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STUDY OF THE PROCESS OF CALIBRATION OF CONFECTIONERY SUNFLOWER SEEDS

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Abstract. The aim of the research was to make the mechanical and technological process of calibrating confectionery sunflower seeds with a vibrating sieve more effective by giving reasons for its rational methodical and technological parameters. The study of calibration of confectionery sunflower seeds had two stages: numerical simulation and experimental verification. For the first stage, the physical models for numerical simulation (in the STAR-CCM+ software package) of the movement of seeds with a vibrating sieve were: k-ε model of separated flow turbulence, gravity field, Van der Waals real gas model, discrete elements model, multiphase interaction model. The second stage, experimental verification of the models obtained, was carried out on a calibration machine (sizer) OKMF. Sieves of three types were selected: perforated sieves, rod sieves, and precision sieves (produced by laser cutting). The numerical simulation of moving the confectionery sunflower seeds with a vibrating sieve has allowed determining how changes in total concentration and productivity depend on the way of the input of the seeds, the sieve angle, the vibration frequency and vibration amplitude of the sieve. To make the seed separation process effective, the vibrating sieve is to operate with the maximum productivity equal to the seed input (1,202 kg/h), with the maximum total seed concentration (10.83%). Experimental studies of moving the seeds of confectionery sunflower with vibrating sieves of different types (perforated screens, rod sieves, and precision sieves) have allowed establishing how changes in total concentration, productivity, and consumed power of the calibrating machine depend on the seed input, sieve angle, and frequency of vibrations of the sieve. To make the seed separation process effective, the vibrating sieve is to operate with the maximum productivity equal to the seed input (perforated screens – 1.116 kg/h, rod sieves – 1,518 kg/h, precision sieves – 1,781 kg/h), with the following total seed concentrations: perforated sieves – 14.54%, rod sieves – 12.45%, precision sieves – 10.41%, and power P (perforated sieves – 0.24 kW, rod sieves – 0.30 kW, precision sieves – 0.35 kW) consumed by the calibrating machine must be minimum. Precision sieves (produced by laser cutting) have the best characteristics of their performance (q=1781 kg/h) and quality (θ=10.41%). For this, the frequency of their vibrations should be 5.9 Hz, and their angle should be 5°.

Key words: seeds, sunflower, vibrating sieve, calibration, numerical simulation, experimental research, parameters.

ДОСЛІДЖЕННЯ ПРОЦЕСУ КАЛІБРУВАННЯ НАСІННЯ КОНДИТЕРСЬКОГО СОНЯШНИКУ

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Анотація. Метою досліджень було підвищення ефективності механіко-технологічного процесу калібрування насіння кондитерського соняшнику під дією вібруючого решета, шляхом обґрунтування його раціональних режимно-технологічних параметрів. Дослідження процесу калібрування насіння кондитерського соняшнику проведено в два етапи: чисельне моделювання і експериментальна перевірка. Для першого етапу в якості фізичних моделей для чисельного моделювання процесу переміщення насіння під дією вібруючого решета в програмному пакеті STAR-CCM+ обрано наступні: k-є модель турбулентності розділеної течії, поле сили тяжіння, модель реального газу Ван-дер-Ваальса, модель дискретних елементів, модель багатофазної взаємодії. Другий етап – експериментальну перевірку отриманих моделей було проведено на калібрувальній машині ОКМФ. Решета обрано трьох видів: пробивні, пруткові і точні (виготовлені шляхом лазерної різки). У результаті чисельного моделювання процесу переміщення насіння кондитерського соняшнику під дією вібруючого решета, отримано залежності зміни сумарної концентрації і продуктивності від подачі насіння, кута нахилу решета, частоти коливань решета і амплітуди коливань решета. За умови забезпечення ефективності процесу розділення насіння під дією вібруючого решета, необхідно щоб його продуктивність була максимальною і дорівнювала значенню подачі насіння (1202 кг/год), при цьому сумарна концентрація насіння повинна бути максимальною (10,83%). У результаті експериментальних досліджень процесу переміщення насіння кондитерського соняшнику під дією вібруючого решета різних видів (пробивні, пруткові, точні) отримано залежності зміни сумарної концентрації, продуктивності і потужності, що споживається калібрувальною машиною, від подачі насіння, кута нахилу і частоти коливань решета. За умови забезпечення ефективності процесу розділення насіння під дією вібруючого решета, необхідно щоб його продуктивність була максимальною і дорівнювала значенню подачі насіння (пробивні – 1116 кг/год, пруткові – 1518 кг/год, точні – 1781 кг/год), при цьому сумарна концентрація насіння (пробивні – 14,54 %, пруткові – 12,45 %, точні – 10,41 %) і потужність P (пробивні – 0,24 кВт, пруткові – 0,30 кВт, точні – 0,35 кВт), що споживається калібрувальною машиною, повинні бути мінімальними. Точні решета (виготовлені шляхом лазерної різки) мають найліпші показники за продуктивністю (q=1781 кг/год) і якістю (θ=10,41%). При цьому частота їхніх коливань повинна складати 5,9 Гц, а кут їхнього нахилу – 5°.

