a conveyor belt. The authors derived an analytical dependence, which determines relationships between a lateral pressure, conditional diameter of a material and the rate of filling. At the same time, they failed to examine the operational reliability of the belt and only indicated a possibility of impact from the results obtained. Work [5] is worth considering as the authors studied and measured the wear of industrial conveyor belts and modeled their performance under an impact mode for the predefined conditions of operating parameters. The analysis of the wear of the tape from impact, in the boot device of the conveyor with different number of supporting rollers, the material about the tape is given. The paper gives an analysis of the wear of a belt due to the impact, in the filling device of a conveyor with a varying number of supporting rollers, of a material and the belt. At the same time, the wear and durability of the belt, which affect capital and operating costs, were not dealt with for the case of its motion with the material on linear roller supports.

Paper [6] employs a classical linear regression model to analyze dependences of a conveyor belt on the impact loading, though with certain assumptions. Study [7] applied a logistic regression equation based on the obtained values of damage in a rubber-textile belt. The application of such approaches is relevant only within the numerical values of the parameters that are obtained under specific conditions of the performed experiments. Paper [8] reports results of research into influence of the number of transportation belts that are equipped with tension rollers on a failure in the place of impact. The research focuses exclusively on the analysis of failures under certain conditions of loading a conveyor belt. Paper [9] describes an analysis of conveyor belt failures under conditions of its impact loading based on the application of a dissipation coefficient. The above study requires the refinement of hypotheses based on which the dissipation was defined. The dependences derived do not account for the compressive forces of a tubular belt with the load on linear roller supports, as well as their influence on the durability of the belt.

Paper [10] reports results of experimental research into estimation of damage to belt conveyors used in the mining industry. The authors did not determine the effect of load transportation cost, which depends on the durability of the belt.

Authors of work [11] describe the study into durability of a tubular belt when transporting bulk cargo. However, there are no results regarding the cost of capital and operating expenditures for belt tubular conveyors.

Therefore, it is an important scientific task to establish optimal parameters for the tubular belt conveyor based on an economic integrated indicator – the cost of transporting a ton of cargo. Resolving this task would make it possible to utilize tubular belt conveyors more efficiently and to bring down economic costs.

Unresolved part of the problem related to the establishment of optimal parameters based on the economic integrated indicator is to determine the dependences between a service time of the conveyor, capital and operational expenses associated with the transportation of cargo. Typically, the life cycle of a tubular belt defines the operation term of a conveyor. A combination of the dependences given in paper [11] with known dependences for the calculation of technical-economic indicators might solve the specified problem.

3. The aim and objectives of the study

The aim of present study is to devise a procedure for determining optimal parameters of the belt tubular conveyor based on the economic criterion, which takes into consideration durability of the belt. That would make it possible to attain a certain economic effect during industrial implementation of the designed transportation installation.

To accomplish the aim, the following tasks have been set:

– to determine parameters for the belt tubular conveyors, which affect a service life of the belt;

– to establish estimation dependences for the integrated economic indicator – the cost of transporting a ton of cargo;

– to propose parameters for belt tubular conveyors, which would provide for a minimum cost of transporting a ton of cargo.

4. Determining the parameters of a belt tubular conveyor, which can be altered during design

There is a sufficient number of parameters for belt tubular conveyors that affect duration of belt operation (as the most expensive part of a transporting installation) enough. There are important parameters that a designer can influence under the assigned conditions, as well as insignificant ones that a designer cannot alter. Changing the significant parameters can help find such an optimal value at which the cost of transporting a ton of cargo would be minimal.

Let us define the importance of the influence of parameters of belt tubular conveyors on belt durability.

Belt durability of belt tubular conveyors for transporting bulk $T_b=T_1$ or lumpy $T_b=T_2$ cargo depends on: the length of conveyor transportation $T_1=f(L_c)$, $T_2=f(L_c)$; a radius of the conveyor belt rolled in a tube $T_1=f(R_t)$, $T_2=f(R_t)$; the distance between linear roller supports $T_1=f(l_p)$, $T_2=f(l_p)$; belt motion speed $T_1=f(V_b)$, $T_2=f(V_b)$; the angle of conveyor positioning $T_1=f(\beta)$, $T_2=f(\beta)$ [11]. It is obvious that the length L_c and the angle of conveyor positioning β are dictated by operational conditions that a designer cannot alter. The distance between linear roller supports l_p is associated with the belt sagging that cannot exceed the permissible one [12]. Therefore, parameters L_c, β, l_p of the distance between linear roller supports, the length of transportation, and the angle of conveyor positioning are not significant for belt durability.

The radius of belt conveyor rolled in a tube R_t and the speed of belt motion V_b are connected by the conveyer performance indicator Q_c. When designing belt tubular conveyors with assigned performance efficiency, parameters of the radius of belt rolled in a tube R_t and the speed of belt motion V_b can be changed, accordingly, by a designer while assessing belt durability and the payback period of a conveyor. Therefore, the parameters R_t of the radius of the belts rolled into a tube, and V_b of the belt motion speed are significant.

5. Establishing estimation dependences of an integrated economic indicator

We shall define estimation dependences of the integrated economic indicator for a belt tubular conveyor whose schematic is shown in Fig. 1.

The longer durability of a transporting installation, the lower the cost of transporting a cargo.

