RESEARCH ON SEED SEPARATION PROCESS ON A GRAVITY-CASCADE SEPARATOR
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ДОСЛІДЖЕННЯ ПРОЦЕСУ СЕПАРУВАННЯ НАСІННЯ НА СЕПАРАТОРІ ГРАВІТАЦІЙНО-КАСКАДНОГО ТИПУ

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ABSTRACT
Different designs of separators are used for separating seeds. The principle of separator operation is based on various physical, mechanical and aerodynamic properties of seeds. Gravitational separators are promising because energy is not spent on separation process in this type of separators. A gravity-cascade separator was proposed, in which the separator sections are connected like “scissors”. The sieve length was theoretically justified, taking into account the condition for passing a small fraction of seeds into the sieve holes. The influence of sieves tilt angle and seed flow rate from hopper on the quality index of separation process was studied experimentally.

АНОТАЦІЯ
Для сепарування насіння використовуються різні конструкції сепараторів. Принцип роботи сепараторів заснований на різних фізико-механічних та аеродинамічних властивостях насіння. Перспективними є гравітаційні сепаратори, оскільки в них енергія не витрачається на процес сепарування. Був запропонований сепаратор гравітаційно-каскадного типу, в якому сепарувальні секції з’єднані по типу “ножиці”. У статті теоретично обґрунтована довжина решета сепаратора із урахуванням умови проходження дрібної фракції насіння в отвори решета. Також експериментально досліджено вплив кута нахилу решіт та подачі насіння з бункера на показник якості процесу сепарування.

INTRODUCTION
After harvesting crops, the collected seed mass is cleared of impurities, and the seeds are separated into fractions by size. Technological processes of separation and cleaning seeds are extremely important *(Dong et al., 2013; Wang et al., 2017)*, since seed quality and cost depend on these processes. The seed separation and cleaning processes are carried out on separators of various types *(Kugbei et al., 2018)*: air-screen cleaner, grader, horizontal and vertical screen cylinders, indent disk separator, indent cylinder separator, gravity separator, air separator, velvet roll separator, spiral separator, magnetic separator, vibrator separator, electrostatic separator, fluidized bed separator and colour separator. In addition, engineers and scientists have developed original designs of seed separators, such as separating conveyor *(Vasylkovskyi et al., 2019)*, belt-type electrostatic separator *(Basiry and Esehaghbeygi, 2012)*, solar grain separator machine *(Nagesh and Lakshminarasimhan, 2014)*, pneumatic separator *(Panasiewicz et al., 2012)* and universal air-screen seed cleaner *(Giyevskiy et al., 2018)*.

Seed separators differ in the principle of operation. The separator design is conditioned by a large number of factors, in particular, the physical-mechanical and aerodynamic properties of the seed mass, the level of cleaning accuracy, efficiency of a technological line *(Panasiewicz et al., 2012)*. The seed separation process occurs according to the physical and mechanical properties of the components of seed mass *(Bracacescu et al., 2016)*: seed size (length, width, and thickness), mass, shape, density, surface texture, electrical conductivity, humidity, colour, aerodynamic properties *(Li et al., 2002; Voicu et al., 2008)*. The operation principle of the most common seed separators provides the separation of seed mass by size and aerodynamic properties of the mass components. According to the seeds shape and size, seeds are separated by sieves with round or oblong holes *(Badretdinov et al., 2020)*. Also, sieves with a different shape of holes are used in agricultural industry. The aerodynamic properties of seed mass components are used when using the airflow to separate light impurities from the seeds.