Ключові слова: насіння, соняшник, вібруюче решето, калібрування, чисельне моделювання.

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Introduction. Formulation of the problem

Separating the seeds of confectionery sunflower by their size is very important for calibration [1]. One of the methods of separating the seeds is to move them on vibrating sieves, with a fluidized layer created [2]. Substantiating the technological parameters of seed calibration with a sieve and developing the corresponding physical and mathematical models are problems to solve.

Analysis of recent research and publications

As shown by an analysis of literary sources and professional scientific publications [2-4], a lot of theories and methods for calculating the positions of the seeds are devoted to the study of the process of material movement caused by a vibrating sieve. In [5], a mathematical model of seed distribution on flat screens is developed, which uses the theory of dimensional analysis, but describes the separation process rather superficially. In the studies [6], the index of quality of separating seeds into fractions is introduced as a criterion of efficiency. The studies [7] were aimed at creating mathematical models that determine how the main parameters of the process kinematics influence the seed separation efficiency. The basis of the research [8] is the physical and mathematical tools to calculate and describe the movement of a material point acted upon by various forces, which does not take into account the interaction of particles having random initial positions. The works [9-10] suggests solving such systems with the finite element method, which is implemented during modelling in the software package STAR-CCM +. However, no experimental validation of these studies has been found.

The aim of the research is to make the mechanical and technological process of calibrating confectionery sunflower seeds with vibrating sieves more effective by establishing the practical parameters of its technology and operation modes.

The **objectives** of the research:

1. To carry out a numerical simulation of moving seeds with a vibrating sieve, using the software package STAR-CCM+, and determine how the changes in the total concentration, productivity, and power consumption of the calibrating machine depend on the factors researched.
2. To study experimentally the movement of seeds acted upon by a vibrating sieve, and determine how the changes in the total concentration, productivity, and power consumption of the calibrating machine depend on the factors researched.
3. To make statistic calculations of the obtained data, and to compare the results of the numerical simulation and experimental studies.

Research materials and methods

The calibration process of sunflower seeds was studied in two stages: numerical simulation and experimental verification.

The research was conducted in seeds of confectionery sunflower of the Smak variety (bred by the Institute of Oilseeds Crops of the National Academy of Agrarian Sciences of Ukraine) [11].

At the first stage, the following models were selected [12-13] as physical models for a numerical simulation (using the software package STAR-CCM+) of the movement of seeds on a vibrating sieve: k-ε model of separated flow turbulence, gravity field, Van der Waals real gas model, discrete elements model, multiphase interaction model. To construct a physical and mathematical model, it is necessary to assume that sunflower seeds have the form of identical ellipsoids with a defined density and effective diameter.

According to the previous studies of the physical and mechanical properties of the confectionery sunflower (the Smak variety) [14-15], the following average values were taken for the numerical simulation: Poisson’s ratio – 0.5; Young’s modulus – 0.2 MPa; density – 800 kg/m^3; stiction coefficient – 0.8; normal COR – 0.5; tangential COR – 0.5; coefficient of rolling resistance – 0.3. The properties of the environment were as follows: medium – air; dynamic viscosity – $1.85508\cdot10^{-5}$ Pa·s; turbulent Prandtl number – 0.9; acceleration of free fall – 9.8 m/s^2; temperature – 293 K; pressure – 101325 Pa. The size of a modelling grid cell was 0.001 m.

For the numerical simulation, a calculation scheme was developed for the movement of confectionery sunflower seeds on a vibrating sieve. This scheme is the basis of the operations of various seed clearing and calibrating machines (Fig. 1).

According to seed processors’ requirements, the best sold fraction of sunflower seeds is “fraction 3.6 +” (pass of the sieve 3.6×20 mm). That is why, the further research is based on this sieve. According to the previous studies [9], the most rational length of the sieve L=2 m was chosen. The relative useful area of the sieve was 0.56. The sieve operates periodically in two coordinates according to the law:

$$x = A\cos\psi t, \quad y = A\sin\psi t, \qquad (1)$$

where A – vibration amplitude, m; ψ – vibration frequency, s^{-1}.

