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THE GRAIN CLEANING PRODUCTION LINES' ENERGYSAVING OPERATION MODES OF ELECTROMECHANICAL SYSTEMS

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ABSTRACT

The research was aimed at reducing the power consumption for grain cleaning by using energy-saving modes in the electromechanical systems of grain cleaning units. Specific consumption of active energy per production unit was adopted as a criterion for assessing energy-saving operation modes. The applied method of mathematical experiment planning (MEP) reduced the number of experiments to a minimum to obtain a reliable mathematical model of the research object. To determine the optimal specific power consumption, a theoretical method was developed to rebuild the mathematical model. Thus, the minimum specific power consumption of grain cleaning production lines was obtained, which allowed developing science-based rates of power usage that allow energy savings up to 8-10%.

Introduction

Energy efficiency is one of the key principles intended to ensure secure, sustainable, competitive and affordable energy supply in the European Union. Rational use of power in grain-cleaning units with energy-intensive technological equipment is especially relevant these days, as it complies with the energy efficiency policy in the EU. Therefore, he search for various energy-saving methods of grain cleaning, and in particular, the energy-saving modes of operation of grain-cleaning units is a relevant research topic as it can save 8-10% on power (Postnikova, 2011).

To determine the optimal energy consumption for grain-cleaning units, the method of mathematical experiment planning (MEP) was used, and specifically, by applying the methods of experiment planning theory to the mathematical model of the adopted research object (Nazar'jan et al., 2012). The possible reductions in power consumption were tested in various operating modes of the ZAV-25 grain cleaning unit, based on patterns of specific consumption patterns.

To reach the adopted goal, the influence of energy factors on specific consumption of power when cleaning grain using the MEP method was investigated. The study involved a research for optimal values of the objective function, based on adequate mathematical models of second order regression equations (Nazar'jan et al., 2012).

The current situation in the energy market requires in-depth analysis of the energy use efficiency of any production, taking into account quantitative and qualitative indicators. Due to the shortage of energy resources, it becomes necessary to save energy in general, and in particular, electrical energy (Postnikova, 2011; Postnikova et al., 2019). One of the ways of rational power usage in grain cleaning units is to ensure the nominal load of drive, i.e., the electric motors. This ensures grain cleaning with a minimum specific power consumption, which serves as a criterion in assessing rational power consumption.

Currently, the Ukrainian market offers the following grain cleaning units: ZAV-10, ZAV-20, ZAV-25, ZAV-40. The upgraded models: ZAV-10A, ZAV-20U, ZAV-40U, ZAV-100A, offer increased productivity and service life by 25% (Drincha et al., 2002). However, the bulk of the grain is cleaned using equipment available on the farms. Therefore, a number of additional retrofitting and upgrading measures should be applied to ensure the equipment operates at a minimal specific power consumption.

In studies conducted thus far, the main attention was paid to the technological issues of grain cleaning on production lines. However, the energy intensity of grain cleaning processes was not sufficiently investigated (Postnikova, 2011).

Moreover, the studies were generally conducted for individual machines and not for units, which makes it impossible to determine the energy intensity of the entire process.

For example, (Jiang and Zhang, 2019) consider process optimization planning necessary to solve energy saving issues. At the same time, to minimize energy consumption, (Abdel-Hadi et al., 2021) recommend obtaining maximum information on the energy intensity of the technological process.

For improved cleaning, Soldatenko and Ostrovkyi (2019) recommend using advanced small-sized disc trier machines. On the other hand, Soldatenko and Hornishnyi (2018) recommend calculating the power of the electric motor using the method of specific power consumption. To minimize electric consumption by electric drives of unit lines, Kupchuk et al. (2021) recommend developing and analyzing a mathematical model of power consumption in electric drives. Postnikova et al. (2019) point out that to reduce power consumption of electromechanical systems, it is necessary to optimize the modes of operation of electrical equipment.

Ways to improve the vibration drives of grain separators were investigated by Linenko et al. (2021). The suitability of the model has been proven experimentally. The difference between experimental model and the one obtained by mathematical modeling does not exceed 6%.

