

ENSURING GRAIN CLEANING IN BLACKOUT CONDITIONS: SUBSTITUTION AND MINIMIZATION OF ENERGY CONSUMPTION OF AIR AND SIEVE SEPARATION OF GRAIN MATERIALS

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The article is devoted to the problem of ensuring effective cleaning of grain materials at minimal electricity consumption, which is relevant for wartime conditions and unstable energy supply. Based on elements of probability theory, a mathematical model of the sieve separation process for sieves with slots of variable size has been developed and the dependence of cleaning efficiency on the design parameters of the sieve and the speed regime has been theoretically substantiated. The relationship between the live cross-section coefficient of the sieve cloth and the specific energy consumption of the process has been analytically established: it is shown that an increase in the live cross-section coefficient from $k_l = 0,50$ to $k_l = 0,95$ reduces the specific electricity consumption from 0.35-0.55 to 0.18-0.28 kWh/t. The condition for automatic self-cleaning of sieves with slots of variable size was derived, which eliminates the need for a separate cleaning device and provides savings of 0.08-0.15 kWh/t. The theory of gravitational aspiration of the grain flow was developed: an expression for the ejection velocity of air in a vertical channel was obtained and it was shown that at a productivity of 10 t/h and a free fall height of 1.0 m, an air flow velocity of ≈ 0.94 m/s is achieved, sufficient for the separation of light impurities without external energy consumption. It is substantiated that the use of string screens with a live cross-section coefficient of 93-99% in combination with a gravitational aspiration zone allows reducing the total specific electricity consumption from 0.75-1.20 to 0.18-0.35 kWh/t (savings of about 74%). The concept of a minimum-energy grain cleaning machine based on four functional blocks is proposed: a string screen, a lightweight vibrating screen, a gravitational aspiration zone and a LiFePO₄ battery power module with a capacity of 10-20 kWh, suitable for power supply from battery stations or photovoltaic panels in conditions of power outages.

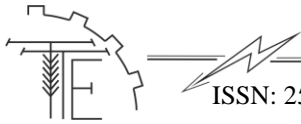
Keywords: grain cleaning machine, blackout, energy saving, sieve separation, aspiration, variable-sized slots, string sieve, gravity blowing, probability theory, mathematical model.

Eq. 5. Fig. 1. Tabl. 2. Ref. 21.

1. Problem formulation

Large-scale attacks on critical infrastructure facilities in Ukraine have turned blackouts into a systemic phenomenon covering industrial enterprises, elevators and agricultural production. In conditions where the duration of outages reaches 12-20 hours per day, traditional grain cleaning complexes with a specific capacity of 0.75-1.20 kWh/t become unviable: after harvesting, uncleaned grain with a moisture content of over 16% requires processing within 24-48 hours, otherwise there is a critical decrease in germination and food quality. Finding ways to minimize energy consumption in technological operations of grain cleaning is gaining not only scientific and technical, but also strategic importance for ensuring the food security of the state. The two most energy-intensive processes – sieve and air separation – deserve special attention, which together consume up to 85% of all electricity. At the same time, a significant part of the consumed power is spent not on the useful work of separation, but on overcoming the design shortcomings of traditional screens - cleaning from clogging, which





also have a small live cross-section coefficient, maintaining excessive air flow from the fan, etc. The lack of systematic theoretical justification in the literature for design solutions of grain cleaning machines specifically aimed at working with limited or intermittent power supply determines the relevance of this study.

2. Analysis of recent research and publications

The theoretical foundations of sieve separation are laid in works [1-3], where the dependences between the speed of movement of the grain layer, the height of the layer and the probability of particles passing through the gaps were established. However, these models do not take into account the self-cleaning of the sieves, which significantly affects the energy consumption of the process. Luzan P.G., Kisilov R.V. and Luzan O.R. [4] developed a mathematical model of the separation of grain mixtures on sieves with gaps of variable size based on probability theory. The model describes the probability of particle separation as the product of three independent events: the location of the center of mass of the particle above the gap plane; the possibility of passing through the gap; the absence of previously unseeded particles in the lower layers. The combined solution of the obtained equations allows us to determine the optimal sieve length, grain speed and reduction coefficient depending on the dimensional characteristics of the grain mixture. It has been established that the metal content of such machines is reduced by 12-14%, and the quality of cleaning is increased by 10-12%.

The concept of an “ideal” sieve of a grain separator was developed by Vasylykovsky O.M. et al. [5]. The concept of the coefficient of live cross-section was introduced $k_l = A_o / A_p$ and it was found that for string fabrics with longitudinal elements with a diameter of 0.15–0.28 mm this coefficient reaches 93-99%, while for standard stamped fabrics it does not exceed 45-5%. Spectra/Dyneema type material provides a breaking load of 9-20 kg at the indicated diameters with “absolute inextensibility”.