It is known that the belt is the most expensive and the least durable part of a transporting installation, which is why one can assume that the full life cycle of a tubular conveyor determines the service life of the belt. Based on the above, the mean cost of transporting a ton of cargo over the entire service life of a belt tubular conveyor shall be derived from dependence:

$$C(T_b)=\frac{C_w(T_b)+C_e(T_b)+D+C_m(T_b)+C_r(T_b)+C_o(T_b)}{Q(T_b)},\ (\text{USD}/m),\quad (1)$$

where $C_w(T_b)$ are the wages of workers over the entire service life of the conveyor (USD); $C_e(T_b)$ is the cost of electricity over the entire service life of the conveyor (USD); D is the cost of depreciation charges (USD); $C_m(T_b)$ is the cost of materials over the entire service life of the conveyor (USD); $C_r(T_b)$ is the cost of repairs over the entire service life of the conveyor (USD); $C_o(T_b)$ are other expenses over the entire service life of the conveyor (USD); $Q(T_b)$ is the mass of transported cargo over the entire service life of the belt, (m); T_b is the belt life cycle (hours).

Other expenditures include taxes, fees, payments to funds, etc. In the absence of actual data, it is recommended to accept their volume to be 10–20 % of the amount specified above:

$$C_o(T_b)=T_b\cdot T_{tar.}\cdot n_{work.},\ (\text{USD}),\quad (2)$$

where $T_{tar.}$ is the hourly tariff rate of workers that operate the conveyor (USD/hour); $n_{work.}$ is the average number of workers that operate the conveyor (workers).

$$C_e(T_b)=\sum N_e K_l K_{util.} T_b T_{can.},\ (\text{USD}),\quad (3)$$

where ΣN_e is the total power of electric motors (kW); K_l is a load factor. For a three-phase induction motor, $K_l=0.8$; $K_{util.}$ is the utilization coefficient of machines over 24 hours; $T_{can.}$ is the cost of one kilowatt-hour of installed capacity (USD).

$$D=K\cdot e_{stan.},\ (\text{USD}),\quad (4)$$

$$K=K_{met.}+K_{el.mot.}+K_b,\ (\text{USD}),\quad (5)$$

where $e_{stan.}$ is the standard coefficient of depreciation; K is the value of fixed assets (USD); $K_{met.}$ is the value of fixed assets (capital expenditures) for purchasing metal parts for a conveyor (USD); $K_{el.mot.}$ is the value of fixed assets (capital expenditures) for purchasing electric motors for a conveyor (USD); K_b is the value of fixed assets (capital spending) to purchase a conveyor belt (USD);

$$K_{met.}=C_{met.}\cdot M_{met.},\ (\text{USD}),\quad (6)$$

where $C_{met.}$ is the average cost of 1 kg of metal part for a conveyor (USD/kg); $M_{met.}$ is the mass of metal parts of the conveyor (kg).

The mass of metal parts of belt tubular conveyors includes: liner part of the conveyor, the mass of rollers, drive and traction devices with drums, as well as the mass of the drive frame. A dependence for determining the mass of metal parts of a belt tubular conveyor was derived in paper [13]:

$$\begin{aligned}M_{met.}&\cong M_{lin.par.}+M_p+M_{d.f.}+M_{t.d.}+M_{d.d.}=\\&=4.45L_c+20L_cB_b+4.2L_cB_b^2+\\&+L_c\left[6943\left(d_{p.l}\right)^{2.6}+279\left(d_{p.e}\right)^{2.4}B_b\right]\left(l_p'\right)^{-1}+\\&+\left(2.6+8.4B_c\right)10^{-3}\sum_{i=1}^{n}\left[W_{Ti}\left(\frac{A_i+1}{A_i-1}\right)\right]+\\&+\left(4.8+15.6B_b\right)10^{-3}\sum_{j=1}^{m}\left[S_{d.i}\sin\frac{\sum\alpha_n}{2}\right],\ (\text{kg}),\end{aligned}\quad (7)$$

where $M_{lin.par.}$ is the mass of liner part of the conveyor, (kg); $M_{p.}$ is the mass of rollers (kg); $M_{d.d.}$is the mass of drive devices with drums, (kg); $M_{t.d.}$is the mass of traction devices with drums, (kg); $M_{d.f.}$ is the mass of the drive's frame, (kg); B_b is the belt width (m); l_p' is the distance between roller supports, [13]; L_c is the length of the conveyor (m); $d_{p.l}$, $d_{p.e}$ $d_{p.l}$, $d_{p.e}$ is the diameter of rollers loaded and empty branches of the conveyor, respectively (m) [13]; W_{Ti} is the traction effort of the i-th drum; in this case, there is one only (Fig. 1) (derived from traction calculation) (N); A_i is a traction coefficient of the i-th drum (taken based on the working condition of the conveyor [12, 13]; $\Sigma\alpha_n$ is the angle of wrapping a non-drive drum by the belt [12] (degrees); $S_{d.i}$ is the pull on non-drive drums (calculated from traction estimation) (N).

$$K_{el.mot.}\approx N_{el.mot.}C_{el.mot.},\ (\text{USD}),\quad (8)$$

where $N_{el.mot.}$ is the power of conveyor's electric motors (kW); $C_{el.mot.}$ is the specific cost of electric motors (USD/kW).

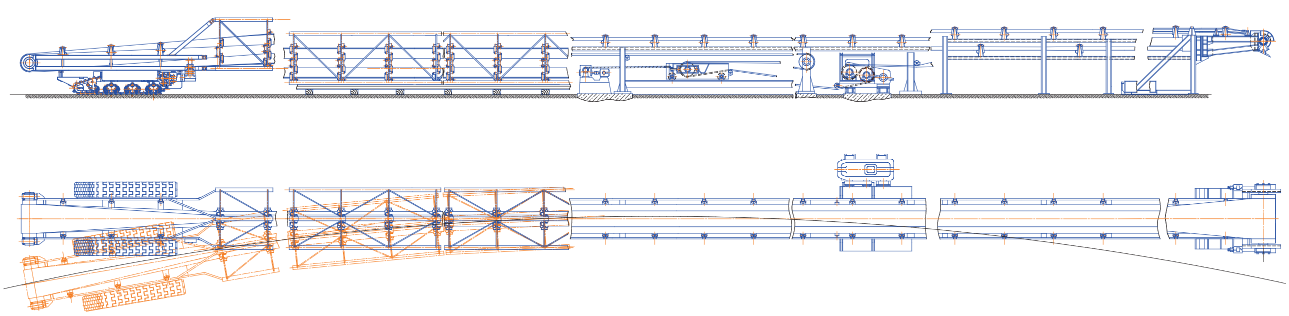


Fig. 1. Belt telescopic tubular conveyor

$$K_b = 2\cdot C_b \cdot L_c,\ \text{(USD)}, \tag{9}$$

where C_b is the specific cost of one meter unit of the belt (USD/1 unit m).