The seed flow was represented by 5 seed fractions of the same quantity, with different thickness D_e, in the range 3.0–3.8 mm, in increments of 0.2 mm. As the factors of numerical modelling, the most important technological parameters were taken: seed input – Q, angle of the sieve – α, sieve vibration frequency – ψ, sieve vibration amplitude – A (range of variations is presented in Table 1). Numerical simulation was performed on a complete factorial study with a total number of experiments – $3^4 = 81$. The exposure started at 100 s.

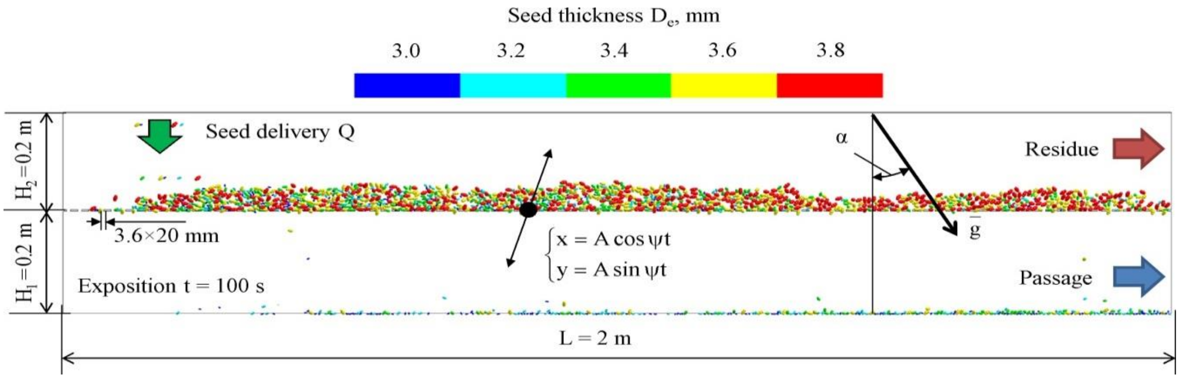


Fig. 1. Calculation scheme of the movement of confectionery sunflower seeds by the action of a vibrating sieve

Table 1 – Variation levels of factors of numerical simulation of moving confectionery sunflower seeds with a vibrating sieve

Variation levels of factors	Factors			
	Seed input Q, kg/h	Sieve angle α,°	Sieve vibration frequency ψ, s^{-1}	Sieve vibration amplitude A, m
(–)	1100	1	4	0.008
(0)	1600	4	5	0.01
(+)	2100	7	6	0.012
Interval	1100	1	4	0.008

As a result of the simulation, a study was carried out of the concentration of each seed fraction that reflected from the surface of the sieve (residue) θ^r and passed through it (passage) θ^p. Due to the fact that the size of the sieve opening has been 3.6 × 20 mm, the condition necessary for the proper separation of the seed mixture is minimizing the values of the concentrations of seed fractions: the fraction 3.8 mm – by passage ($\theta^p_{D_p=3.8}$), and the fractions 3.0 mm, 3.2 mm, 3.4 mm, 3.6 mm – by residue ($\theta^r_{D_p=3.0}$, $\theta^r_{D_p=3.2}$, $\theta^r_{D_p=3.4}$, $\theta^r_{D_p=3.6}$, respectively). So, the total concentration of residue and passage seeds was taken as a research criterion and calculated by the formula:

$$\theta = \theta^p_{D_p=3.8} + \theta^r_{D_p=3.6} + \theta^r_{D_p=3.4} + \theta^r_{D_p=3.2} + \theta^r_{D_p=3.0} \quad (2)$$