To describe the seed separation process, scientists use a method of mathematical modelling, which allows us to better understand the complex flow of seed mass particles on the sieve and optimize the sieve parameters *(Wang et al., 2017)*. Most mathematical models of the separation process are phenomenological models *(Dong et al., 2009)*. Also, discrete element method (DEM) is widely used for modelling the separation process of bulk materials (seed mass) and justifying the operation mode of the separator *(Chen and Tong, 2009; Zhao et al., 2011)*. This method gives results, which are in good agreement with experimental data *(Dong et al., 2013)* and allow us to simulate the separation process of bulk materials with spherical and non-spherical particles *(Delaney et al., 2012; Kruggel-Emden and Elskamp, 2014)*. While using this method, it is established that one of the most influential factors in the separation process is height of the bulk material layer on the sieve *(Li et al., 2002)*. The height of the seed layer on the sieve depends on the seed flow rate from the hopper. The flow rate depends on the unloading velocity of the seed mass and the area of the hopper unloading orifice. In addition to the physical and mechanical seeds properties, the hopper geometry has a significant impact on the flow rate of seed mass during hopper unloading *(Albaraki and Antony, 2014)*. To determine the flow rate of bulk materials in different parts of the hopper during unloading, scientists use a simulation method. This method allows us to determine the dependence of the flow rate of bulk material on hopper opening angle and orifice size *(Magalhaes et al., 2016)*. DEM is also used to determine the flow rate of bulk materials at the unloading orifice of various shaped hoppers (plane-wedged hopper, space-wedged hopper, and flat-bottomed hopper) *(Balevicius et al., 2011)*. The velocity of bulk material unloading from the hopper side orifice can be calculated according to the equation *(Sergeev and Nicolaev, 2010)*:

$$V_0 = \lambda \sin\varepsilon \sqrt{2g\left(2.1R - \frac{3.4\Theta_0}{\rho g}\right)} \tag{1}$$

where:

V_0 – velocity of bulk material flow at the hopper unloading orifice, m·s^{-1}; λ – coefficient of bulk material outflow; ε – tilt angle of the hopper bottom, rad; R – hydraulic radius ($R = F/L_p$), m; Θ_0 – initial shear resistance, Pa; ρ – bulk material density, kg·m^{-3}; g – gravitational acceleration, m·s^{-2}; F – area of the unloading orifice, m^2; L_p – perimeter of the unloading orifice, m.

Reducing energy consumption for the seed separation process is the main direction of developing new designs of seed separators. Gravity separators are the most promising in this direction, since these separators do not spend energy directly on the separation process, but only on loading and/or dosing of the seed mass. In gravity separators, the movement of the seed mass on the working surfaces is due to the forces of gravity, which act on the particles of the seed mass. Thus, studies that provide justification for the parameters of a new design gravity separator, in which the separation process occurs without energy consumption, are relevant. Therefore, the research purpose is to study the seed separation process on a gravity-cascade separator and substantiate its parameters.

MATERIALS AND METHODS

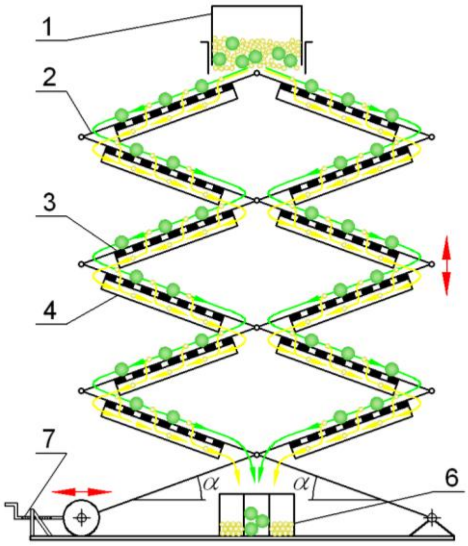
The study of the seed mass separation process took place on an experimental gravity-cascade separator. The separator contains a seed mass hopper, seed fractions containers and system of separation sections that are connected crosswise (like “scissors") (fig. 1, a). Flat sieves and pallets are located on the frames of the separation sections. The seed fractions gutters are located at the end of each sieve and pallet. The gutters direct seed fractions to the beginning of the next sieve or pallet, which are located below. The screw-nut transmission is connected to the lower separation section, which makes it possible to adjust the tilt angle *α* of the sieves and pallets.

Separating of vetch (*Vicia sativa*) seeds into two fractions (a large fraction with a seed size > 4 mm; a small fraction with a seed size ≤ 4 mm) was experimentally studied on the proposed separator. Sieves with round holes with a diameter of 4 mm were used for separating the vetch. Characteristics of separator sieves are sieve width 0.15 m, sieve length 0.2 m, sieve area 0.03 m^2, and area of all sieves 0.36 m^2. The study of the vetch separation process was carried out using the two-factor experiment method (*Montgomery, 2017)*. The study involved determining the quality index of vetch separation process μ_s depending on the tilt angle α of the sieves and the flow rate Q of vetch seeds from the hopper.

