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THEORETICAL FOUNDATIONS FOR IMPROVING THE EFFICIENCY OF POTATO HEAP SEPARATION BY A ROD-TYPE CONVEYOR

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ABSTRACT

The article develops the theoretical foundations of the process of separating potato heap on the web of a rod-type conveyor with tandem rods that form depressions. Such local depressions additionally capture a certain volume of the heap, thereby increasing the conveying and separating capacity of the conveyor. A mathematical model is proposed that takes into account the geometric parameters of the depression, the thickness and state of the heap layer, the speed of the web, the angles of inclination of individual conveyor sections to the horizontal, and the process of restructuring of the heap layer at the boundary of their transition.

To describe the operation of the new conveyor design, coefficients of volumetric soil loosening and conveying capacity were introduced. The model shows that such depressions provide local loosening, redistribution of components between layers, intensification of mixing, and an increased probability of fine particles passing through the gaps between the rods. On the basis of a kinetic approach, analytical dependencies were obtained for determining a number of indicators, in particular, the residual soil mass in the potato heap, the separation coefficient, etc.

Based on the results of the numerical experiment, it was established that increasing the layer thickness from the average value of 0.12 m to 0.16 m leads to a decrease in the coefficients of volumetric loosening and conveying capacity, as well as a reduction in separation intensity. Increasing the conveyor inclination angle to 30° raises the separation intensity by 26.8%, while the separation coefficient increases by 10.5%. Increasing the depression depth from 0.015 to 0.03 m raises the volumetric loosening coefficient by 38.5% and the conveying capacity by 33.3%. It was established that the use of a web with tandem rods increases the separation coefficient by 50-90% compared with a traditional rod-type conveyor, depending on the speed mode of operation, and reduces the residual soil contamination of the potato heap.

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ТЕОРЕТИЧНІ ОСНОВИ ПІДВИЩЕННЯ ЕФЕКТИВНОСТІ СЕПАРАЦІЇ КАРТОПЛЯНОГО ВОРОХУ ПРУТКОВИМ ТРАНСПОРТЕРОМ

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АНОТАЦІЯ

У статті розроблено теоретичні основи процесу сепарації картопляного вороху на полотні пруткового транспортера, який має тандемні прутки, що утворюють западини. Такі локальні западини додатково захоплюють визначений об'єм вороху чим підвищують транспортуючу та сепарувальну здатність транспортера. Запропоновано математичну модель, яка враховує геометричні параметри западини, товщину та стан шару вороху, швидкість руху полотна, кути встановлення окремих ділянок транспортера до горизонту та процес перебудови шару вороху на межі їх переходу.

Для опису роботи нової конструкції транспортера введено коефіцієнти об'ємного розпушування ґрунту та транспортуючої здатності. У моделі показано, що такі западини забезпечують локальне розпушування, перерозподіл компонентів між шарами, інтенсифікацію перемішування та ймовірність проходження дрібних частинок у проміжках між прутками. На основі кінетичного підходу отримано аналітичні залежності для визначення ряду показників, зокрема, визначення залишкової маси ґрунту у картопляному воросі, коефіцієнта сепарації тощо.

За результатами числового експерименту встановлено, що збільшення товщини шару від середнього значення 0,12 м до 0,16 м призводить до зменшення коефіцієнтів об'ємного розпушування та транспортуючої здатності, а також зниження інтенсивності сепарації. Зростання кута встановлення транспортера до 30° підвищує інтенсивність сепарації на 26,8 %, тоді як коефіцієнт сепарації збільшується на 10,5 %. Збільшення глибини западини від 0,015 до 0,03 м підвищує коефіцієнт об'ємного розпушування на 38,5 %, а транспортуючу здатність на 33,3 %. Встановлено, що використання полотна з тандемними прутками забезпечує підвищення коефіцієнта сепарації порівняно з традиційним прутковим транспортером на 50-90 % залежно від швидкісного режиму роботи та зменшує залишкову засміченість картопляного вороху ґрунтом.

