ANALYSIS OF THE ENERGY PERFORMANCE OF A CENTRIFUGAL PNEUMATIC SIEVE SEPARATOR
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АНАЛІЗ ЕНЕРГОЕФЕКТИВНОСТІ ВІДЦЕНТРОВОГО ПНЕВМОРЕШІТНОГО СЕПАРАТОРА

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ABSTRACT
The article focuses on determining the power requirements of the actuator for an original centrifugal pneumatic sieve separator. The research was conducted on a laboratory test bench using the К50 measuring complex. During the study, the functional relationships between the total power consumption of the separator actuator and the power required for seed movement along the sieve were established as functions of the grain mixture velocity along the sieve (V=11.7–19.6 m/s) and the specific grain mixture feed rate for three crops – wheat, oat, and sunflower (q_F=9.6–41.6 kg/m^{2}s). The results showed that the energy intensity of separation for wheat and oat grain mixtures is nearly identical, whereas that for sunflower is lower. At the same time, the influence of the grain mixture velocity on power consumption exceeds the effect of specific feed rate by approximately one order of magnitude. It was determined that the total power consumption of the separator actuator ranges from N = 100–192 W during the separation of wheat and oat grain mixtures and from N = 98–178 W during sunflower separation within the specified velocity and feed rate ranges. The power required for seed movement along the sieve varies from N_n = 7–84 W for wheat and oat grain mixtures and from N_n = 5–70 W for sunflower. In addition, a decrease in the rate of power increase with rising specific feed rate was observed, indicating the presence of interparticle interactions within the material layer during separation.

АНОТАЦІЯ
У статті розглянуте питання визначення потужності для приводу оригінального відцентрового пневморешітного сепаратора зерна. Дослідження проведено на виготовленому лабораторному стенді із застосуванням вимірювального комплексу К50. Шляхом проведення лабораторних експериментальних досліджень, авторами встановлені закономірності зміни потужності холостого ходу. Отримано залежності зміни повної потужності на привід сепаратора і потужності на переміщення зерна по решету від швидкості переміщення зернового вороху по решету (V=11.7–19.6 м/с) і питомої подачі зернового вороху трьох зернових культур – пшениці, вівса і соняшника (q_F=9.6–41.6 кг/м^{2}с). Дослідженнями встановлено, що енергоємності сепарації вороху пшениці і вівса є практично однаковою, а соняшника – дещо меншою, при цьому ступінь впливу швидкості переміщення на порядок перевищує значущість параметру питомої продуктивності. Дослідами визначено, що повна потужність на привід сепаратора складає N=100–192 Вт при сепарації вороху пшениці і вівса і N=98–178 Вт – при сепарації вороху соняшника у зазначених діапазонах варіювання швидкості переміщення матеріалу по решету і питомої продуктивності. Потужність, необхідна на переміщення зерна по решету змінюється знаходиться в межах N_n=7…84 Вт для вороху пшениці і вівса та N_n=5–70 Вт для соняшника. При цьому виявлено ефект зменшення приросту потужності при пропорційному збільшенні питомої продуктивності, що вказує на наявність внутрішньошарових відносних переміщень часток.

INTRODUCTION
Ukraine's favourable climate and natural conditions for growing a variety of crops, next to immense human resources, ensured its food security and before 2022 it used to be one of the major players at the world food market (*Vasylkovska et al., 2021 a; Vasylkovska et al., 2021 b*).

Post-harvest cleaning is an important component of preparation for grain processing and storage. The cleaning operation is carried out mainly by pneumatic sieve grain cleaners, which ensure the separation of grain components by aerodynamic properties and size (*Vasylkovskyi et al., 2018*). The efficiency of grain cleaning machines is assessed by technological, operational and other indicators that have an impact on the final cost of the main product – grain (*Vasylkovskyi et al., 2018*). When designing, improving, and investigating agricultural machinery, many studies focus on establishing and justifying indicators of technological efficiency - such as productivity and cleaning quality - which are considered primary factors influencing attractiveness to potential consumers. At the same time, energy-related indicators, including power consumption and the specific energy intensity of the process, are often overlooked. However, these energy characteristics - particularly the energy intensity of the separation process and the required power - have a significant impact on overall production costs (*Vasylkovskyi et al., 2019(a)*).

Therefore, the development of new grain-cleaning machines and the improvement of existing designs require additional research to obtain objective energy data, enabling a clear understanding of the physical processes occurring in the working components and their technological parameters (*Vasylkovskyi et al., 2019*).