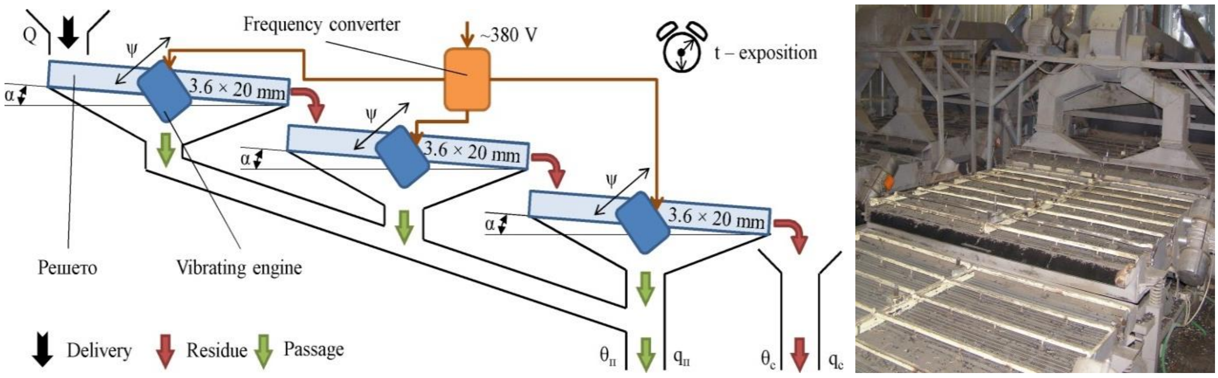
As a quantitative criterion to assess the effectiveness of sunflower seeds separation with a vibrating sieve, the total residue and passage productivity was taken:

$$q = q^p + q^r \quad (3)$$

The second stage, the experimental verification of the models obtained, was carried out on the experimental installation based on the calibration machine OKMF (Fig. 2). Sieves, with the mesh size 3.6 × 20 mm, were of three types: perforated sieves, rod sieves, and precision sieves (produced by laser cutting). The deviations of the sizes of the sieve meshes were 0.09 mm, 0.03 mm, and 0.001 mm, respectively. The relative useful areas of the sieves were 0.42, 0.56, and 0.56, respectively.

The following methodical and technological parameters were taken as experimental research factors: seed input – Q, sieve angle – α, sieve vibration frequency – ψ (variation limits are presented in table 1). According to the results of the numerical simulation in the first stage of the research (equation (4)–(5)) it was established that the vibration amplitude of sieve A does not significantly affect the total productivity q (the influence of the factor – 8.1%). However, the total seed concentration θ is the smallest in the investigated range of factors, with the sieve vibration amplitude A=0.012 m, which is accepted as a condition for experimental studies. The experimental studies were carried out according to the D-optimal Box – Behnken design for three factors, with the number of experiments 15. The exposure of each experiment was 20 minutes.

The seed input was being changed by means of the calibrated valve on the hopper. The angle of the sieve was determined by adjusting the respective levers and controlled by the electronic angle meter Digital inclinometer. The frequency of sieve vibrations coincided with the vibration frequency of the vibratory motor IV-104B-6 (n=1000 min^{-1}, P=0.53 kW, 3 phases) and was being changed with a control unit based on the Danfoss VLT Micro Drive frequency converter. The relation between the vibration frequency of the sieve ψ and the frequency of the electric power supply f powered by the wind turbine IV-104B-6 is presented as: $f\,[Hz]=(50\,Hz)\cdot(60\,s)\cdot\psi\,[Hz]/1000\,(min^{-1})=3\cdot\psi\,[Hz]$.



a b

Fig. 2. Structural and technological scheme (a) and general view (b) of the experimental installation based on the calibration machine OKMF

Each experiment was accompanied by measuring the fractional composition of confectionery sunflower seeds at the input, passage, and output by means of a set of sieves (3.0 mm, 3.2 mm, 3.4 mm, 3.6 mm, 3.8 mm), and a laboratory plansifter RLU-3 in accordance with the generally accepted methodology (GOST 10854-88).

For the research, a seed mixture of the confectionery sunflower of the Smak variety was taken (harvested in 2017, Sonyachne, Zaporizhzhia district, Zaporizhzhia region), with the moisture content 7.6–8.1% and a fraction composition close to the theoretically accepted: 3.0 mm – 19.1%, 3.2 mm – 22.3%, 3.4 mm – 20.1%, 3.6 mm – 18.2%, 3.8 mm – 20.3%. The mixture heterogeneity by fraction composition was 2.6 %. For each experiment, 300 kg of the seed mixture was passed through the calibration machine.

According to the data obtained, it has been determined how the total concentration of seeds, according to the formula (2), and total productivity, according to the formula (3), depend on the factors of research. To compare the dependencies obtained at the two stages of the study, the correlation coefficient was used.

A Danfoss VLT Micro Drive frequency converter was used to determine the dependence of the power consumed by the calibrating machine on the factors of research.

The research results have been processed with the software package Wolfram Mathematica, with the use of correlation and dispersion analysis.