Recommendations on improving the design of pneumatic grain separators were also developed to increase their efficiency. Although pneumatic transportation is considered experimental science, Bortolaia et al. (2008) and Kroulík et al. (2016) noticed a lack of procedures, parameters, and orientation in the literature for tests and comparisons that are fundamental to the design of this type of conveyor (Muratov et al., 2020). On the other hand, to simulate the system of mechanical ventilation of granaries Zhang et al. (2014) recommend using dynamic numerical modeling.

Some authors have laid the foundations for improved mechanization to obtain high-quality grain (Kiurchev et al., 2021). According to theoretical researches of (Linenko et al., 2017; Aipov et al., 2020; Cieślik, 2021) the pulse mode of operation of the grain cleaning unit MVR-2 (SU-0,1) increases its productivity by 20%.

A theoretical analysis of the grain drying process was carried out by Li (2018), followed by theoretical models for a fair and reasonable assessment of energy use in practical applications, which can be used to optimize the grain drying process.

Mathematical modeling and experimental research were carried out during cleaning and calibration of corn grain mixtures. The obtained research results are universal and can be used for different grain cleaning machines (Kharchenko et al., 2019; Panasiewicz et al., 2008; Choszcz et al., 2020; Nesterenko et al., 2019).

The application of the discrete element method in modeling post-harvest grain handling is becoming increasingly popular in post-harvest grain operations, but has not found wide application (Boac et al., 2014). A review of electric motor current state of the modeling and analysis methods does not answer this question (Bilgin et al., 2019). Research on improvement of mechanical and mathematical model of grain separation in the fluidized layer confirmed the suitability of the model when comparing the experimental and theoretical results (Bredykhin et al., 2021).

Ecological issues, such as dust emissions during grain cleaning (Gembicki, 2016; Jin et al., 2021) and gas and heat emissions during grain drying (Wang et al., 2020), are also an urgent research task.

Rational and optimal values of the parameters and operating modes of the pneumatic system separator were also determined by Mikhailov et al. (2019) and Badretdinov et al. (2019).

Based on the literature review, it can be concluded that the grain cleaning energy intensity of the technological process of grain cleaning in unit lines can be estimated only when all working elements proposed by the authors are improved and coordinated in terms of performance. Therefore, increasing the energy efficiency of grain cleaning production lines is an urgent research problem

Materials and Methods

The experiment planning method is currently the most widely used in science, engineering, manufacturing, etc. to solve scientific problems of analysis and synthesis of research objects of varying complexity. At the same time, the theory and practice of experiment planning are advanced and allow to obtain a reliable mathematical model of the research object at the minimum number of experiments, to determine the optimal conditions of its functioning when solving the optimization problem. The first publications on the concept and application of the method of mathematical experiment planning (MEP) were the works of Novakovskaya, Adamenko (Nazar'jan et al., 2012), dedicated to digital optimization of stepper and asynchronous micromotor design.

An important advantage of the MEP method is the low material cost of scientific research compared to planning and conducting full-scale experiments, which has led to great interest and wide-scale application of this method in research work, as proven by (Nazar'jan et al., 2012). The author presents a methodology of reconstruction of initial mathematical models of various research objects in the form of equation regression. This allows a quick selection of analyzed problems and optimization of object. This article draws freely from these works.

The need to rebuild the original mathematical research model of the object results from the fact that model is usually formed based on a literature review. As a rule, it is a set of equations, empirical relationships, graphic dependencies, etc., and it is practically impossible to solve the analysis and optimization problem on such a model. In fact, rebuilding the model poses an interpolation problem of a sufficient algebraic approximation of multidimensional dependencies represented in the original model in an implicit form. For this reason, conventional interpolation methods using formulas recommended in computational mathematics are unsuitable for multidimensional functions. At the same time, such interpolation problems are relatively easy to solve with the required accuracy using the MEP method (Nazar'jan et al., 2012).

The name of the method comes from the methodology for rebuilding the initial mathematical model of the research object. It is based entirely on the use of the mathematical apparatus and techniques of the classical theory of experiment planning.

According to MEP, the "experiment" is a set of analytical calculations of values of the target function or optimization parameter by using a mathematical model of the object in accordance with the line values of the factors presented in the matrix of the adopted experimental plan. Since the results of calculations of the values of the target function *"y"* by the initial mathematical model of the object are single-valued values, in the MEP method there will be no dispersion of the reproducibility of "experiments" $S_{\boldsymbol{B}}^2\{y\}$ and parallel experiments at the same values of factors and randomization of the "experiments" when conducting them.