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BACKGROUND AND PROBLEM STATEMENT

The quality of potato heap separation is one of the determining indicators of potato harvester efficiency. This factor has a direct influence on the cleanliness and degree of damage of the harvested produce, the productivity of the potato harvesting unit, energy consumption, and the need for additional post-harvest operations. In most modern potato harvesters, the main separating and conveying working element is the rod-type conveyor.

The analysis of the literature indicates that the issue of high-quality separation of potato heap during harvesting with potato diggers has not been fully resolved. For example, in *(Li, Y. et al., 2022)*, the process of separating soil from tubers was investigated by simulating this process using specialized software. The authors established that the main influence on the separation process is exerted by the conveyor inclination angle, the linear speed of the conveyor, and the feed of the potato heap, expressed by its thickness. The outcome of this study is the optimization of all these parameters to obtain maximum separation efficiency while preserving the quality of the tubers and the productivity of the machine.

In *(Pan, Y. et al., 2025; Pan, Y. et al., 2026)*, the structural and kinematic parameters of a double-vibration separating conveyor were optimized, and high separation efficiency was achieved, with up to 98% of the soil component of the heap separated.

Other researchers in *(Issa, I. et al., 2025)* propose the design of a multi-stage separating conveyor for a potato harvester, in which several successive separation zones are used, which also generally demonstrates high efficiency in separating the components of the potato heap. The main adjustable parameters are the conveyor inclination angle and its linear speed.

Study *(Wei, Z. et al., 2019)* shows that the intensity of separation depends largely on the oscillation modes of the conveyor web on which the components of the heap are separated. At the same time, increased separation intensity has a direct effect on the degree of tuber damage.

An analysis of recent scientific works *(Bulgakov, V. et al., 2020; Hevko, R. B. et al., 2020; Hrushetskyi, S. M. et al., 2024; Hrushetskyi, S. M. et al., 2019; Ihnatiev, Y. et al., 2019; Xie, S. et al., 2024)* indicates that researchers are searching for optimal designs of separating elements and for the methods of heap separation themselves, substantiating rational modes of their operation and proposing additional elements to intensify separation. At the same time, the question of purposefully changing the geometry of the conveyor web itself, in order to create local zones for accumulating, mixing, and conveying the heap, remains insufficiently studied. In the known works, mathematical models that take into account the presence of local depressions on the conveyor web, which influence the loosening of the heap, the change in its layer thickness, the conveying capacity, and the separation kinetics, are practically absent.

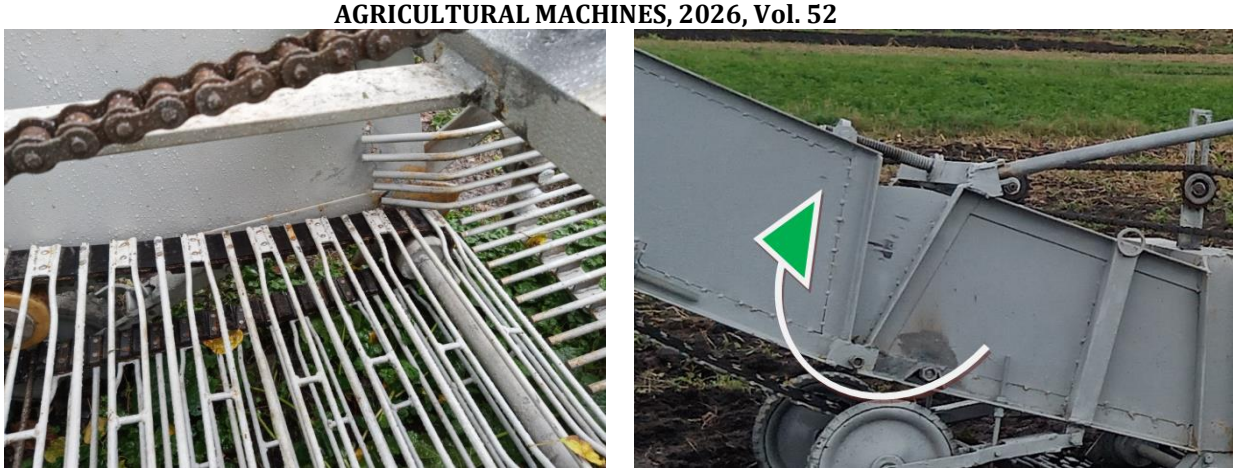
Thus, the scientific and applied problem of improving the efficiency of potato heap separation on a rod-type conveyor by changing the geometry of its web, without the use of additional devices for intensifying the screening of the potato heap components, remains only partially solved. The outlined problem requires both new design solutions and the construction of corresponding mathematical models that describe these processes.