Experiments were performed for the following cases: 1) the seed mass was separated with two sieves (total sieves length was $2L_s$ = 0.4 m); 2) the seed mass was separated with four separator sieves (total sieves length was $4L_s$ = 0.8 m); 3) the seed mass was separated with six sieves (total sieves length was $6L_s$ = 1.2 m). The single sieve length (L_s = 0.2 m) was determined depending on the maximum allowable length *S* of the sieve. According to the method *(Sologubik et al., 2013),* a study on the friction angle φ of vetch seeds on a steel surface was carried out to justify the range of sieve tilt angle variation. Also, the static coefficient of friction was calculated based on the results of this study $f = \text{tg}(\varphi) = \text{tg}(0.331) = 0.344$.

The interval of variation of the sieve tilt angle α = 0.349…0.419 rad was justified taking into account the results of vetch seed friction angle study. All experiments were conducted for the vetch seed moisture content W = 14%, which was determined by the experimental method *(Sologubik et al., 2013)*.

The interval for varying the flow rate Q = 120…140 $kg \cdot h^{-1}$ of vetch seeds from the hopper was justified taking into account that the seed layer height on the sieve did not exceed two seeds.



a) b)

Fig. 1 - Gravity-cascade separator (a) and scheme of seed fractions flows (b)

1 – hopper; 2 – separator sections; 3 – sieve; 4 – pallet; 5 – gutters of seed fractions; 6 – containers; 7 – screw-nut transmission

During the study, a portion of vetch seeds weighing 1 kg was loaded into the separator hopper. After that, the hopper flaps were raised to the required height, which regulated the seed flow rate, and the vetch seeds were fed to the sieves of the upper separation sections. The vetch seeds moved through the separator in two separate symmetrical flows (fig. 1, b). The separated fractions of vetch seeds were fed to the seed fractions containers. Each vetch seed fraction was weighed after the separation process. Vetch seeds from a large fraction container were additionally sifted on a laboratory sieve with round holes with a diameter 4 mm using the sieve method of grain-size analysis *(Lopez, 2016)*. According to the results of such sifting, the mass of a small seed fraction, which was not separated by separator, was determined. According to the obtained data, the quality index of separation process was calculated:

$$\mu_s = \frac{m_{f1}}{m_{f1} + m_{f2}} \cdot 100\% \tag{2}$$

where: μ_s – quality index of separation process, %; m_{f1} – mass of small seed fraction, which was separated by separator, g; m_{f2} – mass of small seed fraction, which was not separated by separator, g.

RESULTS

The proposed gravity-cascade separator separates the seed mass into two fractions: a large one (in fig. 1, b and fig. 2, b the seed fraction is indicated in green), which does not pass into the sieve holes, and a small one (in fig. 1, b and fig. 2 the seed fraction is indicated in yellow), which passes into the sieve holes.

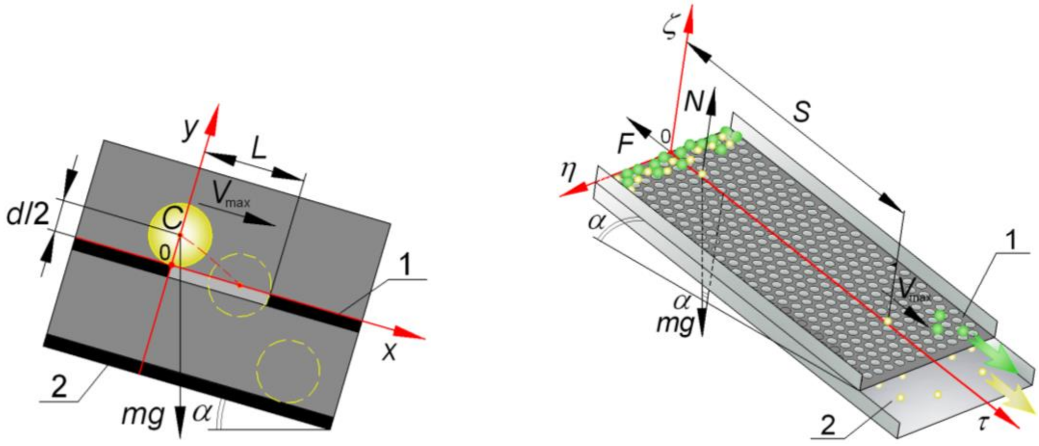
The most important factor, which determines the passage of seeds of small fraction into the sieve holes, is the velocity of seeds movement along the sieve. The probability of seed passing into the sieve holes decreases with increasing seed velocity. The seed velocity increases with increasing seed move path along the sieve and sieve tilt angle α.

