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RESULTS OF EXPERIMENTAL STUDIES OF THE ROTARY BRUSH SEPARATOR OF CRUSHED CAKE FROM NICHE OIL CROPS

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The study addresses the technical challenge of improving the efficiency of the fractionation process of crushed cake from niche oil crop seeds by enhancing the design and parameters of a rotary brush separator. It has been established that traditional devices exert low intensity on the bulk material and do not ensure adequate quality of fraction separation and sieve cleaning. An experimental test rig was developed to investigate the influence of design and technological parameters such as rotor rotational speed, feed rate, brush orientation angle, and brush assembly offset angle on the separator's performance indicators.

The aim of the research is to substantiate and determine the optimal design and technological parameters of the brush rotary separator for effective cleaning of crushed castor cake by means of multi-criteria optimization of machine performance indicators, namely the degree of sieving, the undersieve coefficient, and specific electricity consumption.

As a result of the experimental studies, a test rig for experimental investigation of the rotary brush separator for crushed cake of niche oil crops was created, and dependencies were obtained for the degree of sieving k (%), the undersieve coefficient η (%), the power consumed by the separator P (W), and the specific energy consumption E (MJ/kg) as functions of the crushed cake feed rate q, brush shaft rotational speed n, brush orientation angle α, and brush assembly offset angle β.

Following multi-criteria optimization performed using Wolfram Cloud and the method of multiplicative objective function minimization, the rational values of factors were determined: crushed cake feed rate q=577.2 kg/h, brush shaft rotational speed n=86.4 rpm, brush orientation angle α=14.8°, and brush assembly offset angle β=49.9°. Under these conditions, a high degree of sieving k=33.4% is achieved with a low undersieve coefficient η=3.6%, minimal specific electricity consumption E=0.00566 MJ/kg, and moderate power consumption P=886 W.

The obtained results confirm the feasibility of applying this method for optimizing the operation of machines of this type and demonstrate the effectiveness of coordinating design and operating parameters considering a set of quality criteria.

***Key words**: rotary brush separator, crushed cake, niche oil crops, fractionation, cleaning, degree of sieving, undersieve coefficient, energy consumption, optimization, design and technological parameters, rotor rotational speed, feed rate, brush orientation angle, brush assembly offset angle, multi-criteria optimization.*

Eq. 8. Fig. 4. Ref. 13.

1. Problem formulation

In the current context of the development of Ukraine's agro-industrial sector, there is a growing interest in the cultivation and processing of niche oilseed crops such as flax, mustard, safflower, and others. The high value of the products obtained from their processing-namely oil and oilseed cake-necessitates the improvement of technological processes, particularly the separation of crushed oilseed cake, in order to enhance the quality of the final product, reduce losses, and lower energy consumption [1, 2].

One of the technologically significant stages after pressing is the separation of crushed oilseed cake into hull and protein fractions, which allows for the extraction of over 40% of protein powder with a protein content of no less than 38% [3]. The resulting protein fraction can be used in feed production, while the hull fraction is suitable for manufacturing fuel briquettes or pellets. Existing separation systems generally do not

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provide effective cleaning and sorting of crushed oilseed cake due to design flaws or the mismatch between operating parameters and the physical and mechanical properties of the material [4–8]. This highlights the need for the development of efficient, energy-saving, and technologically adaptable machinery and equipment tailored to the specific characteristics of niche crops.

Rotary brush separators, owing to their structural flexibility and intensive action on the material, show great potential for the effective fractionation of crushed oilseed cake [9–12]. However, their design parameters and operating modes require scientific justification based on the physical and mechanical properties of the cake derived from different crops, which defines the relevance of this research.

Therefore, a study aimed at substantiating the design and technological parameters of a rotary brush separator for the processing of crushed oilseed cake from niche oilseed crops is both timely and in demand, as it contributes to improving the efficiency of processing technologies, ensuring product quality, and enhancing energy efficiency in production.

2. Analysis of recent research and publications

Recent research and developments in the field of cleaning and separation of crushed plant raw materials, particularly castor seed cake, demonstrate a consistent trend towards the implementation of energy-efficient technologies and intelligent methods for controlling process parameters. The main focus is on improving sieving efficiency by optimizing the structural characteristics of working components (brush units, sieve surfaces) and operating parameters (raw material feed rate, rotational speed, and geometric angles).