The aim of the research is to develop a theoretical model of the operation of a rod-type conveyor with tandem rods and to establish the regularities of the influence of its structural and kinematic parameters on the conveying capacity and the efficiency of potato heap separation.

MATERIALS AND METHODS

One of the most significant criteria of potato harvester performance is the quality of potato heap separation. This technological operation in the potato harvesting process, especially with small potato diggers, determines the efficiency of the machine as a whole. The task is easily accomplished on separating devices that perform multi-stage separation in the designs of complex professional potato harvesters. The task is set so as to achieve maximum separation using the simplest devices, such as rod-type conveyors.

A new design of the rod-type conveyor web *(Boiko, V. et al., 2026)* was developed to accomplish the stated task. The distinctive feature of the design is that the web is formed by alternately attached one straight rod and two tandem curved rods, which form a depression on the web, Fig. 1, a. In addition, the design of the potato digger frame allows the conveyor to form two sections at different angles to the horizontal, Fig. 1, b.



a b

Fig. 1 – General view of the conveyor

The operation of such a conveyor is modeled below, and the influence of its structural and kinematic parameters on the conveying capacity and the efficiency of potato heap separation is established.

Consider the operating process of a conveyor-type potato digger according to the classical scheme: the share undercuts the tuber-bearing layer, which is partially separated already at this stage, and then it is transferred to the conveyor, where final separation takes place and the potatoes are deposited on the field surface.

Therefore, the tuber-bearing layer, or potato heap, is a heterogeneous multicomponent medium that must be divided into fractions. In general form, such a medium can be represented by the expression

$$\mathrm{M} = B \bigcup G \bigcup R, \tag{1}$$

where B – tubers;

G – soil component;

R – plant components.

The soil component should be represented by two components

$$G = G_1 + G_2, \tag{2}$$

where G_1 – soil clods;

G_2 – fine soil fraction.

To separate part of the soil fraction on the conveyor web, the following condition must be satisfied

$$d_G < s < d_B, \tag{3}$$

where s – effective inter-rod space;

d_G – dimensions of the soil components of the heap;

d_B – characteristic dimensions of the tubers.

The stated condition (3) is necessary but not sufficient. The separation process also depends on many factors: spatial orientation of particles, thickness of the potato heap, particle-particle interaction, residence time on the conveyor web, its geometry, kinematic operating mode, etc.

A particular feature of the presented conveyor design is the presence of tandem rods that form a depression on the web.

The directions of the coordinate axes are adopted as follows:

x – the coordinate along the direction of motion of the conveyor branch;

y – the coordinate in the plane of the conveyor web, perpendicular to the direction of motion;

z – the coordinate perpendicular to the plane of the conveyor web.

To describe the conveyor surface analytically, the discrete system of rods will be replaced, with a certain approximation, by a smooth enveloping surface that serves as the support for the potato heap.

The local coordinate ξ is introduced for the depression, and the curvature of the depression, with width l_z and depth h_z, is described using an approximating function of the form

$$z_t(\xi) = -\frac{h_z}{2}\left[1 - \cos\left(\frac{2\pi\xi}{l_z}\right)\right],\ 0 \le \xi \le l_z\,. \tag{4}$$

In general, for the *i*-th section of the conveyor web, its inclination can be taken into account by the dependence

$$z_{\alpha,i} = x\tan\alpha_i\,, \tag{5}$$

where α_i – the angle of inclination to the horizontal of the *i*-th section of the web.

Then the position of the local working surface will be determined by the coordinate

$$z_i(x) = x\tan\alpha_i + z_t(x)\,. \tag{6}$$

On the basis of dependence (6), the local coordinate of the conveyor web element is obtained, which takes into account the angle to the horizontal of the entire web α_i and the position of the local depressions formed by the tandem rods.