$$C_r(T_b) = H_{f.lub.}\cdot T_{f.lub.}\cdot \frac{T_b}{30\cdot 24},\ \text{(USD)}, \tag{10}$$

where $H_{f.lub.}$ is the monthly rate of consumption of fuel and lubricants (kg); $T_{f.lub.}$ is the cost of one kilogram of fuel and lubricants (USD/kg).

$$C_r(T_b) = p\cdot \frac{T_b}{365\cdot 24},\ \text{(USD)}, \tag{11}$$

where p is a standard indicator of expenditures for all types of repair, diagnosing and technical maintenance of a transporting installation determined from formula:

$$p = \frac{C_M \cdot H_p}{T\cdot 100\,\%},\ \text{(USD/year)}, \tag{12}$$

where C_M is the renovation cost of the machine, (*USD*); H_p is the norm of annual expenses for repair and maintenance as a percentage of the renovation cost of machines; T is the annual operation mode of machines (machine hours/year):

$$C_o(T_b) = 0.1\begin{pmatrix} C_w(T_b) + C_e(T_b) + D + \\ + C_m(T_b) + C_r(T_b) \end{pmatrix},\ \text{(USD)}, \tag{13}$$

$$Q(T_b) = Q\cdot T_b,\ \text{(t)}. \tag{14}$$

To determine the cost of transporting a ton of cargo over the entire service life of a belt tubular conveyor, we shall employ dependences given in papers [11, 14].

5. 1. 1. Determining the service life of belt operation

Assuming that the full life cycle of a belt tubular conveyor defines a service life of the belt, we shall represent dependences to determine a service life of the belt operation [12].

The durability of a tubular belt when transporting lumpy cargo with an angle of filling $\varphi_{fill.} = \varphi_{opt.} = 37°$ is determined from dependence [11]:

$$T_b = T_2 = \frac{2\cdot 3600\, C_c L_c}{V_b}\times$$
$$\times\left[\begin{aligned} &\left(\Pi_{r1}^{1/m} + \Pi_{b1}^{1/m}\frac{L_c}{l_p}\right) + \\ &+ \frac{0.27}{A_{piece} R_t}\left(\Pi_{ri}^{1/m}\frac{0.3 d_p}{(2 l_{pr} - d_p)} + \Pi_{bi}^{1/m}\frac{L_c}{l_p}\right)\end{aligned}\right]^{-1},\ \text{(hours)}, \tag{15}$$

where C_c is the capacity of a conveyor belt (J); m is a parameter that characterizes the inclination angle of logarithmic characteristics of the belt compression fatigue [11]; L_c is the length of the installation (m); Π_{b1} is the energy of belt compression on the roller support of the linear part of conveyor (J); Π_{r1} is the energy of a conveyor belt compression by a cargo flow that falls from height H at the point of loading (*receiver*) (J); Π_{ri} is the energy of belt compression at the point of loading (*receiver*) when a piece of cargo of the i-the fraction hits it (J); Π_{bi} is the energy of belt compression by pieces of cargo on the rollers of the linear part of the conveyor (J); l_p is the distance between roller supports (m); V_b is the speed of belt motion (m/s); l_{pr} is the distance between roller supports at the point of loading (m); d_p is the diameter of the roller (*m*); R_t is the radius of a tubular belt (*m*); $A_{piece} = 1/d_{piece}$ is the curvature of the asymmetric surface of a piece of cargo (m^{-1}); d_{piece} is the diameter of a piece protrusion (m).

$$\Pi_{b1} = \frac{455.48 k_{p/a} R_t^5 \delta_b d_p}{E_{compr.b}}\times$$
$$\times\sqrt{\frac{R_t(\gamma\cdot g\cdot\cos\beta)^5 l_p}{E_r d_p}}\left(k_d k_p\right)^2,\ \text{(J)}, \tag{16}$$

where $k_{p/a} = 4\div 5$ is a coefficient that characterizes the ratio of passive energy of belt compression on the roller support to the energy of its active collapse; $E_{compr.b}$ is the conveyor belt compression rigidity (N/m); δ_b is the thickness of the belt (m); γ is the volumetric mass of the bulk cargo (kg/m^3); E_r is the modulus of elasticity of rubber (N/m^2); k_d is a coefficient of dynamism that characterizes kinetic energy of the mass of part of the cargo that is involved in a dynamic interaction when the belt passes a linear roller support; k_p is a coefficient of a cargo part's participation in the interaction when the belt passes a linear roller support.

$$k_d = 1 + \frac{k_p V_b^2}{2 g d_p},\quad k_p = k_p'\sigma_0\left(1 - k_p'\right) + \sigma_0\left(k_p' - 1\right), \tag{17}$$

where

$$\sigma_0(x) = \begin{vmatrix} 1 & \text{at} & x \geq 0, \\ 0 & \text{at} & x < 0, \end{vmatrix}$$

$$k_p' = 13.98\frac{d_p V_b}{\left(\chi + V_b^2\right)}\sqrt{\frac{R_t\cdot\gamma\cdot g\cdot l_p\cos\beta}{E_r d_p}}, \tag{18}$$

where χ is a parameter that characterizes the plasticity of cargo being transported, (m^2/s^2); k_p is a coefficient of the cargo mass participation at belt compression.