The separation of grain mixtures by air flow is the subject of publications by Adamchuk (*Adamchuk et al., 2024*), Stepanenko (*Stepanenko et al., 2024; Stepanenko et al., 2023; Stepanenko et al., 2019*), Nesterenko (*Nesterenko et al., 2017*) and Bakum (*Bakum et al., 2016*). The works have created mathematical models of the movement of grain mixture elements during separation. The trajectories of particle movement have been constructed and the basic design parameters of pneumatic separators and their relationship to technological efficiency indicators have been substantiated.

Scientific publications Aliiev (*Aliiev et al., 2019*), Bakum (*Bakum et al., 2022*), Holiachuk (*Holiachuk, 2012*), Kharchenko (*Kharchenko et al., 2019 Kharchenko, 2017*), Piven (*Piven et al., 2020; Piven et al., 2018*) and Tishchenko (*Tishchenko et al., 2016; Tyshchenko et al., 2011*) have established the theoretical basis for the sieve separation of grain mixtures by size in the field of vibration. The works determine the nature of the movement and patterns of particle sieving, which makes it possible to assess the quality of grain mixture separation.

In the works Bredykhin (*Bredykhin et al., 2021*), Dudarev and Kirchuk (*Dudarev et al.,2021; Dudarev, Kirchuk, 2017*), Kobets (*Kobets et al., 2013*), Olkhovskyi (*Olkhovskyi et al., 2021*), Pascoe (*Pascoe et al., 2015*), Rahou (*Rahou et al., 2013*) and Stanger (*Stanger et al., 1977*) describe the operation and results of research on original designs of grain cleaning machines that separate and sort loose mixtures by density, surface shape and other characteristics.

However, the purpose of the above-mentioned works was to justify the geometric, kinematic, or technological parameters of machines and their working bodies. At the same time, the issue of energy efficiency, an important operational indicator, was not investigated.

MATERIALS AND METHODS

At the Department of Agricultural Engineering of the Central Ukrainian National Technical University (CUNTU, Ukraine), an inertial direct-flow separator (fig. 1-4) was developed and manufactured to provide air and sieve cleaning of grain mixtures (*Nesterenko et al., 2017; Vasylkovskyi et al., 2019(b)*).

The operation of the pilot separator is as follows. When the rotor rotates, the blades generate a powerful airflow that is used to remove light impurities through the outlet of channel *2*, even during continuous feeding of the grain mixture. The mass, cleared of light impurities, is directed along path *3* to the arcuate sieve *4*, where it is captured by the rotor blades *1* and accelerated, forming a material layer approximately one grain thick. Separation of fine impurities on the sieve occurs under the combined action of centrifugal force and particle gravity. The cleaned grain is discharged from the machine due to its high initial velocity upon leaving the sieve and the appropriate inclination angle of the discharge unit 5. Cleaning of the sieve apertures from clogging is ensured by the action of the same rotor blades.

As a result of a patent search, no analogous designs were identified either in Ukraine or worldwide. During experimental studies, the main indicators of the separator's energy consumption under idle operating conditions (without grain feed) were determined (*Vasylkovskyi et al., 2018*).

Therefore, an important research task is to determine the total power required for the separator drive, the power consumed directly for grain movement along the sieve, and to establish their dependence on the key design parameters of the blade rotor and the machine throughput.

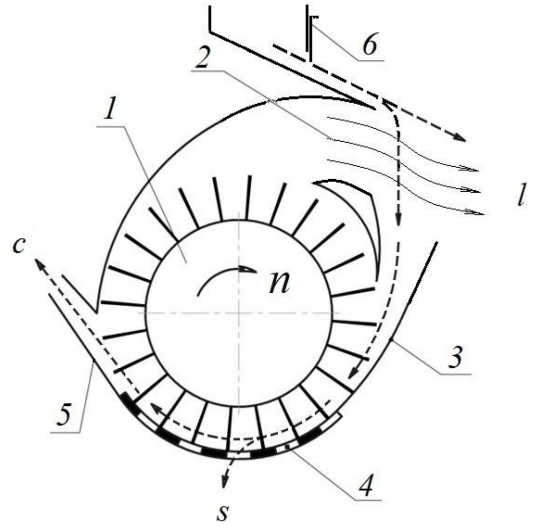


Fig. 1 - Scheme of the experimental pneumatic sieve separator of a grain cleaning machine:
1 - bladed rotor; 2 - air channel; 3 - guide; 4 - arcuate sowing sieve; 5 - inertial unloader of cleaned grain; 6 - hopper; l - light impurities; s - small impurities; c - cleaned grain