The geometry of the described depression, in comparison with the classical design of the conveyor web, forms an additional volume that is filled as the heap slides down into the depression.

The formed volume can be represented by the dependence

$$\Delta V = B_t h_z l_z\,, \tag{7}$$

where B_t – the width of the conveyor.

The following effects can be observed here: redistribution of particles between layers; local mixing of components; loosening of compacted layers; additional screening of fine particles; and more reliable capture and conveying of particles that have not been screened out.

When the tandem rods are placed on the conveyor web with a pitch p, the number of such depressions passing beneath the main layer of the potato heap per unit time will be

$$f_z = \frac{\vartheta}{p}\,. \tag{13}$$

That is, during 1 s, a total additional volume is formed under the heap layer

$$V_d = \Delta V\, f_z \ \text{ or } \ V_d = B_t h_z l_z \frac{\vartheta}{p}\,. \tag{14}$$

Then, on this basis, a dimensionless coefficient of volumetric loosening of the potato heap can be formed

$$K_V = 1 + k_V \frac{h_z l_z}{H\, p}\,, \tag{15}$$

where k_V – an empirical coefficient;

H – the current layer thickness.

In addition to the separating effect, the depressions perform the function of local conveying elements.

The mass of the heap that enters and is conveyed by the depression will be

$$m_z = \rho V_d \varphi_z , \tag{16}$$

where φ_z – the filling coefficient.

On the other hand, this is the additional conveying productivity

$$Q_z = m_z \frac{\vartheta}{p} . \tag{17}$$

To quantify this influence, a coefficient of conveying capacity is introduced

$$K_{tr} = 1 + k_{tr} \frac{h_z l_z}{H\, p} , \tag{18}$$

where k_{tr} – empirical coefficient of the depression effect on potato heap transportation.

An increase in the cross-sectional area of the depression leads to an increase in the local volume of the heap that can be captured and conveyed by the depression in a single pass.

If the continuity equation of the heap flow during steady motion of the machine is written as

$$q = \rho B u H , \tag{19}$$

where u – the average velocity of heap movement, $u = \vartheta K_{tr}$.

On this basis, the change in the heap layer thickness will be determined by the dependence

$$H = \frac{q}{\rho B\, \vartheta K_{tr}} . \tag{20}$$

From the analysis of dependence (20), it can be seen that as the conveying capacity of the depressions increases, the layer thickness decreases. The resulting effect has a positive influence on improving the separation parameters of the potato heap.

The conveying capacity coefficient influences the separation intensity both directly, through additional mixing of the heap, and indirectly, through a reduction in the average thickness of the layer.

Another factor ensuring effective separation of the potato heap is the installation angle of the conveyor web. For the presented design, there are two independent sections at which the conveyor web is set at an angle to the horizontal.

Consider the behavior of a particle of mass m on the inclined plane of the conveyor: it is acted upon by the force of gravity $G = mg$, which can accordingly be resolved into normal and tangential components.

This condition is written in expanded form as

$$\mu mg \cos\alpha_i \geq mg \sin\alpha_i , \tag{21}$$

where μ – the averaged coefficient of friction.

It follows from this that $\mu \geq \tan\alpha_i$.

The limiting value of the angle

$$\alpha_b = \arctan \mu . \tag{22}$$

The obtained value of the limiting angle of elevation of the conveyor web is approximate, since the layer of potato heap is multicomponent and determining the numerical value of the averaged coefficient of friction requires experimental refinement. In addition, the existing depressions increase the conveying capacity of the web. This is a factor that makes it possible to increase the limiting value of the installation angle of the conveyor web sections.

The expected effect of a change in the angle α_2 on the second section is considered in more detail below.