$$\Pi_{r1} = \frac{0.0003(g\cdot\gamma\cdot H)^3 d_p \delta_b}{\left[E_{compr.b}\left(\frac{L_c}{100} + \frac{0.365 R_t}{d_p l_{pr}}\right)\right]},\ \text{(J)}, \tag{19}$$

where γ is the volumetric mass of the bulk cargo (kg/m^3).

$$\Pi_{ri} = g G_{piece.i} H / \left(1 + G_{piece.i} / G_p\right),\ \text{(J)}, \tag{20}$$

where H is the height of the fall of a piece on a belt at the point of loading (m); $G_{piece.i} = 0.22\gamma_{block}\, a^3_{piece.i}$ is the mass of a piece of the i-th fraction (kg); $a_{piece.i}$ is the length of the largest piece of the i-th fraction in the volume of a rock mass (m); γ_{block} is the volumetric cargo weight in block (kg/m^3); G_p is the mass of a roller support (kg).

$$\Pi_{bi} = 4.558\cdot 10^{-3}\frac{V_b^{10}}{E^4_{compr.b}\delta_b^{10}}\frac{\left(1 + \sqrt[3]{A_{piece} d_p}\right)^6}{A^3_{piece} d_p^5}\times$$
$$\times\left[\frac{G_{piece.i}\left(a_{piece.i} + d_p\right) / 2 a_{piece.i}}{1 + G_{piece.i}\left(a_{piece.i} + d_p\right) / \left(2 a_{piece.i} G_p\right)}\right]^5,\ \text{(J)}. \tag{21}$$

A service life of the belt of a tubular conveyor that transports a bulky cargo is determined excluding the components Π_{ri} and Π_{bi}:

$$T_b = T_1 = \frac{2\cdot 3600 C_c L_c}{V_b}\left[\Pi_{r1}^{1/m} + \Pi_{b1}^{1/m}\frac{L_c}{l_p}\right]^{-1}, \text{ (hours)}. \qquad (22)$$

A life cycle of the belt of a tubular conveyor, which transports a bulk cargo, may differ from the service life of the belt of a tubular conveyor that transports a lump cargo.

5. 1. 2. Determining the calculation parameters of a belt tubular conveyor

Calculation parameters of the belt tubular conveyor are derived from the following dependences:

1. At an optimum filling angle of the cross-section of a tubular belt $\varphi_{fill} = \varphi_{opt.}$ [11], a cargo weight per unit length (kg/m) is equal to:

$$q_c = 2.114\gamma R_t^2, \text{ (kg/m)}. \qquad (23)$$

2. The pull at the non-drive drums is equal to the pull of the belt at the point of loading [11] (Fig. 1):

$$S_{di} = S_r = 10^4 B_b^2 (L_c/100) = \\ = 10^3 (8.28 R_t)^2 (L_c/100), \text{ (N)}. \qquad (24)$$

3. The width of the belt of a tubular conveyor can be derived from dependence:

$$B_b = 2\pi R_t + \delta_{over}, \text{ (m)}. \qquad (25)$$

Paper [1] indicates that the magnitude of the zone of overlapping the sides of the belt when it is rolled into a tube should equal $\delta_{over} = 0.5d_t$.

4. A traction effort of the i-th drum is determined from a traction calculation (in this case, there is one drum only (Fig. 1)).

A traction calculation of the belt tubular conveyor is given in paper [14]. It is indicated that applying a method of traversing the contour using a general coefficient of motion resistance $\omega' = 0.04$ is employed to roughly calculate the traction of a conveyor, which is subsequently refined in line with the devised procedure.

In order to identify optimal parameters of a tubular belt based on the economic indicator, which is the mean cost of transporting a ton of cargo over the entire life cycle of a tubular conveyor, approximate traction calculation would suffice.

Traction effort of any belt conveyor is determined as the sum of all forces of motion resistance [12, 14]:

$$W_{Ti} = W_0 = W_{Ti} = W_U + W_B + W_R, \text{ (N)}, \qquad (26)$$

where W_U is the force of belt resistance at the upper branch (N); W_B is the force of belt resistance at the bottom branch (N); W_R is the force of belt motion resistance at the point of loading (N). Assume $W_R \approx 0$.

$$W_U = g\cdot\begin{bmatrix}(q_c + q_b + q_p')\omega'\cdot\cos\beta \pm \\ \pm (q_c + q_b)\sin\beta\end{bmatrix}\cdot L_c, \text{ (N)}, \qquad (27)$$

or

$$W_U = g\begin{bmatrix}(2{,}114\gamma R_t^2 + q_b + q_p')\omega'\cos\beta \pm \\ \pm(2{,}114\gamma R_t^2 + q_b)\sin\beta\end{bmatrix}\cdot L_c, \text{ (N)}, \qquad (28)$$

$$W_B = g\cdot\left[(q_b + q_p'')\omega'\cdot\cos\beta \pm q_b\sin\beta\right]\cdot L_c, \text{ (N)}, \qquad (29)$$

where q_c is the transported cargo mass per unit length (kg/m); q_b is the belt mass per unit length (kg/m); q_p' is the upper roller supports mass per unit length (kg/m); q_p'' is the lower roller supports mass per unit length (kg/m); β is the angle of conveyor positioning (degrees); $\omega' = 0.04$ is a coefficient of motion resistance.

5. A mass of one meter of belt at width B_b can be determined roughly to be refined thereafter based on the results of traction calculation:

$$q_b \cong 250 B_b / g, \text{ (kG/m)}, \qquad (30)$$

or by assigning in advance the i number of spacers according to formula [12]:

$$q_b = 1.1\cdot B_b(\delta\cdot i + h_1 + h_2), \text{ (t/m)}, \qquad (31)$$

where 1.1 is the specific weight of the belt (t/m^3); δ is the thickness of the spacer (m); h_1 is the thickness of the upper layer of a rubber gasket (m); h_2 is the thickness of the bottom layer of a rubber gasket (m).