A known rotary brush sifter [11] consists of a frame, sidewalls with rigidly fixed rings, a cylindrical sieve made of fabric material, clamps, a brush rotor with a shaft, a drive, bearing housings, a loading mechanism, a discharge window for the fine fraction, a discharge window for the coarse fraction, and a protective casing. The brush rotor consists of two flanges with screws, eight pins with plates (four on each flange), and four brushes.

Another known device for material sieving [10] includes a housing made of two sidewalls mounted on a frame, between which a sieve is located. The sieve is clamped between the sidewalls and tensioned into a cylindrical shape by shifting one of the sidewalls along the frame. The rotor brushes are arranged in a helical pattern relative to the sieve surface and are positioned to follow the contour of the inner surface of the sieve.

The drawbacks of these devices include insufficient intensity of interaction with the bulk material in the working zone and low efficiency of sieve cleaning from adhered material. This is due to the rotor design, which has a limited number of brushes (four) placed along the cylindrical sieve, providing inadequate mixing or loosening effects, thereby reducing the efficiency of fraction separation. Furthermore, this design does not ensure uniform and continuous cleaning of the sieve's inner surface, leading to rapid clogging and decreased sieving quality.

Study [12] covers only one type of raw material – crushed rapeseed cake – which prevents evaluation of the sifter's versatility and efficiency for other crops, such as castor, sunflower, or mustard. The experiment does not investigate the influence of key design and technological parameters, such as rotor speed, feed rate, brush orientation angle, or characteristics of the sieve equipment, on the machine's performance indicators, limiting the potential for process optimization. Moreover, the study lacks mathematical modeling or regression equation development, which would allow for result prediction or equipment adaptation to variable conditions. Some efficiency criteria, such as sieving degree, protein and fiber content, are presented without detailing the methodology of their determination, raising concerns about the reproducibility of the results.

The results of experimental studies [13] are presented within a narrow range of variables, without analyzing the influence of other critical factors, such as rotation frequency, brush geometry, brush orientation angles, or feed rate. Additionally, there is no generalization of data in the form of regression dependencies or response surfaces, which prevents the development of recommendations for various equipment operation modes. Energy indicators such as power consumption or specific energy usage are not considered, although they are critically important for evaluating separation efficiency. Furthermore, the study does not include comparisons with alternative sifter designs or market analogs, complicating the assessment of the proposed technical solution's competitiveness.

3. The purpose of the article

The aim of the study is to justify and determine the optimal design and technological parameters of a brush-type rotary separator for the efficient cleaning of crushed castor seed cake through multi-criteria

optimization of machine performance indicators, including sieving degree, undersieving coefficient, and specific energy consumption.

4. Results and discussion

The test stand for experimental studies of the brush-type rotary separator for crushed oilseed cake from niche oil crops (Fig. 1) consists of a main frame, which serves as a robust supporting structure ensuring rigidity and stability of the entire system. An electric motor is mounted on the frame, transmitting rotational motion to the separator shaft via a coupling. The shaft is supported by a bearing assembly that ensures smooth and uninterrupted rotation.

Working elements are attached to the shaft–four flanges, sixteen pins with plates, and eight brushes. The brushes are installed in two brush units, four brushes in each, and are fastened with bolted connections. The brush units are arranged with an angular offset relative to each other. The brushes themselves are oriented at a certain angle to the shaft axis by rotating the flanges.

The brushes rotate together with the shaft and, due to their design, mechanically loosen and push the crushed oilseed cake, which enters the separator through the loading hopper. The loosening of the material contributes to its uniform distribution and improves the process of separation into fractions of different sizes.

