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# THEORETICAL SUBSTANTIATION OF ENERGY-EFFICIENT OPERATING MODES OF TECHNOLOGICAL MACHINES IN THE AGRO-INDUSTRIAL COMPLEX

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*The article is devoted to the theoretical substantiation of energy-efficient operating modes of technological machines of the agro-industrial complex in the conditions of the need to increase productivity, reduce specific energy costs and ensure the stability of technological processes. The relevance of the study is due to the increase in the cost of energy resources, the need to reduce operating costs and increase the resource efficiency of machines and equipment. A significant part of technological machines is operated in nominal modes, which do not always correspond to the actual load, properties of raw materials and conditions of the operation, which causes excessive energy costs.*

*A theoretical and methodological approach to determining energy-efficient modes of operation of technological machines has been formed based on establishing the relationship between structural, kinematic, power, technological and energy parameters. A technological machine is considered as an energy-technological system in which the drive, working bodies, processed material and the external environment interact. The main components of the energy balance have been determined and a system of interrelated parameters has been proposed, including productivity, rotation frequency, torque, drive power, efficiency and specific energy consumption.*

*The use of specific energy consumption as one of the main criteria for the efficiency of a technological machine is theoretically justified. It is established that the dependence of energy consumption on productivity and operating parameters is nonlinear and is characterized by the region of rational modes. Under insufficient load, the proportion of idle losses increases, while excessive load causes an increase in power resistance, mechanical losses and energy consumption. The proposed approach creates a theoretical basis for determining the optimal operating modes of technological machines and further development of adaptive control systems.*

***Keywords:*** *technological machine, agro-industrial complex, energy efficiency, energy consumption, operating mode, mathematical modeling, optimization, productivity, technological process, drive power, specific energy consumption.*

***Eq. 14. Fig. 4. Ref. 11.***

## 1. Statement of the problem

The modern development of the agro-industrial complex is characterized by a constant increase in the requirements for productivity, reliability, technological flexibility and energy efficiency of machines and equipment. Technological machines are one of the key elements of production systems, since it is precisely on their technical condition, design parameters and operating modes that the productivity of technological operations, the quality of the resulting products and the amount of operating costs depend to a large extent. At the same time, a significant part of the technological equipment of agro-industrial production operates under conditions of variable load, uneven supply of raw materials and unstable physical and mechanical properties of the material, which significantly complicates the rational use of energy resources.

The problem of increasing the energy efficiency of technological machines is becoming particularly urgent in the conditions of increasing energy costs, limited fuel and energy resources and the need to reduce the cost of agricultural products. A significant part of the energy consumed by technological machines is not converted directly into useful technological work, but is spent on overcoming mechanical resistance, friction,

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deformation of structural elements, movement of working bodies, heating of parts and other related processes. In the absence of proper regulation of operating parameters, such losses can significantly increase, especially when the machine is operating in suboptimal modes [1].

A feature of technological machines of the agro-industrial complex is the complex nature of the interaction between the working bodies and the processed material. The physical and mechanical properties of agricultural raw materials - humidity, density, strength, fractional composition, friction coefficient and other characteristics - can vary within wide limits. Accordingly, the technological resistance, torque on the shaft of the working body, drive power and total energy consumption of the machine change. Therefore, the establishment of a fixed operating mode, designed for average operating conditions, does not always ensure maximum energy efficiency.

One of the main problems is the lack of a universal approach to determining the rational operating modes of technological machines, taking into account the simultaneous influence of design, technological and energy factors. The traditional approach to selecting modes often involves focusing on the nominal speed, installed drive power or specified performance. However, such parameters do not fully reflect the real nature of the machine's operation and do not allow determining the optimal ratio between productivity, quality of technological operation and energy costs.

Particular attention needs to be paid to establishing the regularity of changes in specific energy consumption depending on the operating parameters of the technological machine. With insufficient load, a significant part of the installed capacity is spent on overcoming idle and constant losses, as a result of which the specific energy consumption per unit of output increases. With excessive load, on the contrary, technological resistance, mechanical losses, load on the drive and working bodies increase, which can also lead to a decrease in overall efficiency. This indicates the existence of a certain area of rational modes, within which the most favorable ratio between energy consumption and technological result is ensured.

## 2. Analysis of recent research and publications

The issue of increasing the energy efficiency of technological machines of the agro-industrial complex has been gaining special importance in the world and domestic scientific literature in recent years. Modern research is gradually shifting from assessing only the fuel efficiency of a single machine to a comprehensive analysis of energy flows in the system "engine - transmission - working body - technological environment". This approach is due to the need to simultaneously ensure high productivity, minimal specific energy costs, stability of the technological process and reducing the negative impact of agricultural machinery on the environment.

In the fundamental direction of research on the energy efficiency of machine-tractor units, considerable attention is paid to determining the relationship between the energy characteristics of the tractor, the parameters of the working machine and the actual technological load. In particular, a modern review by Jensen, Antille and Tullberg [1] systematizes approaches to increasing the efficiency of energy use during the operation of agricultural machinery. The authors emphasize that energy efficiency depends not only on the engine design, but also on the correspondence of the tractor power to the actual load, transmission parameters, driving mode, organization of technological operations and operator qualifications. Particular attention is paid to the gear - up principle and throttle - back, in which, at low traction load, the gear is increased and the engine speed is reduced, while maintaining the required operating speed. According to the results presented in the study, for certain conditions of heavy tillage, this approach allowed reducing fuel consumption by approximately 20% per hectare.