Fig. 2 - General view of the experimental separator (with the sidewall removed)

Fig. 3 - General view of the sieve

Fig. 4 - General view of the blade rotor

The purpose of this study is to determine the energy intensity of an original air-sieve grain separator. To address this objective, a laboratory test bench was employed that fully reproduced the experimental separator. The bladed rotor was driven by an electric motor via V-belts and a variator, which allowed the required rotational speed to be set. The power required to drive the bladed rotor was measured using a K50 measuring device.

The most influential factors affecting the energy intensity of the separation process were identified and ranked as follows:

- specific separator performance, defined as the throughput per unit sieve area;
- grain movement speed.

Since the grain material is transported along the arcuate sieve by the rotor blades, the circumferential speed was adopted as the governing parameter, corresponding to the linear velocity of the rotor blade tips.

The experiments were conducted using natural grain mixtures of wheat, oat, and sunflower obtained directly after harvesting by combine harvesters. The separator throughput was regulated by adjusting the position of the hopper gate, while the feed rate was determined using a stopwatch method.

The specific productivity was varied within the range q_F=9.6–41.6 kg/m^{2}s, which corresponds to mass feed rates of q = 0.2–0.83 kg/s for a sieve area of 0.02 m^2.

The circumferential speed was varied in the range V=11.7…19.6 m/s, which was achieved by changing the rotor rotational speed from 900 to 1500 rpm, given an outer rotor radius of 0.125 m and a total of 24 brush blades.

The power consumption was measured using the K50 measuring complex.

The results of the experimental studies were processed according to the generally accepted methodology (*Pascoe et al., 2015; Vasylkovskyi et al., 2016*).

The total power required to drive the separator consists of two main components: the idle power, consumed to overcome air resistance, bearing friction, and other mechanical losses, and the power required to transport the grain along the sieve, which is practically impossible to measure directly. Therefore, this latter component was determined by calculating the difference between the total power and the idle power.

To analyse the experimental data, statistical models were employed using Microsoft Excel and the STATISTICA software package (*Vasylkovskyi et al., 2016*).

RESULTS

In accordance with the stated objectives, the first stage of the study established the relationship between idle power and rotor circumferential speed over the entire range of investigated values (Fig. 6).

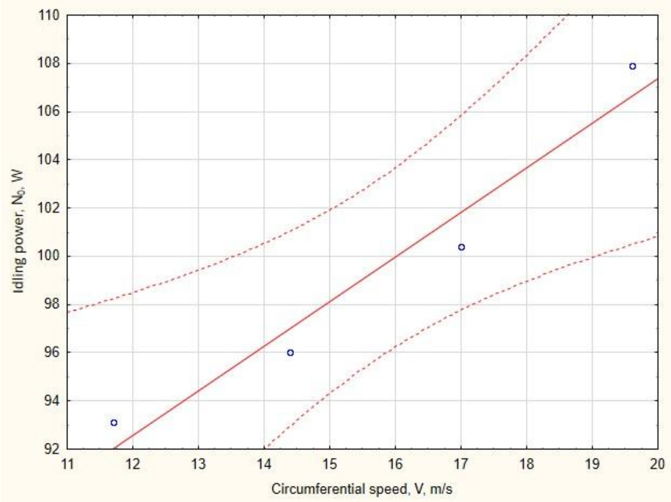


Fig. 6 - Relationship between idle power and rotor circumferential speed, W

Idle power:

$$N_0 = 70.3979 + 1.8477 \cdot V \tag{1}$$

The resulting slightly curved relationship (Fig. 6) reflects the characteristic classical laws governing rotational mechanics. The fact that the function varies by only about 16% over a wide range of the independent variable (nearly a twofold increase in circumferential speed) indicates that the separation process operates under non-critical aerodynamic conditions.

At the second stage of the study, experiments were conducted to determine the total power required to drive the separator when processing different grain materials. The results of the total power measurements are presented in Fig. 7.

The experiments revealed no significant difference in energy performance between the separation of wheat and oat grain heaps (Fig. 7a). At the same time, a slight reduction in power consumption – by approximately 10-14% – was observed during sunflower separation. This effect can be attributed to differences in seed geometry and friction coefficients among the tested crops. The experimental data obtained can be satisfactorily approximated by the following polynomial relationships.