Let the seed of small fraction have a spherical shape and diameter d, and its centre of gravity is centred at point C (the sphere centre). At the initial moment of passing into the sieve hole, the seed has a velocity V_{max}. The sieve hole length along the direction of seed movement is L ($L > d$). The length L is not greater than the size of seeds of large fraction. The sieve is fixed and installed at tilt angle α. The coordinate system xy is located as shown in fig. 2, a. The movement of seed of small fraction during its passage into the sieve hole can be described by equations:

$$\left.\begin{aligned} m\ddot{x} &= mg\sin\alpha; \\ m\ddot{y} &= -mg\cos\alpha, \end{aligned}\right\} \tag{3}$$

where: m – mass of small fraction, kg; $\ddot{x}$, $\ddot{y}$ – projections of seed acceleration on x and y axes, m·s^{-2};

g – gravitational acceleration, m·s^{-2}; α – sieve tilt angle, rad.



a) b)

Fig. 2 - Scheme of the passage of seed of small fraction into the sieve hole (a) and scheme of the movement of seed of small fraction along the sieve (b)

1 – sieve; 2 – pallet

The equations of the system (3) were integrated twice under the initial conditions: time t_0 = 0; the initial coordinates of the seed centre of gravity are $x_0 = 0$ and $y_0 = d/2$; the initial projections of the seed velocities along x and y axes are $\dot{x}_0 = V_{max}$ and $\dot{y}_0 = 0$. After integration, the following equations were obtained:

$$\left.\begin{aligned} x &= \frac{gt^2}{2}\cdot\sin\alpha + V_{max}t \\ y &= -\frac{gt^2}{2}\cdot\cos\alpha + \frac{d}{2} \end{aligned}\right\} \tag{4}$$

where:

x, y – coordinates of the seed centre of gravity C, m; d – seed diameter, m; t – time, s.

The seed of small fraction will pass into the sieve hole when the conditions $x \le L - (d/2)$ and $y \le 0$ for the coordinates of the seed centre of gravity C are implemented. Otherwise, the seed will not pass into the sieve hole and will be pushed out by the seed flow. From the second equation of the system (4), for the case $y = 0$, the time $t_{d/2}$ was determined by equation:

$$t_{d/2} = \sqrt{\frac{d}{g\cdot\cos\alpha}} \tag{5}$$

The time $t_{d/2}$ was used in the first equation of the system (4):

$$x = \frac{d}{2}\mathrm{tg}\alpha + V_{max}\sqrt{\frac{d}{g\cdot\cos\alpha}}\ . \tag{6}$$

If coordinate x obtained in equation (6) satisfies the condition $x \le L - (d/2)$, then the seed will pass into the sieve hole.

The extreme case ($x = L - (d/2)$) for the seed passage into the sieve hole will be considered below. For this case, after substituting $x = L - (d/2)$ in equation (6), an equation for determining the maximum allowable initial velocity of seed, after which the seed will pass into the sieve hole, was obtained:

$$V_{max}=\left(L-\frac{d}{2}(1+\mathrm{tg}\alpha)\right)\sqrt{\frac{g\cos\alpha}{d}} \tag{7}$$

where:

V_{max} – maximum allowable initial velocity of seed of small fraction, m·s^{-1}.

Let the seed mass flow with a height of one seed move down along the sieve. The movement of the small fraction seed selected from seed flow along the tilt sieve will be considered below (fig. 2, b). If the seed slides down a tilt sieve with the initial velocity V_0, then the equations of its movement in a fixed coordinate system $\tau\zeta\eta$ will have the form (the seed movement along the axis η does not occur (η = 0)):

$$\left.\begin{aligned} m\ddot{\tau}&=mg\sin\alpha-F\\ m\ddot{\zeta}&=-mg\cos\alpha+N\\ m\ddot{\eta}&=0\end{aligned}\right\} \tag{8}$$

where: m – mass of small fraction seed, kg; $\ddot{\tau}$, $\ddot{\zeta}$, $\ddot{\eta}$ – projections of seed acceleration on τ, ζ and η axis, m·s^{-2}; F – friction force, N; N – normal reaction of the sieve surface, N.