The lack of dispersions of the reproducibility of the target function does not allow for a mathematical description of the object of study in the form of regression equations with a limited number of terms because it is not possible to conduct a statistical assessment of the significance of the coefficients and the adequacy of the equation. For this reason, when using the MEP method, the reproducibility dispersion $S_{\boldsymbol{B}}^2\{y\}$is added artificially and is determined by the value of the accepted acceptable error of calculations (Postnikova, 2011; Nazar'jan et al., 2012; Postnikova et al., 2019):

$$S_{\boldsymbol{B}}^2\{y\} = \sigma^2 \tag{1}$$

where:

σ^2 – error dispersion.

It is customary to set the error variance at two or three σ standards (Postnikova, 2011; Nazar'jan et al., 2012; Postnikova et al., 2019).

$$\sigma^2 = (3\sigma)^2$$

where:

σ – standard or root mean square error.

In this case, all the prerequisites of the regression analysis are satisfied.

For the normal law distribution, the adopted standard is $\sigma = \sqrt{\sigma^2}$. Assuming, for example, that$\sigma = 0{,}02$, i.e., the calculation error is 2%, then the value of the artificially assumed dispersion will be (Postnikova, 2011; Nazar'jan et al., 2012; Postnikova et al., 2019)

$$S_{\boldsymbol{B}}^2\{y\} = (3\sigma)^2 = (3 \cdot 0.02)^2 \tag{2}$$

Results

Currently, there is no methodology that allows analyzing the effect of electromechanical systems on efficiency of using electrical energy for both for individual production lines and grain cleaning units. At the same time, it was established (Postnikova, 2011) that the most informative indicator for determining energy-saving modes of operation is the specific consumption of electrical energy for the grain cleaning process. The ZAV-25 unit was studied in terms of the influence of its operating modes on its power demand using MEP (Nazar'jan et al., 2012; Kiktev et al., 2021).

Based on the review of modern grain cleaning theory and practice, the studied mathematical model was formed as equation (Postnikova, 2011):

$$W_s = \frac{\sum_{i=1}^{n} P_{ni} \cdot K}{Q \cdot \eta_{n.a}}, \tag{3}$$

where:

$\sum_{i=1}^{n} \mathrm{P}_{ni}$ – total rated power of production line electric motors, (kW)

K – load factor of production line electric motors

Q – production line performance, ($\mathrm{t \cdot h^{-1}}$)

$\eta_{n.a}$ – average rated efficiency of electric motors.

The dependence of the optimization parameter W_s can be presented as a function of power consumption of the motors by using equation (3):

$$W_s = \frac{\sum_{i=1}^{n} P_{1i} \cdot K}{Q} \tag{4}$$

where:
$\sum_{i=1}^{n} P_{1i}$ – total consumed or connected power of electric motors, (kW)

$$\sum_{i=1}^{n} P_{1\mathrm{i}} = \frac{P_{n1}}{\eta_{n1}} + \frac{P_{n2}}{\eta_{n2}} + \frac{P_{n3}}{\eta_{n3}} + \ldots + \frac{P_{nn}}{\eta_{nn}}, \quad (\mathrm{i} = 1, 2, 3, \ldots, \mathrm{n}). \tag{5}$$

The selected variable factors that affect specific power consumption are: Q – unit performance (tons per hour); P_{1i} – connected power of the electric motor (kW); K – load factor of the electric motors.

The levels and variation intervals of the variables for ZAV-25 grain cleaning unit are given in (Nazar'jan et al., 2012) and are selected in accordance with realistic possibilities of adjusting working elements of the unit line.

When solving the problem of optimizing complex research objects for an adequate description of the optimum region, the second-order polynomials of the form are usually used:

$$\mathrm{y} = b_0 + \sum_{i=1}^{n} b_i \cdot x_i + \sum_{i<j}^{n} b_{i,j} \cdot x_i \cdot x_j + \sum_{i=1}^{n} b_{ii}\, x_i^2 + \ldots, \tag{6}$$

where
y – target function; b_0, b_i, b_{ij}, b_{ii} – regression equation coefficients; x_i, x_j, x_i^2 − normalized factor values.