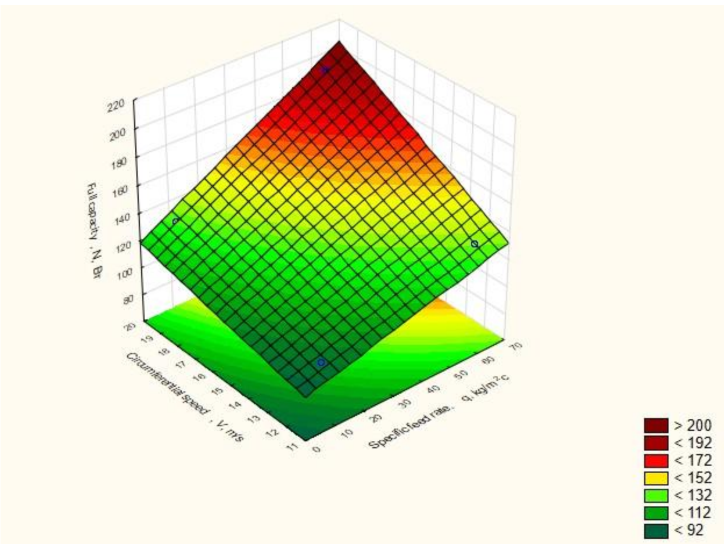
For wheat and oat grain heaps:

$$N = 59.12496 - 0.21608 \cdot q + 2.98174 \cdot V + 0.07179 \cdot q \cdot V \tag{2}$$

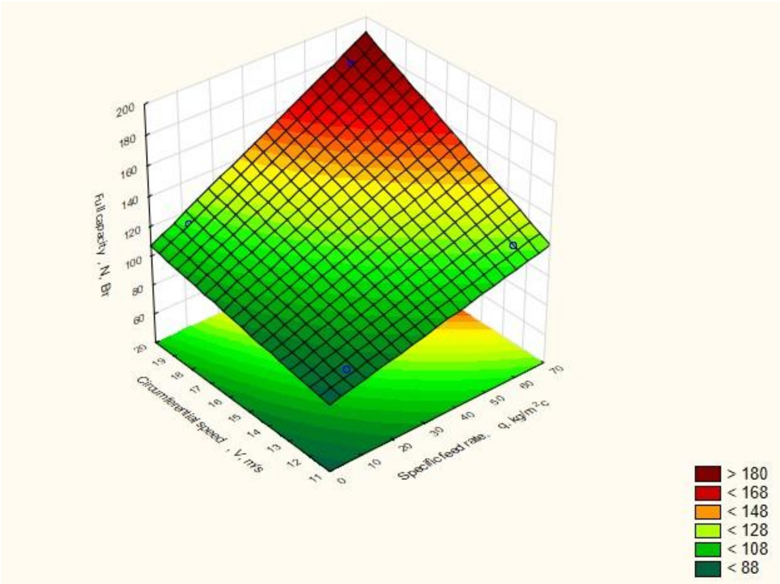
For the sunflower grain heap:

$$N = 57.86220 - 0.30078 \cdot q + 2.45244 \cdot V + 0.07418 \cdot q \cdot V \tag{3}$$

The power consumed for grain transport along the sieve was determined as the difference between the total power (Fig. 7) and the idle power (Fig. 6) at the corresponding grain transport speeds, as illustrated in Fig. 8.



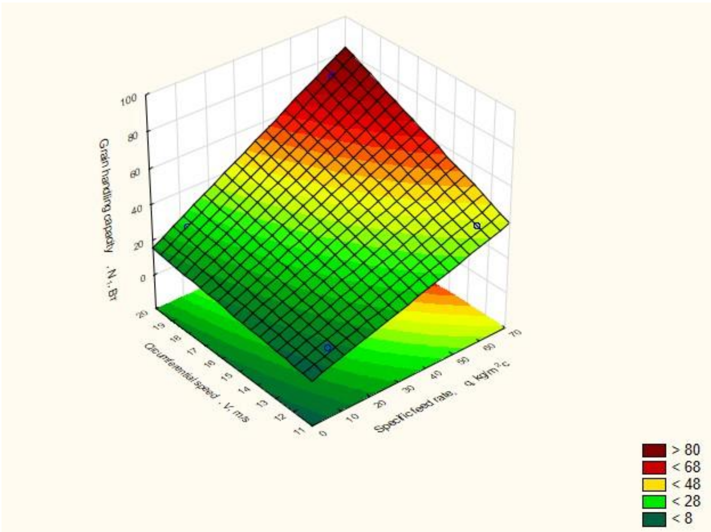
a)