6. The belt speed is defined by the performance of a conveyor; we shall derive it by performing transforms.

A cross-sectional area of the cargo on a belt (Fig. 2):

$$F_c = S_{circle} - S_{segm.BC\ \breve{B}C} + S_{\Delta BCD}, \text{ (m}^2\text{)}. \qquad (32)$$

$$F_c = \pi R_t^2 - 0.5 R_t^2\left[4\varphi_{fill.} - \sin 4\varphi_{fill.}\right] + \\ + \sin^2 2\varphi_{fill.}\cdot \mathrm{tg}\rho, \text{ (m}^2\text{)}. \qquad (33)$$

Here, in expression $0.5R_t[4\varphi_{fill.} - \sin 4\varphi_{fill.}]$ angle $\varphi_{fill.}$ is expressed in radians. Upon transforming radians into degrees, the expression will take the following form:

$0.5R_t[\pi\varphi_{fill.} - \sin 4\varphi_{fill.}]$.

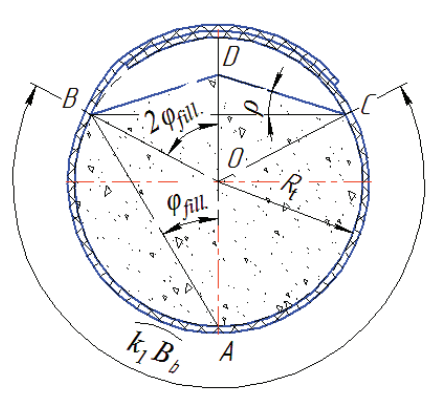


Fig. 2. Geometrical diagram of the belt cross-section: k_1B_b – width of the belt tangent to a cargo; $\varphi_{fill.}$ – angle that characterizes the degree of filling the belt cross-section; ρ – angle of natural inclination of a material in motion

From equation (33):

$$R_t = \sqrt{\frac{F_c}{\pi - 0.5\left[\frac{\pi\varphi_{fill.}}{45^\circ} - \sin 4\varphi_{fill.}\right] + \sin^2 2\varphi_{fill.}\,\mathrm{tg}\rho}},\ (\mathrm{m}). \quad (34)$$

The width of the belt, tangent to a cargo:

$$k_1 B_b = 2\pi R_t\left(360^\circ - 4\varphi_{fill.}\right)/360^\circ,\ (\mathrm{m}), \quad (35)$$

$$k_1 B_b = \pi R_t\left(2 - 4\varphi_{fill.}/45^\circ\right),\ (\mathrm{m}). \quad (36)$$

Substituting equation (34) into equation (36), we obtain:

$$k_1 B_b = 2\pi\sqrt{\frac{F_c}{\pi - 0,5\left[\frac{\pi\varphi_{fill.}}{45^\circ} - \sin 4\varphi_{fill.}\right] + \sin^2 2\varphi_{fill.}\cdot\mathrm{tg}\rho}} \times \left(1 - \frac{\varphi_{fill.}}{90^\circ}\right),\ (\mathrm{m}). \quad (37)$$

A cross-sectional area of the transported cargo, at known productivity, is determined from expression:

$$F_c = \frac{Q_c}{3600 V_b \cdot \gamma},\ (\mathrm{m}^2). \quad (38)$$

Substituting equation (38) into equation (37), we obtain:

$$k_1 B_b = 2\pi\sqrt{\frac{Q_c}{3600 V_b \cdot \gamma\left(\pi - 0.5\left[\frac{\pi\varphi_{fill.}}{45^\circ} - \sin 4\varphi_{fill.}\right] + \sin^2 2\varphi_{fill.}\cdot\mathrm{tg}\rho\right)}} \times \left(1 - \frac{\varphi_{fill.}}{90^\circ}\right),\ (\mathrm{m}). \quad (39)$$

By denoting a value of k_p by the coefficient of productivity, we obtain:

$$k_p = \frac{\pi - 0.5\left(\frac{\pi\varphi_{fill.}}{45^\circ} - \sin 4\varphi_{fill.}\right) + \sin^2 2\varphi_{fill.}\cdot\mathrm{tg}\rho}{\left(1 - \frac{\varphi_{fill.}}{90^\circ}\right)^2}. \quad (40)$$

Substituting equation (40) in (39), we obtain the width of the belt tangent to a cargo expressed through productivity and the productivity coefficient k_p:

$$k_1 B_b = 2\pi\sqrt{\frac{Q_c}{3600 V_b \cdot \gamma \cdot k_p}},\ (\mathrm{m}). \quad (41)$$

The optimum angle of filling the cross-section of a tubular belt $\varphi_{fill.}=37^\circ$ [10]. At $\varphi_{fill.}=37^\circ$, the productivity of a belt tubular conveyor is maximum.

From equation (25):

$$R_t = \frac{B_b}{2(\pi + 0.5)},\ (\mathrm{m}). \quad (42)$$

Substituting equation (42) in equation (36), we shall derive coefficient k_1:

$$k_1 = \frac{\pi\left(2 - \varphi_{fill.}/45^\circ\right)}{2(\pi + 0.5)}. \quad (43)$$

Substituting value $\varphi_{fill.}=37^\circ$ in equation (42) and equation (40), we shall determine $k_{p.opt.}$ and k_1:

$$k_{1.opt.} = \frac{3.14\left(2 - 37^\circ/45^\circ\right)}{2(3.14 + 0.5)} = 0.503, \quad (44)$$

$$k_{p.opt.} = \frac{\pi - 0.5\left(\frac{\pi\cdot 37^\circ}{45^\circ} - \sin(4\cdot 37^\circ)\right) + \sin^2(2\cdot 37^\circ)\cdot\mathrm{tg}\rho}{\left(1 - \frac{37^\circ}{90^\circ}\right)^2} = 2.744(2.231 + \mathrm{tg}\rho). \quad (45)$$