According to (Nazar'jan et al., 2012), second-order central composite design (CCD) is recommended for solving optimization problems. CCD is the experiment planning at five levels, which, in normalized units, can be represented as:

$$1)\ -\alpha;\quad 2)\ -1;\quad 3)\ 0;\quad 4)\ +1;\quad 5)\ +\alpha, \tag{7}$$

where:
α – star point shoulder size.

The OCCP matrix for three factors is presented in (Nazar'jan et al., 2012). Statistical data processing has been performed.

Regression equations were obtained to calculate the specific power consumption depending on the performance of the grain cleaning unit, the connected power, and the load factor of the electric motors in coded units.

$$\begin{aligned} \tilde{\mathrm{y}} = 1.4343 - 0.546\mathrm{x}_1 + 0.489\mathrm{x}_2 + 0.338\mathrm{x}_3 - 0.207\mathrm{x}_1\mathrm{x}_2 - 0.143\mathrm{x}_1\mathrm{x}_3 + \\ + 0.123\mathrm{x}_2\mathrm{x}_3 - 0.048\mathrm{x}_1\mathrm{x}_2\mathrm{x}_3 - 0.089\mathrm{x}_1^2 + 0.135\mathrm{x}_2^2 + 0.135\mathrm{x}_3^2. \end{aligned} \tag{8}$$

The symbols adopted in equation (8) are: $\tilde{\mathrm{y}}$, W_s – specific power consumption; x_1, P_1 – power; x_2, Q – production; x_3, K – load factor of electrical equipment, respectively, in coded and natural values.

After obtaining an adequate second-order mathematical model as in (8), it is necessary to determine the coordinates of the optimum (maximum or minimum, if any) and analyze the response surface properties in the optimum vicinity.

Object optimization problems are usually solved by search methods, which are extremely varied. The main methods include the following: gradient method, saddle-point method and its modifications – steepest ascent, Gauss-Seidel method, simplex method,, random search method and others. There are mathematical transformations that allow obtaining a graphical and analytical interpretation of the optimum area. For these purposes, the mathematical model canonical transformation and the method of two-dimensional sections of the response surface are commonly used.

Regression equation (8) was differentiated for each factor:

$$\frac{\partial\tilde{y}}{\partial x_1} = -0.546 - 0.207\mathrm{x}_2 - 0.143\mathrm{x}_3 - 0.048\mathrm{x}_2\mathrm{x}_3 - 0.178\mathrm{x}_1 = 0;$$
$$\frac{\partial\tilde{y}}{\partial x_2} = 0.489 - 0.207x_1 + 0.123x_3 - 0.048\mathrm{x}_1\mathrm{x}_3 + 0.27x_2 = 0;$$
$$\frac{\partial\tilde{y}}{\partial x_3} = 0.338 - 0.143x_1 + 0.123x_2 - 0.048\mathrm{x}_1\mathrm{x}_2 + 0.27x_3 = 0.$$

The center coordinates were obtained in coded units after solving the system of equations

$$\mathrm{x}_{1S} = 1.0;\ \mathrm{x}_{2S} = -0.4;\ \mathrm{x}_{3S} = -0.827;\ \mathrm{y}_S = 0.664,$$

which correspond to the following values of factors and objective function in physical units

$$Q = 20\ \mathrm{t \cdot h^{-1}};\ P_1 = 26\ \mathrm{kW};\ K = 0.526.$$

The optimal function value corresponds to $W_s = 0.6$ kWh·t^{-1}.