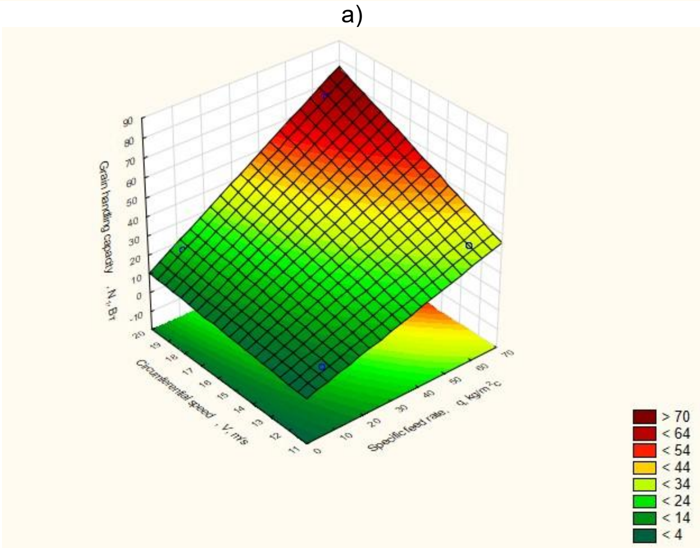
b)

Fig. 7 - Relationship between the total separator drive power and specific productivity at different grain movement speeds, W:

a – wheat and oat grain heaps; b – sunflower grain heap



a)



b)

Fig. 8 - Relationship between the power required for grain transport along the sieve and specific feed rate at different grain movement speeds, W

a – wheat and oat grain heaps; b – sunflower grain heap

The empirical polynomial relationships obtained are as follows.

For wheat and oat grain heaps:

$$N_1 = -7.4216 - 0.08662 \cdot q + 1.1402 \cdot V + 0.05264 \cdot q \cdot V; \quad (4)$$

For the sunflower grain heap:

$$N_1 = -4.34685 - 0.15243 \cdot q + 0.73748 \cdot V + 0.055504 \cdot q \cdot V. \quad (5)$$

Approximation of the experimental data reveals a nonlinear dependence of the power required for grain transport along the sieve on increasing productivity. A reduction in the rate of power increase with a proportional rise in feed rate may indicate a significant increase in the thickness of the grain layer on the sieve (exceeding a single-grain layer), as well as the occurrence of intralayer relative particle motion. Under these conditions, internal friction coefficients become lower than external friction coefficients.

The general character of the obtained dependencies for wheat and oat grain heaps is similar to that observed for sunflower grain heap separation.

CONCLUSIONS

The following conclusions were drawn from the experimental studies:

1. The idle power consumption of the experimental pneumatic sieve separator ranges from 93 to 108 W, as the circumferential speed of the rotor blade tips increases from 11.7 to 19.6 m/s.

2. The total power required to drive the separator depends significantly on both the grain movement speed along the sieve and the specific productivity. However, the influence of grain movement speed is approximately one order of magnitude greater than that of specific productivity. The total power demand ranges from 100 to 192 W during the separation of wheat and oat grain heaps and from 98 to 178 W during sunflower separation, within a grain movement speed range of 11.7–19.6 m/s and a specific productivity range of q_F = 9.6–41.6 kg/m^{2}s.

3. The power consumed for grain transport along the sieve varies from 7 to 84 W for wheat and oat grain heaps and from 5 to 70 W for sunflower. The observed reduction in the rate of power increase with a proportional rise in specific productivity indicates a probable increase in grain layer thickness on the sieve, exceeding a single-grain layer, as well as the presence of intralayer relative particle motion.

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REFERENCES

[1] Adamchuk V., Bulgakov V., Ivanovs S., Holovach I., Ihnatiev Y. (2021). Theoretical study of pneumatic separation of grain mixtures in vortex flow. *Engineering for Rural Development,* 20, 657-664.