If the seed moves along the tilt sieve without leaving its surface ($\ddot{\zeta}$ = 0), then from the second equation of the system (8) the normal reaction of the sieve surface N and friction force F can be obtained:

$$N=mg\cos\alpha \tag{9}$$

$$F=fN=fmg\cos\alpha \tag{10}$$

where: f – static coefficient of friction.

After substituting equation (10) into the first equation of the system (8), the equation can be obtained:

$$\ddot{\tau}=g(\sin\alpha-f\cos\alpha) \tag{11}$$

The equation (11) was integrated twice under the initial conditions: time t_0 = 0; initial seed coordinate along the τ axis was τ_0 = 0; initial projection of the seed velocity along the τ axis was $\dot{\tau}_0=V_0$ (the velocity V_0 was calculated from the dependence (1)). After integration, the following equations were obtained:

$$\dot{\tau}=gt(\sin\alpha-f\cos\alpha)+V_0 \tag{12}$$

$$\tau=\frac{gt^2}{2}(\sin\alpha-f\cos\alpha)+V_0t \tag{13}$$

where: $\dot{\tau}$ – projection of the seed velocity on the τ axis, m·s^{-1}; τ – coordinate of the seed, m; t – time, s.

Let us define the time t_V, during which the seed, moving along the sieve down, reaches the velocity V_{max}. After substituting velocity $\dot{\tau}=V_{max}$ into the equation (12), the equation was obtained:

$$t_V=\frac{V_{max}-V_0}{g(\sin\alpha-f\cos\alpha)} \tag{14}$$

The move path S, which the small fraction seed will pass along the sieve during time t_V, can be determined by equation (13):

$$\tau=S=\frac{V_{max}^2-V_0^2}{2g(\sin\alpha-f\cos\alpha)} \tag{15}$$

where: S – path, which the seed of small fraction will pass along the sieve during time t_V, m.

Thus, the maximum sieve length of the proposed separator, on which it is possible to pass the seed into the sieve hole, is equal to S. To increase the sieve length S, on which the seed mass is separated, is possible by reducing the angles α and ε, as evidenced by the analysis of the graph (fig. 3). Complete separation of seed mass on the sieves of the gravity separator cannot always be provided by reducing the angles α and ε. Also, the slowing down of the seed mass on the separator sieves (reducing seed flow speed) improves the condition of seed mass separation. The slowing down of the seed mass can be achieved by design changes in the separator. In the proposed separator the sieves are arranged in a cascade, so the seed flow slowdown occurs at the stage of the transition of the seed flow from one sieve to another sieve, due to a change in the direction of the seed flow. In case of separating vetch seeds into two fractions, the maximum sieve length should be $L_s \le S$ = 0.203 m (the sieve length was calculated for the parameters: α = 0.349 rad, φ = 0.331 rad, ε = 0.349 rad, λ = 0.6, F = 7.5·10^{-4} m^2, L_p = 0.31 m, d = 1.2·10^{-3} m, L = 4·10^{-3} m).