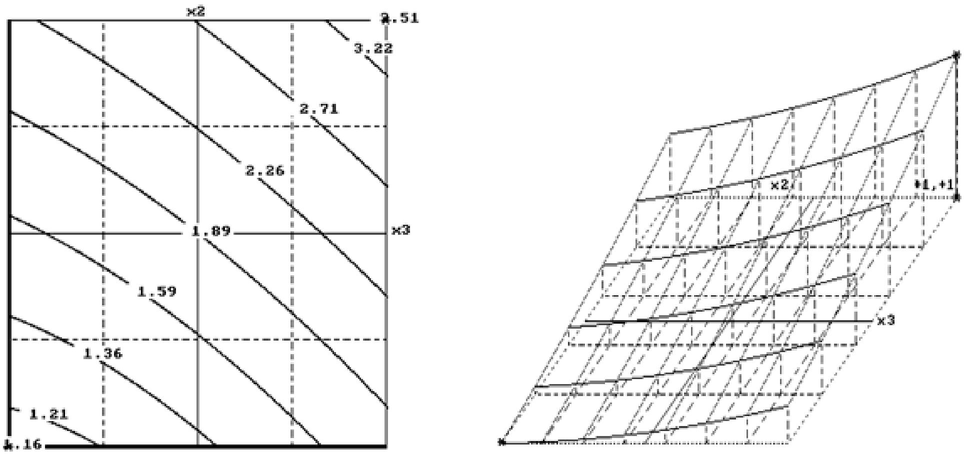
Possible two-dimensional sections, which are of the greatest practical importance for determining the specific power consumption, depending on the performance of the unit, the connected power and the load factor of the electric motors, are as follows:

− At $x_1 = 0$ (Fig. 1a) the response surface of objective function; б) two-dimensional sections for ZAV-25

$$\frac{\partial\tilde{y}}{\partial x_2} = 0.489 + 0.123x_3 + 0.27x_2 = 0;$$
$$\frac{\partial\tilde{y}}{\partial x_3} = 0.338 + 0.123x_2 + 0.27x_3 = 0;$$
$$\mathrm{x}_{2S} = -1.566;\ \mathrm{x}_{3S} = -0.534;\ \mathrm{y}_S = 0.96,$$

which corresponds to factors values and objective function in physical units

$$P_1 = 14.34\ \mathrm{kW};\ K = 0.57 \text{ and } W_s = 0.96\ \mathrm{kWh \cdot t^{-1}}.$$



а) б)

Figure 1. The objective function response surface (a) and its two-dimensional sections (b) for ZAV-25 at $x_1 = 0$

To find the optimal value of the target function, the system has been solved:

$$f(B) = \begin{vmatrix} 0.27 - B & 0.5 \cdot 0.123 \\ 0.5 \cdot 0.123 & 0.27 - B \end{vmatrix} = (0.27 - \mathrm{B}) \cdot (0.27 - B) - 0.0038 = 0.$$

As a result, the equation is:

$$Y - 0.96 = 0.209X_2^2 + 0.331X_3^2.$$

− At $x_2 = 0$ (Fig. 2a) the response surface of objective function; б) two-dimensional sections for ZAV-25:

$$\frac{\partial \tilde{y}}{\partial x_1} = -0.546 - 0.143x_3 - 0.178x_1 = 0;$$
$$\frac{\partial \tilde{y}}{\partial x_3} = 0.338 - 0.143x_1 + 0.27x_3 = 0;$$
$$\mathrm{x}_{1S} = -1.446;\ \mathrm{x}_{3S} = -2.018;\ y_S = 1.488,$$

which corresponds to factors values and objective function in physical units:

$Q = 7.9$ t·h^{-1}; $K = 0.35$ and $W_s = 1.488$ kWh·t^{-1}

To find the optimal value of the target function, the system has been solved as follows:

$$f(B) = \begin{vmatrix} -0.178 - B & -0.5 \cdot 0.143 \\ -0.5 \cdot 0.143 & 0.27 - B \end{vmatrix} = (-0.178 - \mathrm{B}) \cdot (0.27 - \mathrm{B}) - 0.25 \cdot 0.143^2 = 0.$$

As a result of solving the system, the equation is:

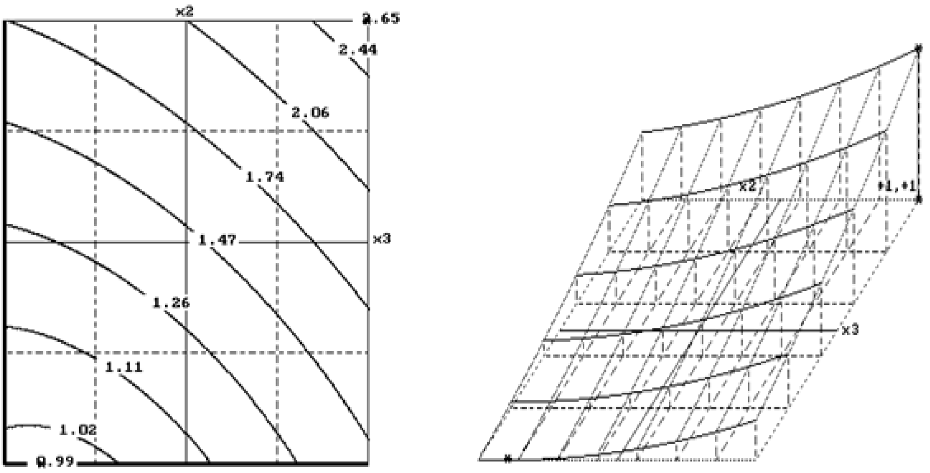
$$Y - 1.488 = -0.189X_1^2 + 0.281X_3^2.$$