On the second section of the conveyor, the potato heap is already partially separated, that is, the masses of the heap are $M_{G_2} < M_{G_1}$. A decrease in the average thickness of the layer can be expected here. If the condition $\alpha_2 > \alpha_1$, was set previously, the normal component of the self-weight decreases accordingly, $mg\cos\alpha_2 < mg\cos\alpha_1$, but at the same time the tangential component increases, $mg\sin\alpha_2 > mg\sin\alpha_1$. The latter factor increases the probability of backward movement of the heap components down the web. This effect can be used to increase the residence time of the heap on the conveyor and to conditionally increase the path of relative sliding in order to improve separation. It must also be taken into account that the angle α_2 is an adjustable parameter, and therefore it can be selected as optimal for the specific operating conditions of the conveyor.

Developing this research further, one more effect of using such a conveyor, which contains two sections at different angles to the horizontal, can be traced. This effect is observed at the boundary of the transition between the two sections, where $\alpha_1 \to \alpha_2$ and restructuring of the soil layer takes place.

Denote: $\Delta\alpha = \alpha_2 - \alpha_1$. With the same web velocity, the change in the direction of the mass motion vector has a characteristic magnitude, and the restructuring of the soil layer takes place here.

To identify the expected effect, the following coefficient is applied

$$K_\Delta = 1 + k_\Delta \sin^2\left(\frac{\Delta\alpha}{2}\right), \tag{23}$$

where k_Δ – the coefficient of intensity of the restructuring of the heap layer at the junction of the two conveyor sections.

Each of the stated factors must have its own optimal value, which ultimately leads to maximum separation of the potato heap on the conveyor web.

We now proceed to formulate the separation kinetics model itself.

If $M_G(t)$ is denoted as the mass of the soil component remaining in the heap, then its separation, to a first approximation, can be described by the expression

$$\frac{dM_G}{dt} = -\lambda M_G , \tag{24}$$

where λ – the separation rate constant, s^{-1}.

Integrating expression (24), we obtain

$$M_G(t) = M_{G0} e^{-\lambda t} , \tag{25}$$

where M_{G0} – the initial mass of the soil.

Then the separation coefficient is

$$\eta = 1 - e^{-\lambda t}. \tag{26}$$

It is advisable to determine the separation coefficient at each stage.

On the first section we have

$$\eta_1 = 1 - \exp\left(-\lambda_1 \frac{L_1}{u_1}\right), \tag{27}$$

the mass of soil remaining after the first section

$$M_{G1} = M_{G0} \exp\left(-\lambda_1 \frac{L_1}{u_1}\right); \tag{28}$$

on the second section

$$M_{G2} = M_{G1} \exp\left(-\lambda_2 \frac{L_2}{u_2}\right). \tag{29}$$

Or the residual soil mass after the two separation sections can be represented by a single expression

$$M_{G2} = M_{G0} \exp\left(-\left(\lambda_1 \frac{L_1}{u_1} + \lambda_2 \frac{L_2}{u_2}\right)\right). \tag{30}$$

The total separation coefficient will be

$$\eta_\Sigma = 1 - \exp\left(-\left(\lambda_1 \frac{L_1}{u_1} + \lambda_2 \frac{L_2}{u_2}\right)\right). \tag{31}$$

Analyzing expressions (27) – (31), we come to the conclusion that the separation intensity λ_i cannot be a constant characteristic of the conveyor.

The following model is proposed

$$\lambda_i = \lambda_0 K_s K_H K_{\alpha,i} K_V K_{tr} K_\Delta K_W, \tag{32}$$

where λ_0 – the base separation intensity, corresponding to the separation intensity of a classical conveyor;

K_s – the coefficient characterizing the geometric permeability of the web;

K_H – the coefficient of the influence of layer thickness;

$K_{\alpha,i}$ – the coefficient of the influence of the installation angles of the sections;

K_V – the coefficient of volumetric loosening;

K_{tr} – the coefficient of conveying capacity;

K_Δ – the coefficient of the influence of the transition between sections;

K_W – the coefficient of the influence of soil moisture and condition.

The expression for the coefficient K_s is represented as follows

$$K_s = \left(\frac{s}{d_G}\right)^n, \ 0 < n < 1.$$

The expression for the separation intensity λ_i is rewritten in expanded form

$$\lambda_i = \lambda_0 \left(\frac{s}{d_G}\right)^n e^{-k_H \frac{H_i}{H_0}} (1 + k_\alpha \sin\alpha_i) \left(1 + k_V \frac{h_z l_z}{H\, p}\right) \left(+ k_{tr} \frac{h_z l_z}{H\, p}\right) \left(1 + k_\Delta \sin^2\left(\frac{\Delta\alpha}{2}\right)\right) K_W, \qquad (33)$$

where H_0 – the normalized layer thickness.