The maximum productivity of a tubular belt will be determined by substituting equation (45) and equation (44) into equation (41):

$$Q_c = 63.388 V_b \cdot \gamma \cdot B_b^2(2.231 + \mathrm{tg}\rho),\ (\mathrm{t/hours}) \quad (46)$$

or

$$Q_c = 63.388 V_b B_b^2(2.231 + \mathrm{tg}\rho),\ (\mathrm{m^3/hours}). \quad (47)$$

Hence:

$$V_b = \frac{Q_c}{63.388 B_b^2(2.231 + \mathrm{tg}\rho)},\ (\mathrm{m/s}). \quad (48)$$

Substituting equation (25) into equation (48), we obtain:

$$V_b = \frac{Q_c}{63.388\left[2R_t(\pi + 0.5)\right]^2(2.231 + \mathrm{tg}\rho)},\ (\mathrm{m/s}), \quad (49)$$

$$V_b = 2.98\cdot 10^{-4} Q_c/\left[R_t^2(2.231 + \mathrm{tg}\rho)\right],\ (\mathrm{m/s}). \quad (50)$$

Hence:

$$R_t = \sqrt{\frac{Q_c}{253.552 V_A(2.231 + \mathrm{tg}\rho)(\pi + 0.5)^2}},\ (\mathrm{m}) \quad (51)$$

or

$$R_t = \sqrt{\frac{Q_c}{3359.462 V_b(2.231 + \mathrm{tg}\rho)}},\ (\mathrm{m}). \quad (52)$$

7. Capacity of a belt conveyor drive is derived from dependence:

$$N_c = \frac{K_r \cdot W_0 \cdot V_b}{1000\cdot\eta},\ (\mathrm{kW}), \quad (53)$$

where $K_r = 1.1...1.2$ is a coefficient of power reserve; $\eta = 0.85$ is the drive's performance efficiency.

A drive engine is to be selected from reference literature.

6. Determining the recommended parameters for a belt tubular conveyor

Let us define the optimal parameters for a belt tubular conveyor based on the economic indicator by performing calculations in the Mathcad software.

General initial data accepted for calculation are: $\delta_b = 0.0176$ m; $R_t = 0.1...1$ m; $d_p = 0.195$ m; $\gamma = 2.4\cdot10^3$ N/m^3; $H = 1.0$ m; $E_r = 0.5\cdot10^7$ N/m^2; $\beta = 0°$; $l_p = 1.2$ m; $l_{pr} = 0.5$ m; $C_c = 0.6\cdot10^4$ J; $\chi = 0.4$ m^2/s^2; $k_{p/a} = 5$; $i = 6$; $A_{piece} = 350$ m^{-1}; $V_b = 0.1...10$ m/s; $L_c = 200$ m; $Q_c = 95...7{,}300$ m^3/year; $G_{piece.i} = 6$ kg; $q_p = 28$ kg; $A_i = 4.09$; $\Sigma\alpha_n = 180°$; $g = 10$ m/s^2; $C_{met.} = 5.7$ USD/kg; $K_r = 1$; $K_{util.} = 1$; $T_{can.} = 0.00087$ USD; $T_{tar.} = 0.019$ USD/hours; $n_{work} = 2$ people; $T_{f.lub.}\cdot H_{f.lub.}\cdot T_b/(30\cdot24) = 0.0000038$ USD/kg; $C_b = 11.407$ USD/1 unit length; $K_r = 1.1$; $\eta = 0.85$; $C_{el.mot.} = 19.011$ USD/kW; $p = 0.0000076$ USD/hours; $e_{stan} = 0.15$; $m = 6/11$.

The result of the software implementation of the calculation of optimal parameters for a belt tubular conveyor, we obtained charts of change in the cost of transporting a ton of cargo for the radius $C = f(R_t)$ and the belt motion speed $C = f(V_b)$.

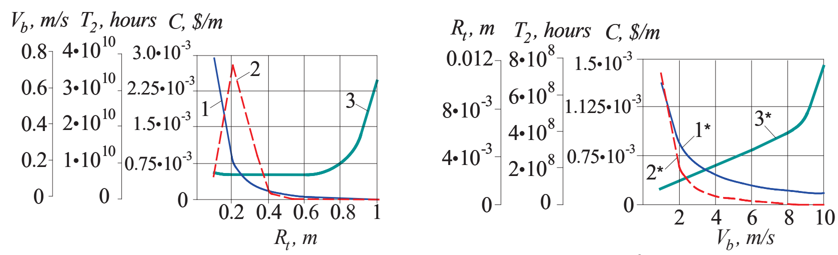
For a lump transported cargo, these are Fig. 3–6, for a loose cargo – Fig. 7–10.

For productivity $Q_c = 95$ m^3/hour – Fig. 3, 7.

For productivity $Q_c = 430$ m^3/hour – Fig. 4, 8.

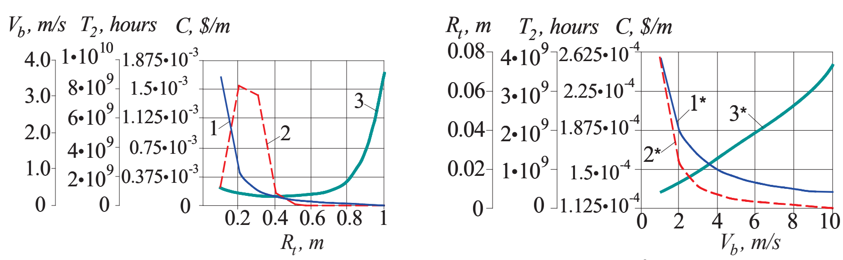
For productivity $Q_c = 1{,}300$ m^3/hour – Fig. 5, 9.