− At $x_3 = 0$ (Fig. 3a) the response surface of objective function; б) two-dimensional sections for ZAV-25:

$$\frac{\partial \tilde{y}}{\partial x_1} = -0.546 - 0.207x_2 - 0.178x_1 = 0;$$
$$\frac{\partial \tilde{y}}{\partial x_2} = 0.489 - 0.207x_1 + 0.27x_2 = 0;$$
$$\mathrm{x}_{1S} = -0.508;\ \mathrm{x}_{2S} = -2.2;\ y_S = 1.035,$$

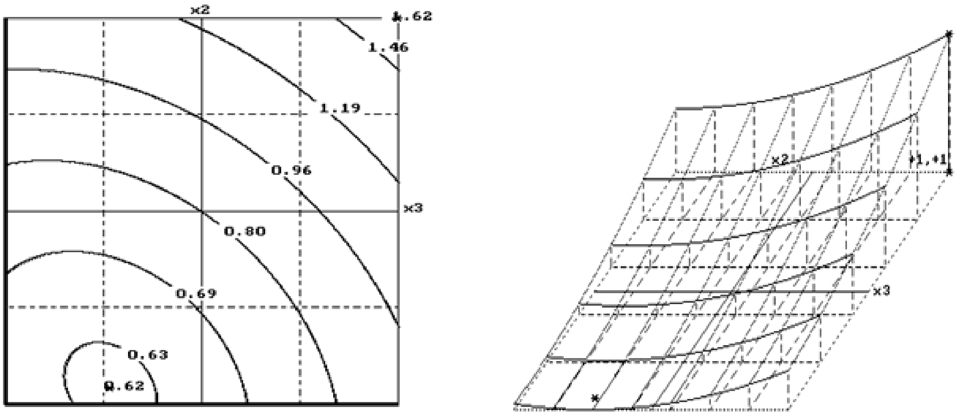
which corresponds to factors values and objective function in physical units:

Q = 14.44 t·h^{-1}; P_1 = 8 kW and W_s = 1.035 kWh·t^{-1}.



а) б)

Figure 2. The objective function response surface (a) and its two-dimensional sections (b) for ZAV-25 at $x_2 = 0$



а) б)

Figure 3. The objective function response surface (a) and its two-dimensional sections (b) for ZAV-25 at $x_3 = 0$

To find the optimal value of the target function, the system has been solved as follows:

$$f(B) = \begin{vmatrix} -0.178 - B & -0.5 \cdot 0.207 \\ -0.5 \cdot 0.207 & 0.27 - B \end{vmatrix} = (-0.178 - B) \cdot (0.27 - B) - 0.25 \cdot 0.207^2 = 0.$$

As a result of solving the system, the equation is:

$$Y - 1.035 = -0.201 X_1^2 + 0.293 X_3^2.$$

According to the analysis and solution result of the equations obtained for minimax using a package of specialized mathematical software, the minimum specific power consumption possible values of the ZAV-25 production lines were obtained. The factor change was taken into account.

Discussion

The main research objective was to study the influence of dominant factors on the power indexes in the grain cultivation and storage systems. The ultimate goal of research is to establish a pattern in the form of functional or correlation equations. This will give the opportunity to properly solve the problems of rational choice of electrical equipment, planning and implementation of organizational and technical measures, contributing to the improvement of energy use (Postnikova, 2011). Additionally, science-based methods of rationing of electric power indicators were developed based on the obtained regularities (Postnikova, 2008; Lutsiak et al., 2021).