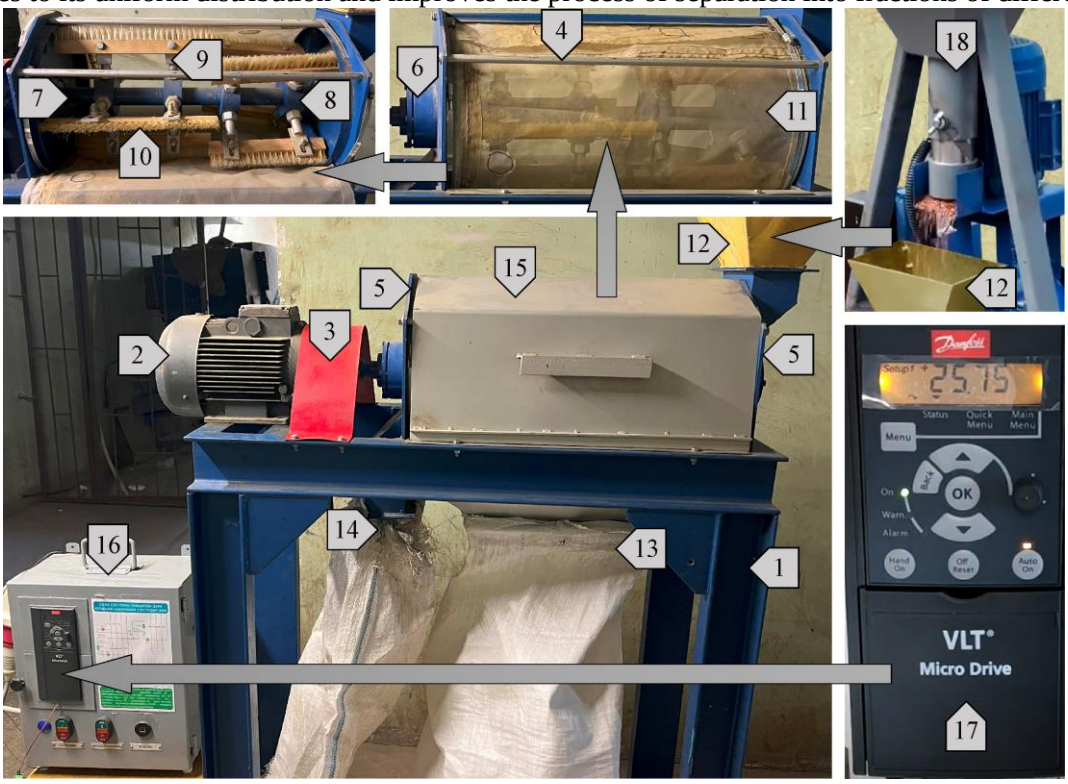

Fig. 1. Test stand for experimental research of the brush-type rotary separator for crushed oilseed cake from niche oil crops:1 – frame; 2 – electric motor; 3 – coupling; 4 – outer casing; 5 – side wall; 6 – bearing unit; 7 – shaft; 8 – flange; 9 – pin with plate; 10 – brush; 11 – sieve; 12 – feed hopper; 13 – fine fraction outlet; 14 – coarse fraction outlet; 15 – protective cover; 16 – control panel; 17 – Danfoss Micro Drive frequency inverter; 18 – vibratory feeder

During each experiment, 10 kg of crushed oilseed cake is fed into the working chamber, where the rotating brushes separate the material: fine particles pass through the sieve, which acts as the separating element, while coarse particles remain on top. The sieve is made of nylon threads with a mesh size of 250 μm.

Fine particles are collected through a dedicated fine fraction outlet, while coarse particles are discharged through the coarse fraction outlet. All separation processes occur inside the protective outer casing and side wall, which prevent material dispersion and ensure operator safety. The additional cover directs the material flow and protects against accidental contact with moving parts. The process is controlled via a control unit equipped with a Danfoss Micro Drive frequency inverter, allowing smooth adjustment of rotor speed. This enables optimization of the separator's operating mode depending on the properties of the cake and the required separation quality, improving efficiency and reducing energy consumption. The rotational speed of the shaft

with brushes is monitored using a Benetech GM8905 non-contact tachometer. The controlled feeding of crushed cake is ensured by a vibratory feeder with a calibrated gate position.

The studied factors (Fig. 2) include:

– feed rate of crushed cake q (200, 600, 1000 kg/h);
– rotational speed of the brush shaft n (60, 90, 120 rpm);
– brush orientation angle α (0, 10, 20°);
– angular offset of brush units β (0, 30, 60°).