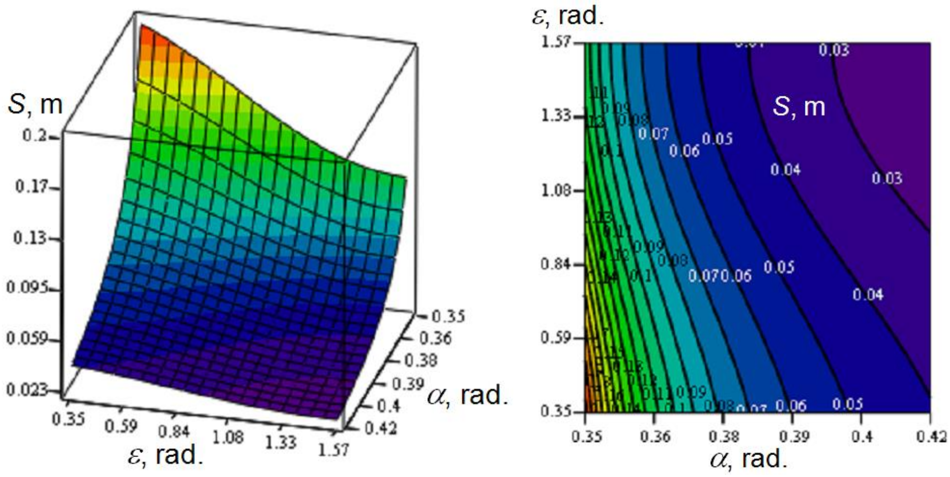


Fig. 3 - The maximum sieve length *S*, on which the separation of the seed mass is possible, depending on the angles α and ε

(f = 0.344, λ = 0.6, $F = 7.5 \cdot 10^{-4}$ m^2, L_p = 0.31 m, $d = 1.2 \cdot 10^{-3}$ m, $L = 4 \cdot 10^{-3}$ m)

The influence of the sieve tilt angle α and seed flow rate Q on the quality index of separation process μ_s of vetch seed was studied on the proposed gravity-cascade separator. According to the result of experimental study, equations were obtained for the following cases (fig. 4):

1) the seed mass was separated with two separator sieves ($2L_s$ = 0.4 m):

$$\mu_s = 161.81 - 185.71\alpha - 0.3Q \tag{16}$$

2) the seed mass was separated with four separator sieves ($4L_s$ = 0.8 m):

$$\mu_s = 200.97 - 195.23\alpha - 0.4Q \tag{17}$$

3) the seed mass was separated with six separator sieves ($6L_s$ = 1.2 m):

$$\mu_s = 176.78 - 140.48\alpha - 0.308Q \tag{18}$$

where:

μ_s – quality index of separation process, %; α – sieve tilt angle, rad.; Q – vetch seeds flow rate, kg·h^{-1}.

Data analysis shows that the quality index of separation process μ_s decreases with increasing sieve tilt angle α and vetch seeds flow rate Q. With increasing sieve tilt angle from α = 0.349 rad to α = 0.419 rad and increasing seed flow rate from Q = 120 kg·h^{-1} to Q = 140 kg·h^{-1} the quality of separation process is reduced: 1) the seed mass was separated with two separator sieves ($2L_s$ = 0.4 m) – from μ_s = 61.0% to μ_s = 42.0% (fig. 3, a, b); 2) the seed mass was separated with four separator sieves ($4L_s$ = 0.8 m) – from μ_s = 84.8% to μ_s = 63.2% (fig. 3, a, c); 3) the seed mass was separated with six sieves ($6L_s$ = 1.2 m) – from μ_s = 90.8% to μ_s = 74.8% (Fig. 3, a, d). Such research results can be explained by the fact that with increasing sieve tilt angle α probability of small fraction seed passage into the sieve holes decreases due to the high velocity of seed movement. The increasing of seed flow rate Q also creates unfavourable conditions for the separation process, as the thickness of the seed layer on the sieves increases.

Analysis of research results also indicates that the quality index μ_s increases with the increase in the number of sieves into which the seed flow passes. It should be noted that the intensity of the separation process is the highest during the seed passage of the first two sieves, but the intensity of the process decreases on the next sieves. So, in the case of $2L_s$ = 0.4 m (the first and second sieves), the quality index of separation process is within μ_s = 42.0…61.0%; in the case of $4L_s$ = 0.8 m – μ_s = 63.2…84.8% (only 21.2…23.8% small seed fraction was separated on the third and fourth sieves); in the case of $6L_s$ = 1.2 m – μ_s = 74.8…90.8% (only 6.0…11.6% small seed fraction was separated on the fifth and sixth sieves).

It was also found that individual seeds flew out from the sieves during seed separation on the proposed separator. This is the result of changing the direction of seed movement during the transition from one sieve to another sieve. During the research, the percentage of such seeds was 0.2% of the initial seed mass. Installing the covers over the separator sieves allows eliminating this disadvantage.