The issues of energy-efficient aspiration are considered in works [6-8]. The analysis shows that traditional centrifugal fans consume 0.40-0.80 kWh/t. Gravity aspiration schemes practically do not require external energy [9], however, their efficiency significantly depends on the geometry of the separation channel and the distribution of air flow speeds, which requires theoretical justification.

Thus, even despite thorough research [10-14], the available literature lacks a comprehensive theoretical justification that would directly link the design parameters of the sieve cloth and aspiration system with the specific energy consumption indicators and operating conditions under autonomous power supply.

3. The purpose of the article

The aim of the work is to develop, based on the analysis of the concept of a grain cleaning machine, a design with minimum energy consumption suitable for operation under blackout conditions.

4. Results and discussion

The most informative indicator that combines the technological and energy characteristics of the sieves is the specific electricity consumption per unit mass of grain material per unit time. As stated in the problem statement, a significant part of the power consumption of general-purpose grain cleaning machines is spent on ensuring separation in conditions of low live cross-section coefficient, cleaning holes from clogging, maintaining excessive air flow from the fan. Therefore, let's consider the possibilities of increasing the energy efficiency of the structure in the following three directions.

Direction 1 - increasing the specific energy efficiency by increasing the live cross-section coefficient of the sieves.

Specific energy consumption for the sieve drive (vibrostand):

$$w_p = \frac{N}{Q} \quad (1)$$

where N – vibrostand drive power, kW; Q – productivity, t/h.

Power N proportional to the mass of the moving parts. The transition from a stamped web (the live cross-section coefficient $k_l = 0,50$) to the string [15] ($k_l = 0,95$) reduces the mass of the web approximately 10 times, and the mass of the vibrostand - by 20-35%.

Dependence of specific electricity consumption on k_l is approximated by the expression [4, 5]:

$$w_p(k_l) \approx \frac{w_0 \cdot (1 - k_l)^{0,6}}{(1 - k_{l0})^{0,6}} \quad (2)$$



Substituting into formula (2) the values of the live cross-section coefficients of the corresponding types of sieves k_l and their specific energy consumption of the basic sieve w_0 we will obtain the value of specific electricity consumption, which are given in the third column of table 1 (lines 1-3).

Direction 2 - increasing specific energy efficiency due to self-cleaning of sieves.

Technically, self-cleaning can be ensured by using sieves with working openings (slots) of variable size (Fig. 1), which expand in the direction of longitudinal movement of the processed material. This is especially organic in the case of rod and string sieves on grain materials that have various physical-mechanical and mechanical-technological properties [16]. Here, self-cleaning occurs without additional energy consumption, which eliminates the need for a separate cleaning device (savings are 0.08–0.15 kWh/t).

Direction 3 - increasing specific energy efficiency due to the use of gravitational aspiration of the grain flow (light particle rejection method).

Classical (vertical) aspiration [17-19] of grain materials involves giving the ascending air flow a significant velocity, which leads to significant energy consumption.

The critical velocity of a particle in the ascending air flow is:

$$v_v = \sqrt{\frac{4 \cdot g \cdot d_e \cdot (\rho_{corn} - \rho_{pov})}{3 \cdot C_x \cdot \rho_{pov}}} \quad (3)$$

For wheat $v_g = 8,5-11,5$ m/s, for half and dust $v_g = 0,3-2,5$ m/s. Condition for separation of light impurity: $v_h < v_a < v_{vcom}$.

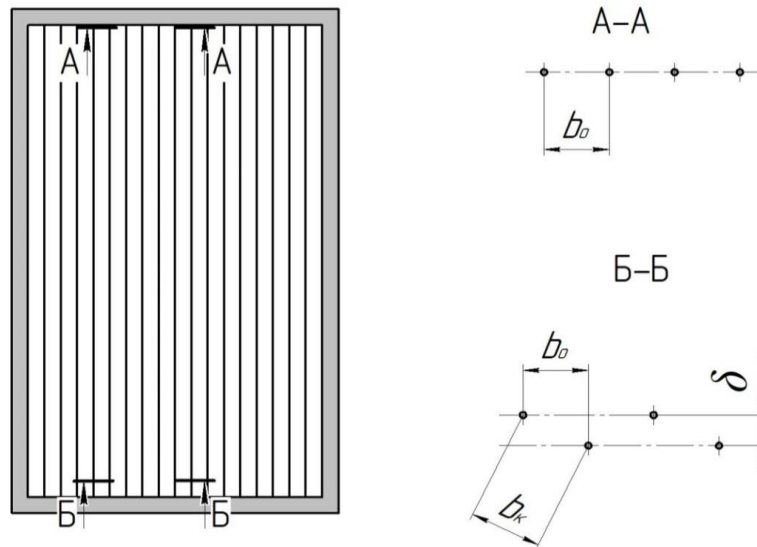


Fig. 1. Technical support for self-cleaning of sieves with working holes (slots) of variable size