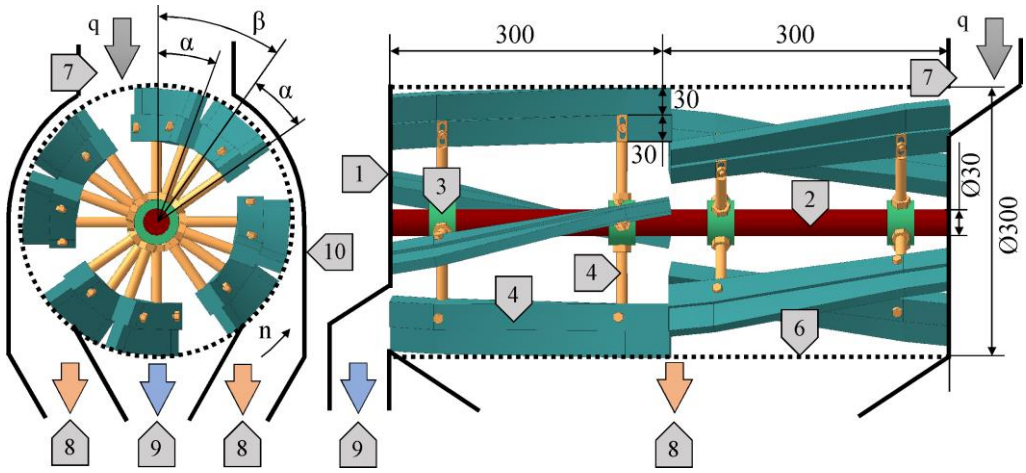

Fig. 2. Geometrical dimensions and research factors of the brush-type rotary separator for crushed oilseed cake from niche oil crops: 1 – side wall; 2 – shaft; 3 – flange; 4 – pin with plate; 5 – brush; 6 – sieve; 7 – feed hopper; 8 – fine fraction outlet; 9 – coarse fraction outlet; 10 – protective cover

The following criteria were selected for the study:

– Sifting efficiency k (%):

$$k = 100\frac{m_s}{m_g}, \quad (1)$$

where m_s – mass of the fine fraction in the fine fraction outlet, kg; m_g – total mass of the crushed oilseed cake, kg;

– Under-sifting coefficient η (%):

$$\eta = 100\frac{m_{s-l}}{m_g}, \quad (2)$$

where m_{s-l} – mass of the fine fraction in the coarse fraction outlet, kg; m_g – total mass of the crushed oilseed cake, kg;

– Power consumed by the separator P (W);

– Specific energy consumptionE (MJ/kg):

$$E = \frac{P}{q}. \quad (3)$$

The mass of the fractions was determined using CAS SW-20 electronic scales.

The power consumed by the separator was measured via the Danfoss Micro Drive frequency inverter. The object of the research was crushed oilseed cake from white mustard (Sinapis alba) of the "Zaporizhanka" variety. The crushing was carried out using a DM-800 crusher.

The experiments were conducted according to a second-order Box–Behnken design for four factors at three levels, with a total of 27 runs. Each experiment was repeated three times.

As a result of the experimental studies, the dependence of the sieving degree k (%) and the under-separation coefficient η (%) on the research factors was obtained in the form of quadratic regression equations:

$$k = 23.7796 + 0.222493\,n - 0.000996501\,n^2 - 0.00920329\,q + 0.199995\,\alpha - 0.0142185\,\alpha^2 + 0.0881415\,\beta + 0.0028125\,\alpha\,\beta - 0.00126069\,\beta^2, \quad (4)$$

$$\eta = 13.9875 - 0.208056\,n + 0.00132407\,n^2 + 0.005375\,q - 0.3625\,\alpha + 0.0116667\,\alpha^2 - 0.0902778\,\beta - 0.00116667\,\alpha\,\beta + 0.00111574\,\beta^2, \quad (5)$$

where q – feed rate of crushed cake, kg/h; n – rotation speed of the brush shaft, rpm; α – brush

orientation angle, °; β – brush unit displacement angle, °.

Graphical interpretations of dependences (4) and (5) are presented in Fig. 3.