For productivity $Q_c = 7{,}300$ m^3/hour – Fig. 6, 10.



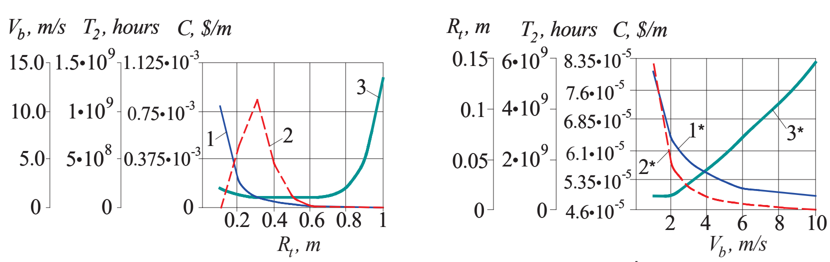
a *b*

Fig. 3. Charts of change when transporting a lump cargo at a belt tubular conveyor productivity at $Q_c = 95$ m^3/hour: *a* – 1 – $V_b = f(R_t)$, 2 – $T_2 = f(R_t)$, 3 – $C = f(R_t)$; *b* – 1* – $R_t = f(V_b)$, 2* – $T_2 = f(V_b)$, 3* – $C = f(V_b)$, where V_b is the speed of belt motion, R_t – radius of the belt rolled into a tube, T_2 – belt service life, C – cost of transporting a ton of cargo



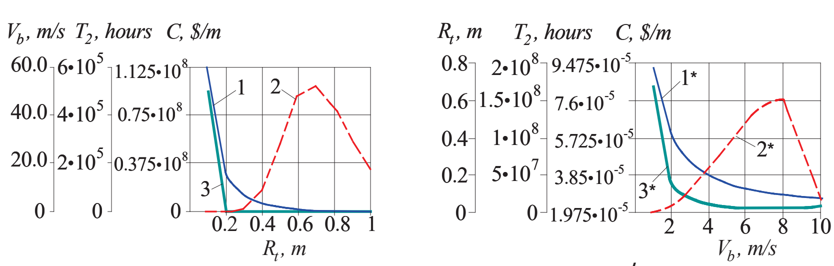
a *b*

Fig. 4. Charts of change when transporting a lump cargo at a belt tubular conveyor productivity of $Q_c = 430$ m^3/hour: *a* – 1 – $V_b = f(R_t)$, 2 – $T_2 = f(R_t)$, 3 – $C = f(R_t)$; *b* – 1* – $R_t = f(V_b)$, 2* – $T_2 = f(V_b)$, 3* – $C = f(V_b)$



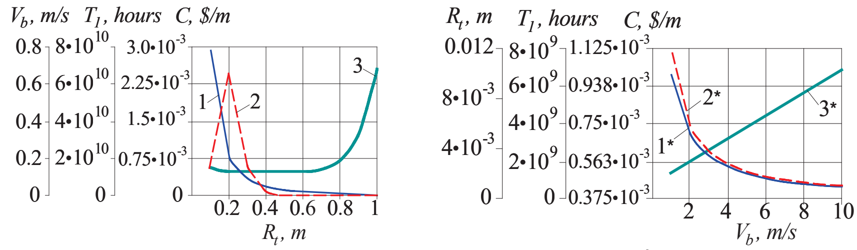
a *b*

Fig. 5. Charts of change when transporting a lump cargo at a belt tubular conveyor productivity of $Q_c = 1{,}300$ m^3/hour: *a* – 1 – $V_b = f(R_t)$, 2 – $T_2 = f(R_t)$, 3 – $C = f(R_t)$; *b* – 1* – $R_t = f(V_b)$, 2* – $T_2 = f(V_b)$, 3* – $C = f(V_b)$



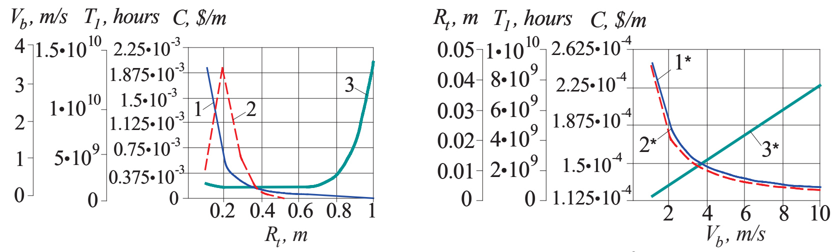
a *b*

Fig. 6. Charts of change when transporting a lump cargo at a belt tubular conveyor productivity of $Q_c = 7{,}300$ m^3/hour: *a* – 1 – $V_b = f(R_t)$, 2 – $T_2 = f(R_t)$, 3 – $C = f(R_t)$; *b* – 1* – $R_t = f(V_b)$, 2* – $T_2 = f(V_b)$, 3* – $C = f(V_b)$



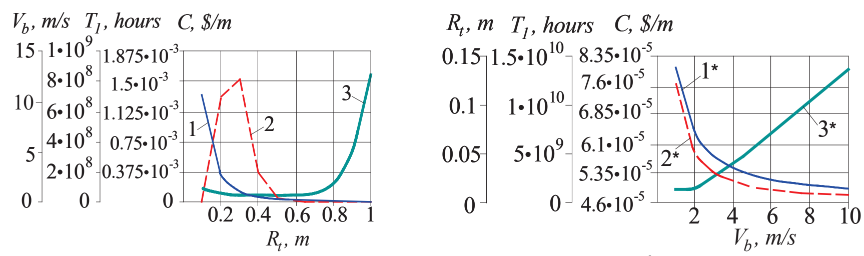
a b

Fig. 7. Charts of change when transporting a loose cargo at a belt tubular conveyor productivity of $Q_c = 95$ m^3/hour: a – 1 – $V_b = f(R_t)$, 2 – $T_1 = f(R_t)$, 3 – $C = f(R_t)$; b – 1* – $R_t = f(V_b)$, 2* – $T_1 = f(V_b)$, 3* – $C = f(V_b)$