In the gravity scheme, the air flow is formed by the ejection effect of the grain flow. The velocity of the ejected air:

$$v_a = \frac{\eta_e \cdot (Q \cdot v_3)}{\rho_{pov} \cdot F_k \cdot 3600} \quad (4)$$

where Q – productivity, t/h; v_3 – grain falling speed, m/s; η_e – ejection coefficient (0.12-0.25); F_k – channel cross-sectional area, m².

Under the conditions: $Q = 10$ t/h, $v_3 = 4,5$ m/s, $F_k = 0,04$ m², $\eta_{ex} = 0,18$ we get $v_a \approx 0,94$ m/s, which is sufficient to separate light impurities without external energy consumption.

Use of a small-sized booster fan ($N_B \approx 0,32$ кВт) increases v_a to 1,5-2,5 m/s and reduces the specific air separation flow rate to $w_a \approx 0,032$ kWh/t, which is 12-25 times less than the traditional scheme.

Taking into account the above, the total specific electricity consumption of the process:

$$w_\Sigma = w_p + w_a + w_{dop} \quad (5)$$

where $w_{дон} = 0,03-0,06$ kWh/t – average costs for auxiliary equipment.

Thus, for serial machines, the total specific electricity consumption will be $W_\Sigma = 0,72$ kWh/t.

For the proposed concept (string sieve + gravity aspiration) $w_\Sigma = 0,29$ kWh/t, which is almost 2.5 times less.

Comparative characteristics of different variants of the applied working bodies are given in Table 1.

**Comparative characteristics of separation methods by specific energy consumption**

Separation method	Working body design	Specific power, kWh/t
Sieve (standard)	Flat stamped grille	0,35–0,55
Sieve (variable-sized slots)	Self-cleaning sieve with rods	0,20–0,30
Mesh (string/bar)	String or bar canvas	0,18–0,28
Air (fan)	Centrifugal fan	0,40–0,80
Air (gravity)	Natural thrust + deflector	0,00–0,05
Combined (string + passive aspiration)	String web + gravity channel	0,18–0,35

Justification of the autonomy of the grain cleaning machine from the power source.

The key parameter for blackout conditions is autonomy - the number of hours of continuous operation from a battery source.

The power consumed by the machine proposed by us at a productivity of $Q = 10$ t/h is 2.9 kW. For a serial machine, operation under similar conditions will be characterized by power consumption at the level of $N_{\text{sar}} = 7,2$ kW. That is, the proposed concept consumes 2.5 times less power, which directly affects the choice of an autonomous power source [20-21] (Table 2).

Table 2

Comparison of battery autonomy for different machine schemes

Work scheme	Power type	Battery capacity, kWh	Autonomy at $Q=10$ t/h, h
Classic machine (0.72 kWh/t)	380 V network	–	0 (network dependency)
Proposed concept (0.27 kWh/t)	Battery + inverter	5	$\approx 1,9$
Proposed concept (0.27 kWh/t)	Battery + inverter	10	$\approx 3,7$
Proposed concept (0.27 kWh/t)	SES (2 kW) + battery 10 kWh	10	unlimited (daytime)

From Table 2 it follows that a battery station with a capacity of 10 kWh, which costs significantly less than a diesel generator of the corresponding capacity, ensures the operation of the proposed machine for 3.7 h at a productivity of 10 t/h, i.e. processing of 37 t of grain in one cycle of autonomous operation. In combination with solar panels with a capacity of 2 kW, autonomy during the daytime becomes practically unlimited, since generation (2 kW) is comparable to consumption (2.9 kW).

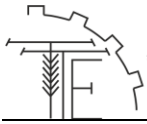
Based on the theoretical justifications set out above, a concept of a grain cleaning machine has been formed, which includes four main units.

1. String screen cloth (seeding + earing) with longitudinal elements with a diameter of 0.15-0.28 mm (Spectra/Dyneema type material). Live cross-section coefficient $k_l = 0,93-0,99$. Width of the slots $b_0 = 2,0-2,5$ mm (sowing), $b_0 = 3,0-5,0$ mm (spike). The absence of transverse partitions eliminates jamming and the need for a cleaning mechanism.

2. Vibrostand with crank drive from an electric motor. The motor is powered via an inverter from a battery or mains. The reduced mass of the vibrostand (thanks to the stringed canvas) reduces starting currents and allows the use of compact inverters.