RESULTS AND DISCUSSION

To evaluate the efficiency of the new conveyor design, a numerical experiment is conducted with the following main initial data:

length of the first conveyor section – $L_1 = 1.2$ m; length of the second section – $L_2 = 0.8$ m; conveyor width – $B = 0.5$ m; depression width – $l_z = 0.08$ m; depression depth – $h_z = 0.015$ m; pitch of the depressions on the conveyor web – $p = 0.12$ m; minimum thickness of the heap layer – $H = 0.08$ m.

The numerical values of the empirical coefficients k_V, k_{tr}, k_Δ are adopted on the basis of preliminary estimates and will be refined in further laboratory and field experiments.

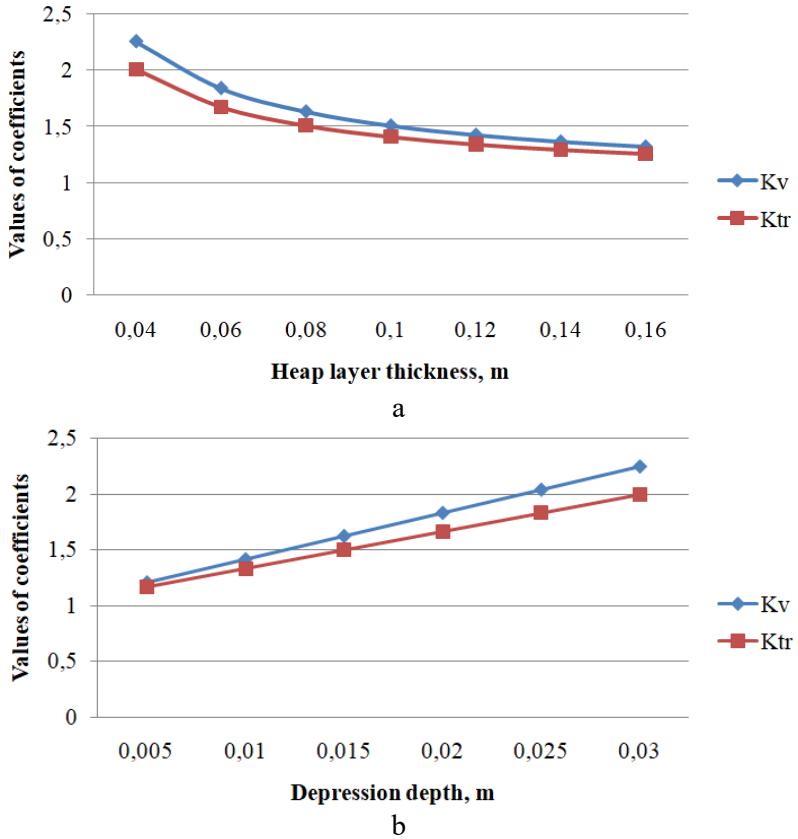


Fig. 2 – Graphical dependencies of the coefficients of volumetric loosening K_V and conveying capacity K_{tr} on the heap layer thickness (a) and the depression depth (b)

The graphical dependencies presented in Fig. 2, a demonstrate clearly defined trends: an increase in the

thickness of the heap on the conveyor web reduces the values of the coefficients of volumetric loosening and conveying capacity. This relative decrease in the specified indicators is expected, since as the heap thickness on the conveyor web increases, the specific share of the volume of the depression formed by the tandem rods decreases. At the same time, Fig. 2, b shows the opposite trend: the depression depth increases the values of these coefficients, since the volume of the depression itself increases, which leads to an increase in its capturing capacity. It should be understood here that the limits on increasing the depression depth are determined by the structural design of the conveyor itself.