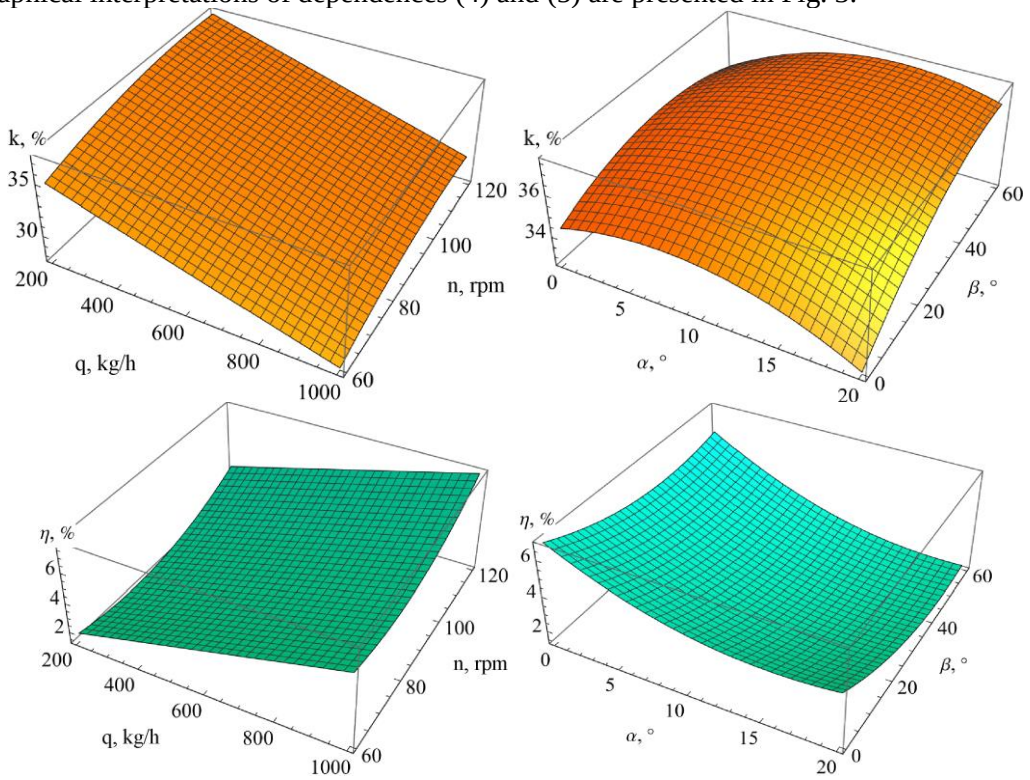

Fig. 3. Dependence of the sieving degree k (%) and under-separation coefficient η (%) on the feed rate of crushed cake q, brush shaft rotation speed n, brush orientation angle α, and brush unit displacement angle β

The sieving degree k is positively influenced by the brush shaft rotation speed and the brush orientation angle; however, the presence of negative coefficients for the quadratic terms n^2 and α^2 indicates the existence of an extremum (at n = 111.6 rpm, α = 11.8∘), after which further increases in these factors lead to a decrease in sieving efficiency. An increase in the cake feed rate negatively affects the sieving degree. The effect of the brush unit displacement angle β\betaβ is moderately positive but limited by quadratic reduction with increasing β (extremum at 48.1∘). A weak interaction between factors α\alphaα and β\betaβ is reflected by the small coefficient for the product α·β.

Increasing the shaft rotation speed and brush orientation angle decreases the under-separation coefficient η\etaη, with their quadratic terms indicating a minimum (at n = 78.6 rpm, α = 18.0∘, β = 49.9∘). Increasing the crushed cake feed rate contributes to increased under-separation, though with a minor effect. Increasing the brush unit displacement angle also reduces under-separation; however, excessive increase in this parameter reduces the effect due to the positive β^2 term. A small negative coefficient for the interaction α·β indicates a weak combined effect of these factors.

Thus, the obtained equations quantitatively evaluate the impact of the studied parameters on the separator's efficiency and allow determination of optimal conditions for achieving maximum sieving degree with minimal under-separation coefficient.

As a result of the experimental research, the dependences of power consumption by the separator P (W) and specific electricity consumption E (MJ/kg) on the study factors were obtained in the form of quadratic regression equations:

$$P = 484.271 + 3.57056\ n + 0.161354\ q, \quad (6)$$

$$E = 0.0170833 + 0.0000645805\ n - 0.0000380878\ q - 6.26475\cdot10^{-8}\ n\ q + 2.43187\cdot10^{-8}\ q^2. \quad (7)$$

Graphical interpretations of dependences (6) and (7) are shown in Fig. 4.

Equation (6) is linear with respect to both factors, indicating a proportional increase in power with increasing shaft rotational speed and cake feed rate. The higher coefficient for n compared to q shows that the rotational speed of the shaft has the greatest influence on the separator's energy consumption. In other words, as the brush rotation speed increases, the mechanical load on the drive increases, which leads to a higher power consumption. Similarly, an increase in the feed rate creates additional resistance force that requires more energy.