[2] Aliiev E., Gavrilchenko A., Tesliuk H., Tolstenko A., Koshulko V. (2019). Improvement of the sunflower seed separation process efficiency on the vibrating surface. *Acta Periodica Technologica,* 50, 12-22. https://doi.org/10.2298/apt1950012a

[3] Bakum M.V., Kharchenko S.O., Kovalyshyn S.Y., Kiełbasa, P., Miernik A. (2022). Identification of parameters of the separation process of safflower seed material on sieves. *Journal of Physics: Conference Series,* 2408(1), 012013. https://doi.org/10.1088/1742-6596/2408/1/012013

[4] Bakum M.V., Krekot M.M., Abduiev M.M. (2016). Results of studying the influence of control parameters on the efficiency of separation of radish seed mixture by a pneumatic separator with an inclined channel (Результати дослідження впливу параметрів регулювання на ефективність розділення суміші насіння редьки пневматичним сепаратором з похилим каналом). *Bulletin of Sumy National Agrarian University (Вісник Сумського національного аграрного університету): Mechanization and automation of production processes*, 10 (2), 67-71. Ukrainian

[5] Bredykhin V., Pak A., Gurskyi P., Denisenko S., Bredykhina K. (2021). Improving the mechanical-mathematical model of pneumatic vibration centrifugal fractionation of grain materials based on their density. *Eastern-European Journal of Enterprise Technologies,* 4(1), 54-60. https://doi.org/10.15587/1729-4061.2021.236938

[6] Dudarev I., Kirchuk R. (2017). Simulation of bulk materials separation process in spiral separator. *INMATEH - Agricultural Engineering,* 53(3). 57-64.

[7] Dudarev I., Olkhovskyi V., Panasyuk S., Khomych S. (2021). Simulation of the bulk and granular materials separation process in the scissor type gravity separator. *Advances in Design, Simulation and Manufacturing IV (Lecture Notes in Mechanical Engineering: Conference Paper).* 218-227. https://doi.org/10.1007/978-3-030-77823-1_22
[8] Holiachuk S.Ie. (2012). Grain separation using gravitational forces. *Interuniversity collection "Scientific Notes"*, 39, 27-33. Ukrainian
[9] Kharchenko S., Zavgorodniy A., Kharchenko F., Kovalishin S., Mikhaylov, Y. (2019). Effective sifting of flat seeds through sieve. *INMATEH - Agricultural Engineering*, 58(2), 17-26.
[10] Kharchenko S.O. (2017). *Intensification of grain sifting on flat sieves of vibration grain separators (Інтенсифікація просіювання зерна на плоских решетах вібраційних зерноочисників).* Kharkiv: «Disa+», Ukraine. 220 p. Ukrainian
[11] Kobets A.S., Chursinov Yu.O., Chernykh S.A., Sabadash M.P., Hrekova N.V., Kanunnikov V.P. (2013). *Machinery and equipment for grain storage and processing (Машини та обладнання для зберігання та переробки зерна)*. Dnipropetrovsk: DSAU, Ukraine. 766 p. Ukrainian
[12] Nesterenko O.V., Leshchenko S.M., Vasylkovskyi O.M., Petrenko D.I. (2017). Analytical assessment of the pneumatic separation quality in the process of grain multilayer feeding. *INMATEH - Agricultural Engineering,* 53(3), 65-70.
[13] Olkhovskyi V.O., Dudarev I.M. (2021). Grain separation methods and separators. *Agricultural machinery,* 47, 102-112. https://doi.org/10.36910/acm.vi47.655
[14] Pascoe R.D., Fitzpatrick R., Garratt J.R. (2015). Prediction of automated sorter performance utilising a Monte Carlo simulation of feed characteristics. *Minerals Engineering,* 72, 101-107. https://doi.org/10.1016/j.mineng.2014.12.026
[15] Piven M., Spolnik A., Sychova T., Piven, A. (2020). Patterns of influence exerted by the side walls of a vibratory sieve on the motion of a loose mixture flow. *Eastern-European Journal of Enterprise Technologies*, 4(1(106), 29–38. https://doi.org/10.15587/1729-4061.2020.208640
[16] Piven M., Volokh V., Piven A., Kharchenko S. (2018). Research into the process of loading the surface of a vibrosieve when a loose mixture is fed unevenly. *Eastern-European Journal of Enterprise Technologies,* 6(1(96), 62–70. https://doi.org/10.15587/1729-4061.2018.149739
[17] Rahou F., Tilmatine A., Bilici M., Dascalescu L. (2013). Numerical simulation of the continuous operation of a tribo-aero-electrostatic separator for mixed granular solids. *Journal of Electrostatics*, 71 (5), 867–874. https://doi.org/10.1016/j.elstat.2013.06.004
[18] Stanger E.A. (1977). Graing - cleaning machinery. *Milling feed and fertiliser*, 160(8), 11-15.
[19] Stepanenko S., Kotov B., Kuzmych A., Demchuk I., Melnyk V., Volyk D. (2024). Modelling of aerodynamic separation of grain material in combined centrifugal-pneumatic separator. *Proceedings of 23rd International Scientific Conference Engineering for Rural Development,* 23, 1143-1149. https://doi.org/10.22616/ERDev.2024.23.TF236
[20] Stepanenko S., Kotov B., Kuzmych A., Kalinichenko R., Hryshchenko V. (2023). Research of the process of air separation of grain material in a vertical zigzag channel. *Journal of Central European Agriculture,* 24 (1), 225-235. https://doi.org/10.5513/JCEA01/24.1.3732
[21] Stepanenko S., Rogovskii I., Titova L., Trokhaniak V., Trokhaniak O. (2019). Experimental study in a pneumatic microbiocature separator with apparatus camera. *Bulletin of the Transilvania University of Brasov, Series II: Forestry, Wood Industry, Agricultural Food Engineering,* 12(61), 1, 117-128. https://doi.org/10.31926/but.fwiafe.2019.12.61.1.10
[22] Tishchenko L., Kharchenko S., Kharchenko F., Bredykhin V., Tsurkan, O. (2016). Identification of a mixture of grain particle velocity through the holes of the vibrating sieves grain separators. *Eastern-European Journal of Enterprise Technologies*, 2(7(80), 63–69. https://doi.org/10.15587/1729-4061.2016.65920
[23] Tyshchenko L.N, Olshansky V.P., Olshansky S.V. (2011). *Vibrating sieve separation of grain mixtures (Вібраційне просіювання зернових сумішей)*. Kharkiv: Miskdruk, Ukraine. 280 p. Ukrainian
[24] Vasylkovska K., Andriienko O., Vasylkovskyi O., Andriienko A., Popov V., Malakhovska V. (2021 b). Dynamics of export potential of sunflower oil in Ukraine. *HELIA,* 44(74), 115-123. https://doi.org/10.1515/helia-2021-0001