3. Gravity aspiration zone – a vertical or inclined channel with a deflector distributor, which forms an ejection air flow $v_a \approx 0.9-1.2$ m/s due to the kinetic energy of the grain flow. For a guaranteed result – an additional microfan with a capacity of 0.15-0.30 kW, connected to a renewable source or network if available.

4. LiFePO₄ power module with a capacity of 10-20 kWh with a 5 kW inverter and a charger compatible with solar panels (MPPT). When fully charged, the module provides 3.7-7.4 hours of autonomous operation at $Q = 10$ t/h.



5. Conclusion

The dependence of the efficiency of sieve separation on the design parameters of the sieve is theoretically substantiated: it is shown that an increase in the live cross-section coefficient from $k_l = 0,50$ to $k_l = 0,95$ reduces the specific electricity consumption from 0.35-0.55 to 0.18-0.28 kWh/t due to the reduction of the mass of the vibrating screen and the increase in the active area of the sieve.

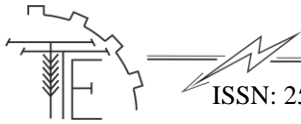
A condition for automatic self-cleaning of sieves with slots of variable size has been established, which eliminates the need for a separate cleaning device and saves 0.08-0.15 kWh/t.

The total specific electricity consumption of the proposed concept (stringed canvas + gravitational aspiration) is $w\Sigma = 0,29$ kWh/t, which is 2.5 times less than serial grain cleaning machines ($w\Sigma \approx 0,72$ kWh/t).

With a power of 2.9 kW, the proposed machine is compatible with 10 kWh battery stations (autonomy ≈ 3.7 h at $Q = 10$ t/h) and 2 kW solar panels, which is a sufficient condition to ensure grain processing in blackout conditions. A serial machine with a power of 7.2 kW requires a diesel generator or a powerful UPS, which is a much more expensive and complex solution.

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ОЧИЩЕННЯ ЗЕРНА В УМОВАХ БЛЕКАУТИВ: ОБҐРУНТУВАННЯ ТА МІНІМІЗАЦІЯ ЕНЕРГОСПОЖИВАННЯ ПОВІТРЯНО-РЕШІТНОЇ СЕПАРАЦІЇ

У статті розглянуто актуальну проблему енергоефективного очищення зерна в умовах воєнного часу та блекаутів, коли традиційні зерноочисні комплекси з питомим енергоспоживанням 0,75–1,20 кВт·год/т стають непридатними до роботи під час відключень електроенергії тривалістю 12–20 годин на добу. На основі теорії ймовірностей розроблено математичну модель решітної сепарації на решетах із щілинами змінного розміру та теоретично обґрунтовано залежність ефективності очищення від конструктивних параметрів і швидкісного режиму. Виведено аналітичний вираз, що пов'язує коефіцієнт живого перерізу решета з питомим енергоспоживанням: показано, що збільшення коефіцієнта живого перерізу від $kl = 0,50$ до $kl = 0,95$ знижує питоме енергоспоживання з 0,35–0,55 до 0,18–0,28 кВт·год/т. Встановлено умову автоматичного самоочищення решіт зі змінним зазором, що усуває потребу в окремому очисному механізмі та забезпечує економію 0,08–0,15 кВт·год/т. Розроблено теорію гравітаційної аспірації зернового потоку: виведено вираз для швидкості ежекційного повітря у вертикальному каналі та показано, що за продуктивності 10 т/год і висоти вільного падіння 1,0 м у каналі площею поперечного перерізу 0,04 м² досягається швидкість повітря приблизно 0,94 м/с, достатня для відокремлення легких домішок без будь-яких зовнішніх витрат енергії. Обґрунтовано, що використання струнних решіт із коефіцієнтом живого перерізу 93–99 % у поєднанні з гравітаційною аспіраційною зоною знижує загальне питоме енергоспоживання з 0,75–1,20 до 0,18–0,35 кВт·год/т, що становить економію близько 74 %. Запропоновано концепцію зерноочисної машини з мінімальним енергоспоживанням, яка включає чотири функціональні вузли: струнний решітний стан, полегшену вібраційну раму, гравітаційну аспіраційну зону та акумуляторний модуль живлення LiFePO₄ ємністю 10–20 кВт·год, що робить її придатною до роботи від акумуляторних систем зберігання енергії або фотоелектричних панелей під час відключень електроенергії.

Ключові слова: зерноочисна машина, блекаут, енергозбереження, решітна сепарація, аспірація, решето зі змінним зазором, струнне решето, гравітаційна аспірація, теорія ймовірностей, математична модель.

Ф. 5. Рис. 1. Табл. 2. Літ. 21.

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