Results of the research and their discussion

According to the first stage, the simulation has resulted in obtaining a visual representation of the technological process of the movement of oilseed crops seeds under the action of a vibrating sieve (Fig. 3). The histogram of Figure 3 illustrates the distribution of the seed concentration of a corresponding fraction at the output of the residue θ^c and the passage $\theta^п$, as well as the corresponding value of the total productivity q.

Accordingly, for each seed fraction at the output and during the passage, the concentration has been determined, and the total concentration for a corresponding experiment θ has been calculated.

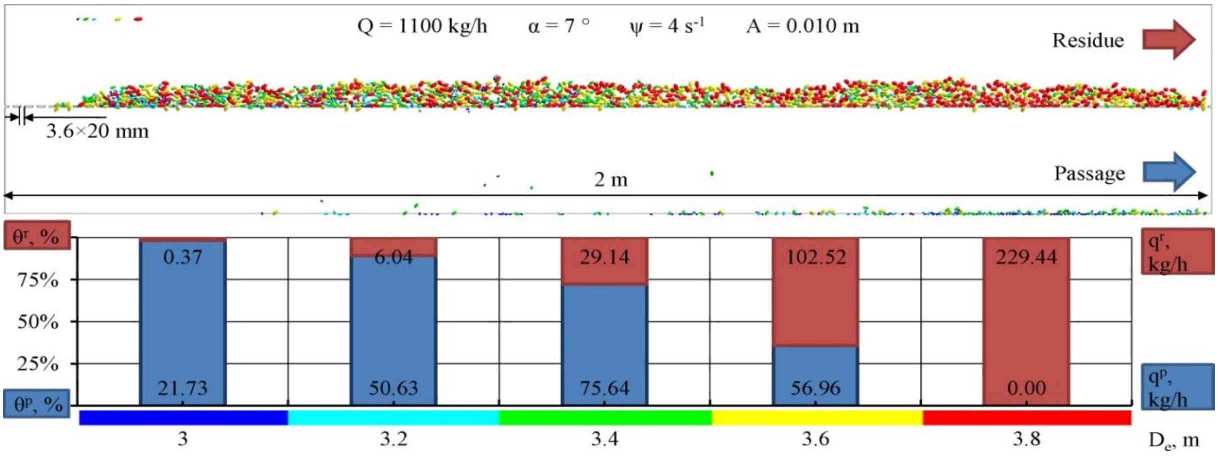


Fig. 3. Distribution of seed fractions at the input, output, and during the passage under the action of the vibrating sieve

Using the Mathematica software package, a mathematical expression has been created that links the productivity q with the research factors in the following form:

$$q = -6637.82 + 162.22\,\alpha + 33577.7\,A + 0.013423\,Q + 2433.85\,\psi - 32.444\,\alpha\,\psi + 0.140125\,Q\,\psi - 227.453\,\psi^2 \qquad (4)$$

A visual interpretation of this dependence (4) is presented in Figure 4.

From Figure 4, it can be seen that with the increase in the seed input Q and the sieve vibrations amplitude A, the productivity q increases linearly; with the decrease in the sieve angle α, the efficiency q does not significantly increase linearly; when increasing the frequency of vibrations of the sieve ψ, the productivity q increases parabolically.

With the Mathematica software package, a mathematical expression has been created that links the total concentration of seeds θ with the research factors in the following form:

$$\theta = 198.853 - 1.733\ \alpha - 14055.2\ A + 284999\ A^2 + 0.00852581\ Q - 39.653\ \psi + 0.303737\ \alpha\ \psi + 1364.8\ A\ \psi - 0.00170516\ Q\ \psi + 2.27037\ \psi^2. \qquad (5)$$

A visual interpretation of this dependence (5) is presented in Figure 5.

From Figure 5, it can be seen that with the increase in the seed input Q, the total seed concentration θ increases linearly; with a decrease in the sieve angle α, the total seed concentration θ increases linearly; and with reduced frequency of sieve vibrations ψ and sieve vibrations amplitude A, the total seed concentration θ increases parabolically.

As the analysis of these dependencies proves, it is necessary to solve a tradeoff problem: in order to ensure the effectiveness of seed separation with a vibrating sieve, its productivity q should be maximum and equal to the seed input Q, with the minimum total seed concentration θ:

$$\begin{cases} q(Q, \alpha, \psi, A) = Q \to \max, \\ \theta(Q, \alpha, \psi, A) \to \min. \end{cases} \qquad (6)$$

With the Mathematica software package, it has been determined that the solution of the system of equations (6) for the results of the numerical simulation is θ=10.83%, Q= q= 1202 kg/h, α=1°, ψ=5.62 s^{-1}, A=0.012 m.