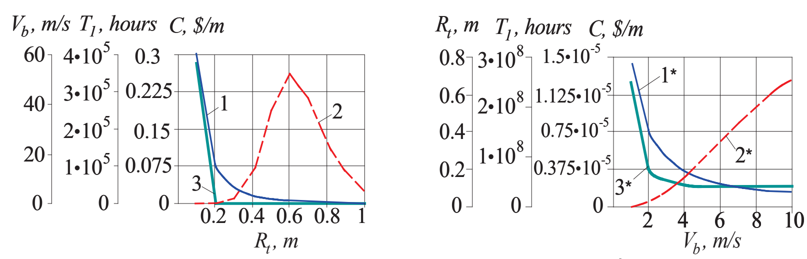
a b

Fig. 8. Charts of change when transporting a loose cargo at a belt tubular conveyor productivity of $Q_c = 430$ m^3/hour: a – 1 – $V_b = f(R_t)$, 2 – $T_1 = f(R_t)$, 3 – $C = f(R_t)$; b – 1* – $R_t = f(V_b)$, 2* – $T_1 = f(V_b)$, 3* – $C = f(V_b)$



a b

Fig. 9. Charts of change when transporting a loose cargo at a belt tubular conveyor productivity of $Q_c = 1{,}300$ m^3/hour: a – 1 – $V_b = f(R_t)$, 2 – $T_1 = f(R_t)$, 3 – $C = f(R_t)$; b – 1* – $R_t = f(V_b)$, 2* – $T_1 = f(V_b)$, 3* – $C = f(V_b)$



a b

Fig. 10. Charts of change when transporting a loose cargo at a belt tubular conveyor productivity of $Q_c = 7{,}300$ m^3/hour: a – 1 – $V_b = f(R_t)$, 2 – $T_1 = f(R_t)$, 3 – $C = f(R_t)$; b – 1* – $R_t = f(V_b)$, 2* – $T_1 = f(V_b)$, 3* – $C = f(V_b)$

By analyzing the charts denoted by positions 3 and 3* we determine at which values of the radius and the belt motion speed the cost of transporting a ton of cargo is minimal. When selecting the optimal parameters, one should consider the charts denoted by positions 1 and 1* since a parameter for the speed of belt motion and a parameter for the radius of a tubular belt are related by an inversely proportional dependence.

Regarding the actual calculation at a conveyor productivity of:

– 95 m^3/hour: recommended – $V_b = 1{,}0 \div 1{,}5$ m/s, $R_t = 0.15 \div 0.075$ m;

– 430 m^3/hour: recommended – $V_b = 1.5 \div 2.0$ m/s, $R_t = 0.2 \div 0.15$ m;

– 1300 m^3/hour: recommended – $V_b = 2.0 \div 2.5$ m/s, $R_t = 0.3 \div 0.2$ m;

– 7300 m^3/hour: recommended – $V_b = 5.0 \div 6.0$ m/s, $R_t = 0.45 \div 0.3$ m.

7. Discussion of results of studying the parameters of belt tubular conveyors that affect a belt service time

The results of present research include the development of a procedure for determining the optimal parameters of a belt tubular conveyor based on the economic criterion, which takes into consideration belt durability. This is a fundamentally new result. We have investigated the mean cost of transporting a ton of cargo over the entire lifetime of a tubular conveyor. We have shown a possibility to design parameters of a tubular conveyor at which average cost of transporting a ton of cargo over the entire period of conveyor operation would be minimal.

Correctness of the chosen procedure for determining the optimal parameters of a belt tubular conveyor is confirmed by the parameters, specified in papers [1, 2, 15, 16], provided by manufacturers from Germany, France, Italy, Great Britain, India, the United States, South Korea and others. The obtained optimal parameters reflect the same dynamics of the growth of values of speed and radius of the belt relative to productivity as the belt tubular conveyors' parameters given in the above studies.

The research performed is continuation of the previously conducted studies into durability of a conveyor belt whose tubular cross-section is not fully filled with a cargo (Fig. 1) [11].

The next stage of research could be the development of and research into a mathematical model of the belt durability, vertical or steeply inclined conveyors whose tubular cross-section is filled with material to the full. Upon the development of a mathematical model it would be possible to determine the optimal parameters for a vertical or a steeply inclined conveyor based on the economic indicator – the cost of transporting a ton of cargo. Thus, the results reported here could only be used for a conveyor with an incomplete filling of the intersection of a belt tube (Fig. 1).

When conducting research, we assumed that the full lifespan of a tubular conveyor determines a service life of the belt; that does not take into consideration possible failures of a mechanical system and metal parts of a conveyor. However, at strict execution of the factory instruction for operation of the conveyor such failures seem unlikely.

The results of the cost of transporting a ton of cargo were approximated during economic calculations and have been obtained relative to the prices of Ukraine at the rate of exchange as of May 05, 2018, so they require clarification.

8. Conclusions

1. We have established parameters for a belt tubular conveyor, which affect the term of service of the belt and which can be altered in proportion at the stage of design, specifically the radius and the speed of belt motion.

2. We have obtained dependences to determine the minimum magnitude of the cost of transporting a cargo, which take into consideration the durability of the belt, capital and operating costs over the entire service life of the tubular conveyor.

3. We have developed a procedure for determining the optimal radius and the speed of belt motion for a designed tubular conveyor. Applying the dependences derived, we constructed charts of change in the cost of transporting a cargo depending on the radius and the speed of belt motion. Analysis of the charts has allowed us to propose the radius and the speed of belt motion for a designed conveyor under different operating conditions at which the cost of cargo transportation would be minimal.

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