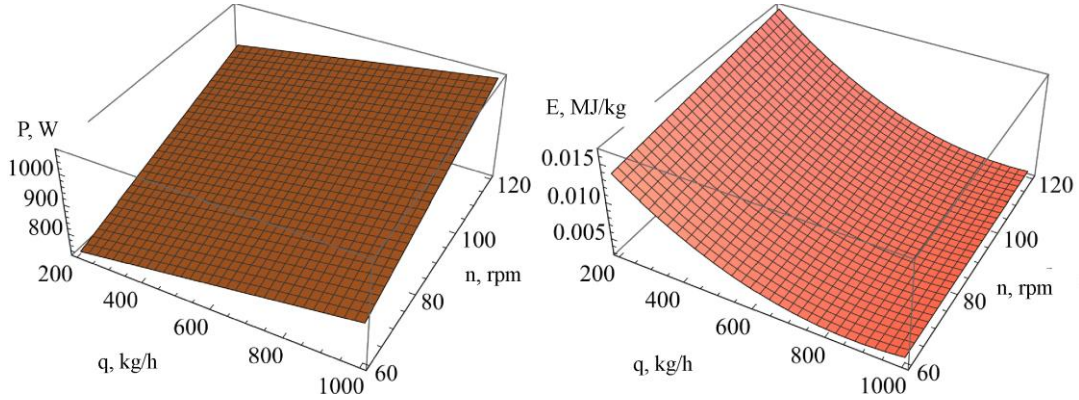

Fig. 4. Dependence of power consumed by the separator P (W) and specific electricity consumption E (MJ/kg) on the feed rate of crushed cake q, rotational speed of the brush shaft n, brush orientation angle α, and brush unit displacement angle β.

Equation (7) is quadratic and reflects a more complex dependence of specific consumption on the studied factors. The positive coefficient for n indicates that increasing the rotational speed causes a slight rise in specific electricity consumption. In contrast, the coefficient for q is negative, meaning that as the feed rate of crushed cake increases, the electricity consumption per unit mass of product decreases, i.e., the process becomes more energy-efficient. However, the presence of the q^2 term with a positive coefficient indicates that at excessively high feed rates, this effect diminishes – specific consumption increases due to system overload or reduced sieving efficiency. The presence of the combined term $n \cdot q$ with a negative coefficient indicates a weak compensatory effect between increasing rotational speed and feed rate – under simultaneous increase of both parameters, specific consumption can remain stable or even decrease.

Thus, analysis of the obtained equations allows us to conclude that a rational combination of parameters n and q enables reducing specific electricity consumption while maintaining process efficiency, and that the most significant factor affecting power consumption is the rotational speed of the brush shaft.

One effective approach to multicriteria optimization was implemented using Wolfram Cloud and the minimization method of a multiplicative objective function formed by scalar ranking. This approach allows determining the optimal factor value combinations that provide the best results simultaneously for several criteria. Its feature is the transformation of a multi-criteria problem into an equivalent single-criterion one based on constructing a multiplicative function that integrates all criteria into a single objective dependence. In cases where an optimum must be achieved for several functions (sieving degree k, under-sieving coefficient η, and specific electricity consumption E), instead of optimizing each separately, a generalized aggregated function is used – the product of normalized relative criterion values weighted according to their importance:

$$G(q,n,\alpha,\beta)=\frac{k(q,n,\alpha,\beta)-\min[k]}{\max[k]-\min[k]}\,\frac{\max[\eta]-\eta(q,n,\alpha,\beta)}{\max[\eta]-\min[\eta]}\,\frac{\max[E]-E(q,n,\alpha,\beta)}{\max[E]-\min[E]}\rightarrow\max. \quad (8)$$

As a result of solving equation (8) combined with equations (4), (5), and (7), the optimal constructive-technological parameters of the machine for cleaning crushed ricinus cake were determined. The rational values of the factors are: feed rate q = 577.2 kg/h, brush shaft rotational speed n = 86.4 rpm, brush orientation angle α = 14.8°, and brush unit displacement angle β = 49.9°. Under these parameters, the achieved sieving degree is k = 33.4%, under-sieving coefficient η = 3.6%, specific electricity consumption E = 0.00566 MJ/kg, and power consumed by the separator drive P = 886 W.