[25] Vasylkovska K., Vasylkovskyi O., Popova S., Malakhovska V. (2021 a). The directions for optimizing Ukraine's export potential of grain crops in the context of changing climatic conditions. *Bulletin of the Transilvania University of Braşov. Series V: Economic Sciences,* 14(63)-1, 129-136. https://doi.org/10.31926/but.es.2021.14.63.1.14

[26] Vasylkovskyi O. M. Leshchenko S. M. Vasylkovska K. V., Petrenko D.I. (2016). The textbook of a researcher. Study guide for students of agrotechnical specialties (Підручник дослідника: Навчальний посібник для студентів агротехнічних спеціальностей). Kharkiv: Machulin, Ukraine. 204 p. Ukrainian

[27] Vasylkovskyi O., Vasylkovska K., Moroz S., Sviren M., Storozhyk L. (2019 b). The influence of basic parameters of separating conveyor operation on grain cleaning quality. *INMATEH - Agricultural Engineering,* 57(1). 63-70. https://doi.org/10.35633/INMATEH_57_07

[28] Vasylkovskyi O.M., Leshchenko S.M., Moroz S.M., Petrenko D.I. (2018). Investigation of the energy intensity of the centrifugal grain separator idling (Дослідження енергоємності холостого ходу відцентрового сепаратора зерна). *Design, production and operation of agricultural machinery (Конструювання, виробництво та експлуатація сільськогосподарських машин). National interdepartmental scientific and technical collection,* 48, 176-183. https://doi.org/10.32515/2414-3820.2018.48.176-183 Ukrainian

[29] Vasylkovskyi O.M., Leshchenko S.M., Moroz S.M., Petrenko D.I. (2019 a). Experimental studies of the energy consumption of a centrifugal direct-flow grain separator (Експериментальні дослідження енергоємності роботи відцентрового прямоточного сепаратора зерна). *Design, production and operation of agricultural machinery (Конструювання, виробництво та експлуатація сільськогосподарських машин). National interdepartmental scientific and technical collection,* 49, 67-74. https://doi.org/10.32515/2414-3820.2019.49.67-74 Ukrainian