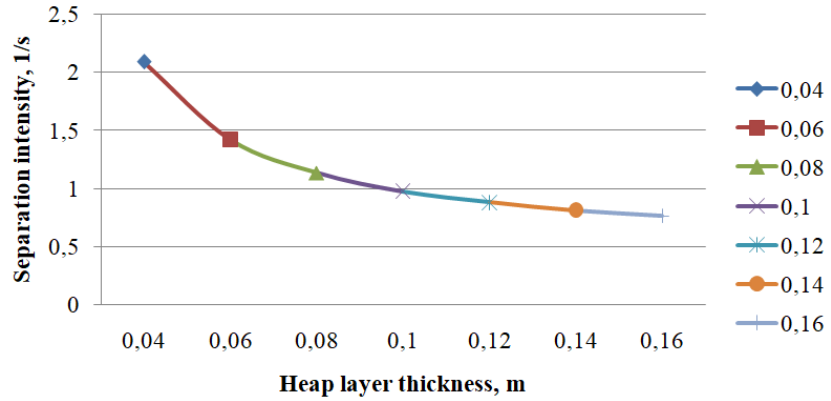


Fig. 3 – Dependence of the separation intensity coefficient on the heap layer thickness

The graphical dependence presented in Fig. 3 shows an expected trend, expressed as a decrease in the separation intensity coefficient λ_i as the heap layer thickness increases.

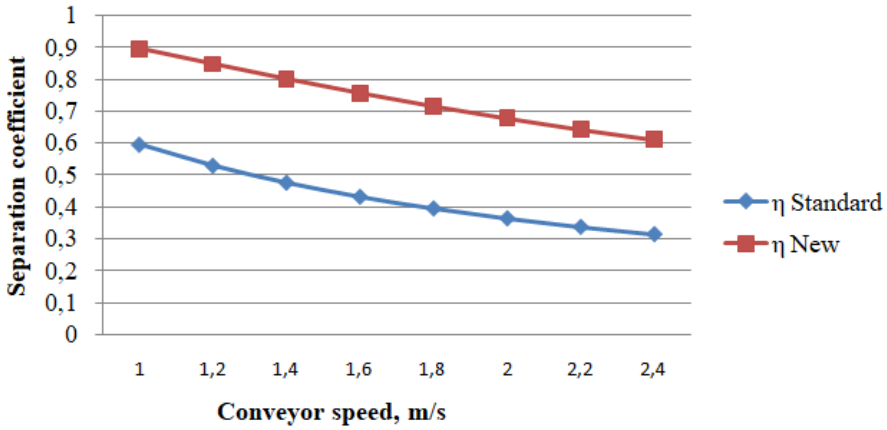


Fig. 4 – Dependence of the separation coefficient on the conveyor speed

When comparing the dependences of the separation coefficients on the conveyor speed for the base design (standard), that is, with straight rods, and for the developed design (new), which contains tandem rods forming a depression on the web, the new design shows a significantly higher value, all other conditions being equal, Fig. 4. At conveyor speeds ranging from 1 m/s to 2.4 m/s, the separation coefficient on the web with depressions is 50%-90% higher than for the base design.

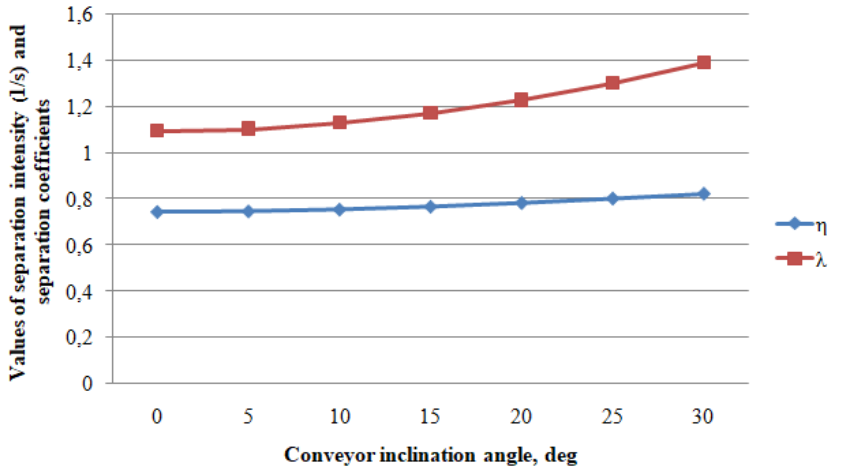


Fig. 5 – Dependences of the separation intensity and separation coefficients on the conveyor web installation angle