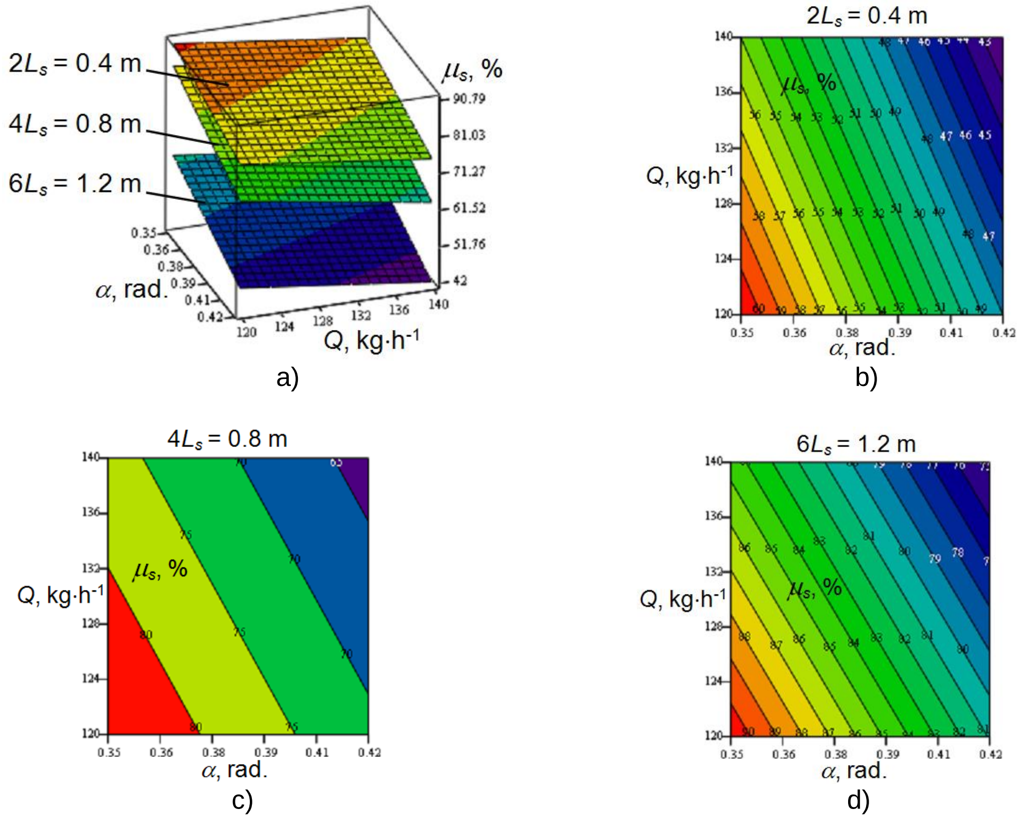


Fig. 4 - The quality index of separation process μ_s depending on the sieve tilt angle α and seed flow rate Q
a – three cases ($2L_s$, $4L_s$, $6L_s$); b – $2L_s$ = 0.4 m; c – $4L_s$ = 0.8 m; d – $6L_s$ = 1.2 m

CONCLUSIONS

The obtained theoretical equations allow us to justify the maximum sieve length on which it is possible to separate the seed mass. It was found that as the sieve tilt angle α increases, the sieve length, on which it is possible to pass the small fraction seeds into the sieve holes, decreases. For the case of vetch seed separation in the proposed separator the recommended sieve length is S = 0.203 m (the sieve length was calculated for the parameters: α = 0.349 rad and ε = 0.349 rad). As the results of experimental study show, the sieve length S is not sufficient for complete separation of the seed mass. It is recommended that the sieves be arranged in a cascade, as in the proposed design of a gravity-cascade separator. This arrangement of sieves allows us to slow down the seed flow by changing the direction of its movement between sieves and, accordingly, increase the number of sieves on which it is possible to pass the small fraction seeds into the sieve holes. Thus, increasing the total length of the sieves contributes to an increase of the quality index of separation process. The design of the proposed separator also allows us to easily adjust the sieve tilt angle, depending on the physical and mechanical properties of the seed mass components. As a result of experimental studies, it was found that with the increase in the sieve tilt angle the percentage of separated seeds of small fraction decreases. The quality index of separation process also decreases with the increase in the seed flow rate from the hopper. It was experimentally found that the percentage of separated small seed fraction increases with increasing the number of sieves. However, the intensity of separation process decreases on each subsequent sieve.

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