One of the important factors that affect the efficiency of power resources is the rate of power consumption (Didur et al., 2008; Kovalenko et al., 2021; Tryhuba et al., 2020). The latter is known to be a criterion for evaluating electrical consumption.

In the industries associated with the processing and storage of grain crops, the norms of specific power consumption were set by reported consumption, with no scientific analysis and confirmation by experimental research. Sometimes there was no norms at all. In addition, the lack of science-based data on the influence of various factors on energy performance led to great difficulty in adjusting the norms as a result of changes in technological conditions. If the norms do not correspond to the optimal energy-saving modes of operation of the equipment, their mobilizing role is reduced and sometimes completely eliminated. In this case, the norms are not a factor that stimulates energy saving.

Science-based norms were based on the results of technological and energy research, on the analysis of electrical balances, and on the application of reporting and statistical materials using the methods of probability theory and mathematical statistics.

Science-based norms of specific power consumption for technological schemes in the ZAV-25 grain cleaning unit were developed due to conducted research (Postnikova, 2008; Didur et al., 2008). These norms were discussed and approved at the technical councils of the regional administrations of agriculture of Zaporizhzhya, Melitopol and Velikolepetikha (Ukraine), which is confirmed by the acts of implementation of the results of research work.

Recommended norms of power consumption are intended for the regional economic departments of agriculture in the south of Ukraine. They are used for planning and controlling energy consumption for technological processes of production lines grain cleaning units. Similar research is being conducted for other grain cleaning units manufactured in Ukraine.

Conclusions

1. To determine the general influence of various factors on the specific power consumption during grain cleaning, most of which are variable, it is recommended to carry out a multifactor experiment. The calculation error should not exceed 2-3%.
2. Through the optimization of ZAV-25 grain cleaning unit parameters, the following average optimal values of parameters and factors were obtained for their different combined indexes: W_s = 0.6 kW·t-^{1}; P_1 = 26 kW; Q = 20 t·h^{-1} and K = 0.526. At the same time, the specification of ZAV-25 unit contains the following data: productivity of food material (wheat with a moisture content of 16-20%, weediness up to 20%) is Q = 25 t·h^{-1}; installed power of electric motors P_1 = 38.6 kW; specific power consumption W_s = 1.55 kWh·t^{-1}.
3. A significant disparity between the passport and calculated optimal energy consumption practically twice is explained by the fact that the control of grain cleaning technological process is non-optimal in terms of energy consumption. Moreover, the ungrounded total installed electric motors power overestimation of ZAV-25 unit equal to 38.6 kW is noteworthy. According to research, the optimal power, in terms of minimum power consumption is P_1 = 26 kW.
4. Thus, research has shown possibility of using calculated data for the development of science-based norms of power consumption by the ZAV-25 grain cleaning unit.

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TRYBY ENERGOOSZCZĘDNEGO DZIAŁANIA SYSTEMÓW ELEKTROMECHANICZNYCH W LINIACH PRODUKCYJNYCH CZYSZCZENIA ZIARNA

Streszczenie. Badania miały na celu zmniejszenie zużycia energii elektrycznej w układach elektromechanicznych linii produkcyjnych czyszczenia ziarna poprzez zastosowanie energooszczędnych trybów pracy. Wpływ czynników energetycznych na jednostkowe zużycie energii elektrycznej badano metodą matematycznego planowania eksperymentu (MEP). Zastosowano jednostkowe zużycie energii czynnej na jednostkę produkcji jako kryterium oceny energooszczędnych trybów pracy. Badania przeprowadzono metodą MEP. Umożliwiło to przeprowadzenie minimalnej liczby badań i uzyskanie wiarygodnego modelu matematycznego obiektu badań. Opracowano teoretyczną metodę restrukturyzacji modelu matematycznego w celu wyznaczenia optymalnej wartości jednostkowego poboru mocy. Zaproponowana technika pozwoliła na uzyskanie minimalnego jednostkowego poboru mocy linii do czyszczenia ziarna oraz opracowanie naukowo uzasadnionych wskaźników zużycia energii elektrycznej. Daje to oszczędności energii sięgające 8-10%.

Słowa kluczowe: oszczędność energii, zużycie energii, racjonowanie energii elektrycznej, optymalizacja