For the second stage, according to the data obtained from the experimental studies, the Mathematica software package has compiled a mathematical expression that links the productivity of q with the research factors in the following form:

– for perforated sieves:

$$q = -5592.57 + 0.527369\ Q + 177.915\ \alpha - 35.583\ \psi\ \alpha + 2113.22\ \psi - 179.262\ \psi^2; \qquad (7)$$

– for rod sieves:

$$q = -7202.09 + 0.706424\ Q + 171.881\ \alpha - 34.3762\ \psi\ \alpha + 2670.95\ \psi - 229.179\ \psi^2; \qquad (8)$$

– for precision sieves:

$$q = -7277.2 + 0.642679\ Q + 177.512\ \alpha - 39.6273\ \psi\ \alpha + 2721.17\ \psi - 232.098\ \psi^2. \qquad (9)$$

Comparing the experimental models obtained (7) – (9) with the numerical simulation model (4), we can assert their mutual correlation, which is confirmed by the corresponding correlation coefficients R (8)=0.91, R (8)=0.92, R (9)=0.91.

According to the data obtained from the experimental studies, the Mathematica software package has compiled a mathematical expression that links the total concentration of seeds θ to the factors of research in the following form:

– for perforated sieves:

$$\theta = 109.431 + 0.00867581\ Q - 0.00173516\ \psi\ Q - 2.68759\ \alpha + 0.43346\ \psi\ \alpha - 30.9058\ \psi + 2.56031\ \psi^2 \qquad (10)$$

– for rod sieves:

$$\theta = 98.6656 + 0.00845081\ Q - 0.00169016\ \psi\ Q - 2.31106\ \alpha + 0.392071\ \psi\ \alpha - 28.0976\ \psi + 2.33626\ \psi^2; \qquad (11)$$

– for precision sieves:

$$\theta = 88.203 + 0.0111675\ Q - 0.0022335\ \psi\ Q - 2.17078\ \alpha + 0.384571\ \psi\ \alpha - 26.2659\ \psi + 2.32216\ \psi^2. \qquad (12)$$

Comparing the experimental models obtained (10) – (12) with the numerical simulation model (5), we can assert their mutual correlation, which is confirmed by the corresponding correlation coefficients R (10) = 0.79, R (11) = 0.78, R (12) = 0.81.

According to the data obtained from the experimental studies, the Mathematica software package has compiled a mathematical expression that links the power P with the research factors in the following form (Fig. 6):

– for perforated sieves:

$$P = -0.00351984 + 0.0000625\ Q + 0.03125\ \psi \qquad (13)$$

– for rod sieves:

$$P = 0.0803921 + 0.000106\ Q + 0.0111\ \psi; \qquad (14)$$

– for precision sieves:

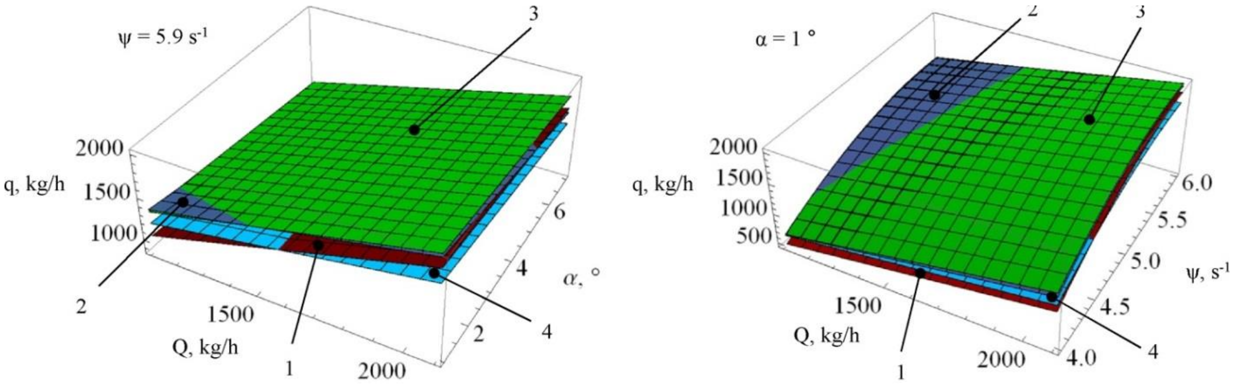
$$P = 0.0913286 + 0.0000793333\ Q + 0.0198333\ \psi \qquad (15)$$

As can be seen from the dependences (13) – (15), the power P is linearly influenced only by the seed input Q and the frequency of sieve vibrations ψ.