5. Conclusion

As a result of experimental studies, a test bench was developed for the experimental investigation of a rotary brush separator for crushed cake of niche oilseed crops. Additionally, dependencies of the sieving degree k (%), under-sieving coefficient η (%), power consumed by the separator P (W), and specific electricity consumption E (MJ/kg) on the feed rate of crushed cake q, brush shaft rotational speed n, brush orientation angle α, and brush unit displacement angle β were obtained.

Through multicriteria optimization using Wolfram Cloud and the minimization method of a multiplicative objective function, the rational values of the factors were determined: crushed cake feed rate q = 577.2 kg/h, brush shaft rotational speed n = 86.4 rpm, brush orientation angle α = 14.8°, and brush unit displacement angle β = 49.9°.

Under these conditions, a high sieving degree k = 33.4% is achieved with a low under-sieving coefficient η = 3.6%, minimal specific electricity consumption E = 0.00566 MJ/kg, and moderate power consumption P = 886 W.

The obtained results confirm the feasibility of applying this method for optimizing the operation of machines of similar purpose and indicate the effectiveness of coordinating structural and operational parameters considering a set of quality criteria.

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РЕЗУЛЬТАТИ ЕКСПЕРИМЕНТАЛЬНИХ ДОСЛІДЖЕНЬ РОТОРНОГО ЩІТКОВОГО СЕПАРАТОРА ПОДРІБНЕНОЇ МАКУХИ НІШЕВИХ ОЛІЙНИХ КУЛЬТУР

У роботі розглянуто технічну задачу підвищення ефективності процесу фракціонування подрібненої макухи з насіння нішевих олійних культур, шляхом удосконалення конструкції та параметрів роторного щіткового сепаратора. Встановлено, що традиційні пристрої мають низьку інтенсивність впливу на сипкий матеріал і не забезпечують належної якості розділення фракцій та очищення сита. Розроблено експериментальний стенд для дослідження впливу конструктивно-

технологічних параметрів, таких як частота обертання ротора, швидкість подачі, кут орієнтації щіток та їх зміщення, на показники роботи сепаратора.

Метою дослідження є обґрунтування та визначення оптимальних конструктивно-технологічних параметрів щіткового роторного сепаратора для ефективного очищення подрібненої макухи з насіння рицини шляхом багатокритеріальної оптимізації показників роботи машини, зокрема ступеня просіювання, коефіцієнта недосіву та питомих витрат електроенергії.

В результаті експериментальних досліджень створено стенд для експериментальних досліджень роторного щіткового сепаратора подрібненої макухи нішевих олійних культур, а також отримані закономірності ступеня просіювання k (%), коефіцієнту недосіву η (%), потужності, що споживається сепаратором P (Вт) і питомих витрат електроенергії E (МДж/кг) від подачі подрібненої макухи q, частота обертання валу з щітками n, кута орієнтації щіток α і кута зміщення щіткових вузлів β. У результаті проведеної багатокритеріальної оптимізації з використанням Wolfram Cloud та методу мінімізації мультиплікативної цільової функції визначено раціональні значення факторів: подача подрібненої макухи q = 577,2 кг/год, частота обертання щіткового вала n = 86,4 об/хв, кут орієнтації щіток α = 14,8°, кут зміщення щіткових вузлів β = 49,9°. За цих умов досягається високий ступінь просіювання k = 33,4% при низькому коефіцієнті недосіву η = 3,6%, незначних питомих витратах електроенергії E = 0,00566 МДж/кг та помірному енергоспоживанні P = 886 Вт.

Отримані результати підтверджують доцільність застосування даного методу для оптимізації роботи машин подібного призначення та свідчать про ефективність узгодження конструктивних і режимних параметрів з урахуванням комплексу критеріїв якості.

Ключові слова: *роторний щітковий сепаратор, подрібнена макуха, нішеві олійні культури, фракціонування, очищення, ступінь просіювання, коефіцієнт недосіву, енергоспоживання, оптимізація, конструктивно-технологічні параметри, частота обертання ротора, швидкість подачі, кут орієнтації щіток, кут зміщення щіткових вузлів, багатокритеріальна оптимізація.*

Ф. 8.Рис. 4. Літ. 13.

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