Analyzing the angle at which the sections of the conveyor web are set to the horizontal, which influences the separation intensity and the separation coefficient, the following trend is observed (Fig. 5): as the installation angle increases, the separation intensity rises markedly, while the separation coefficient also rises, but only slightly. The limitation on the installation angle of the conveyor web to the horizontal is, first of all, the loss of its conveying capacity: tubers and clods roll off the web in the reverse direction. At a large installation angle of the conveyor, the effective width of the gaps between the rods, through which the fine fractions of the potato heap must pass, decrease.

Since the installation angle of the conveyor and its linear speed are the main adjustable parameters, the influence of the conveyor web speed on the relative residual soil contamination of the potato heap is analyzed, Fig. 6.

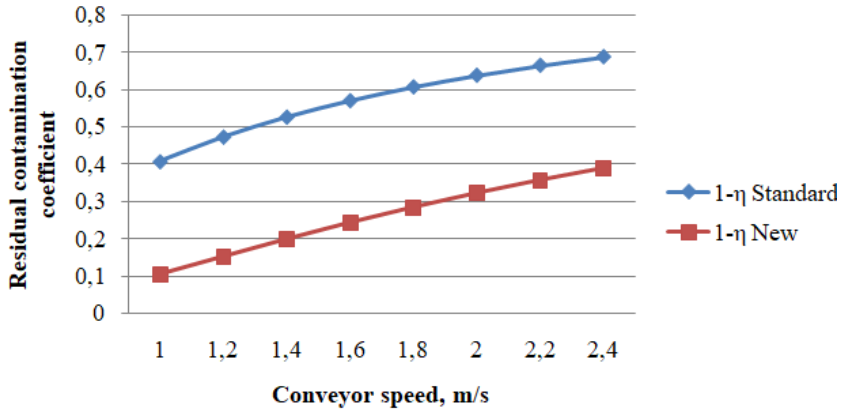


Fig. 6 – Dependence of the residual soil contamination coefficient on the conveyor speed

The graphical dependences presented in Fig. 6 are the inverse of the results for the separation coefficient shown in Fig. 4. Comparing the two conveyor designs, it is clearly seen that the new conveyor design is considerably more effective than the base design at different kinematic operating modes. For example, at a conveyor speed of 1 m/s, the contamination is 40.6% for the base design and 10.4% for the improved one. As the conveyor speed increases, the residual contamination grows, but the separation efficiency of the new design remains proportionally higher.

CONCLUSIONS

Based on the developed theory describing the main parameters of the rod-type conveyor of a potato harvester, the following has been established. The thickness of the potato heap layer in the range from 0.08 m to 0.16 m has a significant influence on the coefficient of volumetric loosening, which decreases by 22% as the layer thickness increases; a similar trend is observed for the conveying capacity coefficient, which

decreases by 18.8%. Here, the comparative reference is taken from the average layer thickness of 0.12 m. When comparing the separation intensity of the potato heap for the base and new conveyor designs, as the layer thickness increases, this coefficient decreases by 42.2% for the base design and by only 21.5% for the new one.

The installation angle of the conveyor web to the horizontal, from 0° to 30°, increases the separation intensity of the potato heap by 26.8%; at the same time, the separation coefficient increases by only 10.5%.

An increase in the depression depth has a significant influence on the coefficient of volumetric loosening, which increases by 38.5% when the depression depth increases from 0.015 m to 0.03 m; the conveying capacity coefficient increases by 33.3% under the same conditions.

Increasing the conveyor speed generally reduces both the separation intensity and the separation coefficient itself. This is due to the reduction in the residence time of the layer on the conveyor web.

Thus, the main dependences were obtained, on the basis of which the numerical values of the key operating parameters of the conveyor were found and the regularities of their variation were established. The described theory is the basis for finding the optimal values of the structural and kinematic parameters of the new conveyor design.

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