The statistical analysis of the experimental data and the mathematical models (7) – (15) are presented in Table 2, and their graphical interpretation in Fig. 4–6.

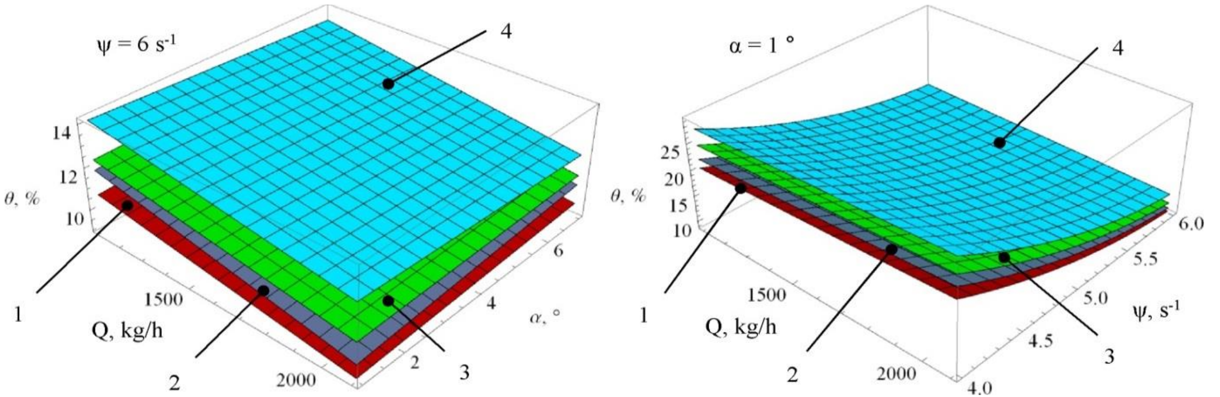
Table 2 – Statistical analysis of the experimental data and models obtained

Sieve type	Productivity q, kg/h		Total seed concentration θ, %		Power P, kW	
	Cochran's Q test	F-test	Cochran's Q test	F-test	Cochran's Q test	F-test
Perforated	$G = 0.1918 < G_{0.05}(2, 15) = 0.3346$	$F = 1.85 < F_{0.05}(9, 30) = 2.21$	$G = 0.1010 < G_{0.05}(2, 15) = 0.3346$	$F = 1.62 < F_{0.05}(8, 30) = 2.27$	$G = 0.1215 < G_{0.05}(2, 15) = 0.3346$	$F = 1.34 < F_{0.05}(11, 30) = 2.13$
Rod	$G = 0.1144 < G_{0.05}(2, 15) = 0.3346$	$F = 1.39 < F_{0.05}(9, 30) = 2.21$	$G = 0.1320 < G_{0.05}(2, 15) = 0.3346$	$F = 1.15 < F_{0.05}(8, 30) = 2.27$	$G = 0.1461 < G_{0.05}(2, 15) = 0.3346$	$F = 1.49 < F_{0.05}(11, 30) = 2.13$
Precision	$G = 0.1207 < G_{0.05}(2, 15) = 0.3346$	$F = 1.88 < F_{0.05}(8, 30) = 2.27$	$G = 0.1350 < G_{0.05}(2, 15) = 0.3346$	$F = 1.26 < F_{0.05}(8, 30) = 2.27$	$G = 0.1368 < G_{0.05}(2, 15) = 0.3346$	$F = 1.37 < F_{0.05}(11, 30) = 2.13$



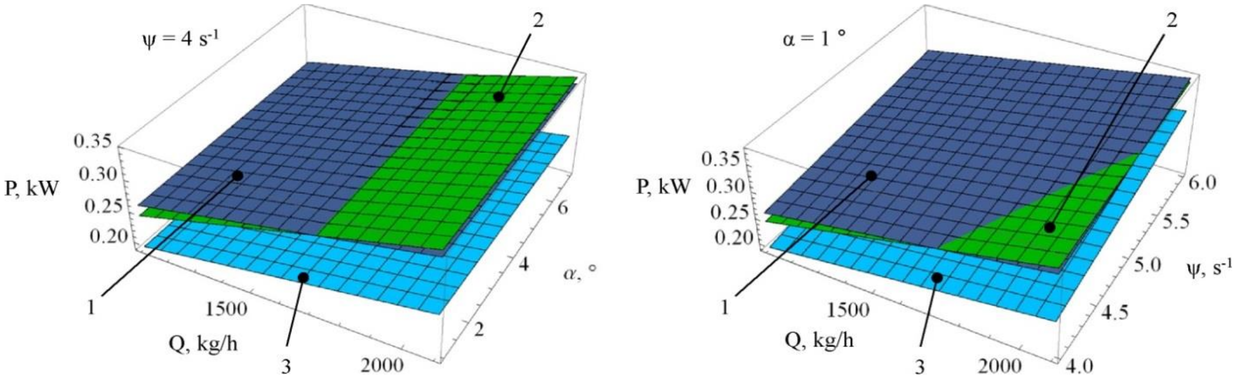
1 – numerical simulation data; 2 – perforated sieves; 3 – rod sieves; 4 – precision sieves

Fig. 4. Dependence of the productivity q on the seed input Q, sieve angle α, and sieve vibration frequency ψ



1 – numerical simulation data; 2 – perforated sieves; 3 – rod sieves; 4 – precision sieves

Fig. 5. Dependence of the total seed concentration θ on the seed input Q, sieve angle α, and sieve vibration frequency ψ



1 – perforated sieves; 2 – rod sieves; 3 – precision sieves

Fig. 6. Dependence of the power P consumed by the calibrating machine on the seed input Q, sieve angle α, and sieve vibration frequency ψ

The analysis of the empirical dependencies presented proves the necessity of solving the following tradeoff problem: in order to ensure the effectiveness of seed separation with a vibrating sieve, its productivity q should be maximum and equal to the seed input Q, while the total seed concentration θ and the power P consumed by a calibrating machine should be minimum:

$$\begin{cases} q(Q,\alpha,\psi)=Q\rightarrow \max, \\ \theta(Q,\alpha,\psi)\rightarrow \min, \\ P(Q,\alpha,\psi)\rightarrow \min. \end{cases} \qquad (16)$$

With the Mathematica software package, a solution of the system of equations (16) has been obtained for the results of the experimental studies. It is presented in Table 3.

Table 3 – Practical technological parameters of the mechanical and technological process of calibration of confectionery sunflower seeds with a vibrating sieve

Sieve type	**Q = q, kg/h**	**α,°**	**ψ, Hz**	**θ, %**	**P, kW**
Perforated	1116	4.5	5.5	14.54	0.24
Rod	1518	6.2	5.5	12.45	0.30
Precision	1781	5.0	5.9	10.41	0.35

Table 3 shows that the precision sieve (produced by laser cutting) has the best performance characteristics (q = 1781 kg/h), quality (θ=10.41%), and energy consumption (P=0.35 kW). In this case, the frequency of its vibrations should be ψ=5.9 Hz, and its angle of inclination α=5°.

Conclusions

As a result of the numerical simulation of the process of moving the confectionery sunflower seeds on a vibrating sieve, dependences of the change in the total concentration θ and the productivity q on the seed input Q, sieve angle α, sieve vibration frequency ψ, and sieve vibration amplitude A have been obtained. Provided that the seed separation process with the use of a vibrating sieve is effective, the productivity q should be maximum and equal to the seed input value Q= q =1202 kg/h, with the maximum total seed concentration θ=10.83%, and α=1°, ψ=5.68 s^{-1}, A=0.012 m.

As a result of the experimental studies of the movement of confectionery sunflower seeds on vibrating sieves of different types (perforated, rod, precision), it has been determined how the change in the total concentration θ, productivity q, and power P consumed by the calibrating machine depends on the seed input Q, sieve angle α, and sieve vibrations frequency ψ. Provided that the seed separation process with the use of a vibrating sieve is effective, its productivity q should be maximum and equal to the seed input Q (perforated sieves – 1116 kg/h, rod – 1518 kg/h, precision – 1781 kg/h), while the total seed concentration θ (perforated sieve – 14.54%, rod – 12.45%, precision – 10.41%) and power P (perforated sieve – 0.24 kW, rod – 0.30 kW, precision – 0.35 kW) consumed by the calibrating machine should be minimum, and α=4.5–6.2°, ψ=5.5–5.9 s^{-1}.

Precision sieves (made by laser cutting) have the best performance (q=1781 kg/h) and quality (θ=10.41%) characteristics. The frequency of their vibrations should be ψ=5.9 Hz, and their angle α=5°.

Comparing the experimental models with the numerical simulation model, we can assert their mutual correlation, which is confirmed by the correlation coefficient R=0.79–0.92.

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