An important area of world research is the mathematical optimization of the use of agricultural machinery. Researchers [2] proposed models that take into account not only direct fuel consumption during the performance of a technological operation, but also unproductive movements of machines. Thus, in the work devoted to the optimization of fuel consumption during the harvesting of grain crops, a mathematical model of planning the work of agricultural machines with the minimization of fuel consumption for unproductive distances was formed. The use of mixed integer programming and a search algorithm allowed in the model example to reduce fuel consumption for unproductive operations by 19.5%, and the total fuel consumption by combines by 16.3%. This indicates that a significant reserve of energy saving is located not only in the constructive improvement of the machine, but also in the rational organization of its operating mode and technological movements.

A separate direction is research into forecasting the energy needs of machine and tractor fleets. In particular, Tieppo [3] and co-authors developed a deterministic model for forecasting the required power, fuel consumption, operating costs and energy needs of machines during the cultivation of soybeans and corn using No - Till technology. Modeling of various options for the composition of the machine fleet and the production

area showed the feasibility of simultaneously taking into account energy and economic characteristics when choosing machines and planning technological operations.

In recent years, global research has significantly intensified in the direction of electrification, hybridization and intelligent control of energy flows of technological machines [4]. In particular, mathematical and simulation models of hybrid tractors, electric power plants and control systems are being developed, which allow maintaining the engine in the zone of high efficiency. In the study [4, 5] of the hybrid tractor power plant, an energy control strategy based on dynamic programming was proposed. The modeling results showed the possibility of reducing the equivalent fuel consumption by approximately 10–11% depending on the operating mode. Similar approaches are used for fuel cells: mathematical models of electromechanical and hydraulic interaction allow optimizing power distribution and reducing theoretical hydrogen consumption.

Recent research in 2026 demonstrates a further shift towards multi-criteria and intelligent control. In particular, modern models for optimizing the operation of several machines simultaneously take into account soil conditions, carbon emissions, logistical constraints and productivity. The use of machine learning algorithms and hyperheuristic methods is considered a promising means of optimizing the operation of machine-tractor systems in variable production conditions. Another modern direction is related to the coordination of energy efficiency and stability of the movement of a hybrid tractor during plowing, where the possibility of simultaneously reducing fuel consumption and increasing the accuracy of movement was demonstrated using a model and a multi-level control system.

Domestic research [6, 7] on the problem of energy efficiency of technological machines has a solid theoretical basis, formed by the works of Ukrainian scientific schools in the field of tractor construction, operation of agricultural machinery, mechanization and energy of agro-industrial production. Considerable attention is paid to the energy assessment of machine-tractor units, determination of traction and coupling properties, optimization of parameters of energy means and substantiation of rational aggregation. According to the results of research presented in the scientific works of Ukrainian scientists, it is advisable to determine the energy indicators of MTA through a system of direct and indirect energy costs, related both directly to the performance of a technological operation and to maintenance, repair and operation of machines.

A significant contribution to the development of the theory of efficient use of energy resources was made by the research of V. V. Adamchuk, V. T. Nadykt, V. M. Bulgakov [9] and other scientists. One of the important directions is to establish the dependence of the efficiency of a machine-tractor unit on the ratio of engine power and tractor operating weight. Modern Ukrainian research emphasizes that high engine power alone does not guarantee the efficient operation of the unit, since it is necessary to ensure its rational implementation through the tractive effort and working parts of the machine.

In particular, studies on the rational level of energy saturation of wheeled tractors have shown that excessive increase in engine power without a corresponding increase in technological load may be economically and energetically inexpedient. To increase productivity in such conditions, the use of wide-grip and combined machines, as well as engines with increased traction and coupling properties, is promising. It is also important to ensure sufficient engine load in terms of power and tractive effort.

Another direction of Ukrainian research is related to the improvement of running systems and transmissions. The study of the conditions of use of dual and geared drives of wheeled power vehicles is based on the theoretical provisions of the theory of tractors and agricultural machinery and is aimed at increasing traction efficiency under specific operating conditions. In parallel, the use of continuously variable transmissions as a means of increasing the operational efficiency of tractors is being studied, since the possibility of smooth speed regulation allows for better coordination of the operating mode of the power vehicle with the current technological load.

Thus, the analysis of global and domestic research indicates the formation of several main scientific directions: optimization of engine and transmission operating modes; rational aggregation of energy resources with a technological machine; mathematical modeling of energy flows; optimization of technological routes and unproductive movements; electrification and hybridization of machines; application of intelligent control systems and multi-criteria optimization. At the same time, modern global science is increasingly moving from the analysis of individual machine elements to the complex optimization of the entire machine-technological system.

## 3. Purpose of the study

The purpose of the study is to theoretically substantiate energy-efficient operating modes of technological machines of the agro-industrial complex based on establishing the patterns of the relationship between structural, kinematic, power, technological and energy parameters, as well as developing a

mathematical approach to determining their rational values, which ensure the minimization of specific energy costs while maintaining the required productivity and quality of the technological process.

## 4. Results and discussion

Theoretical research on the energy efficiency of technological machines of the agro-industrial complex is based on the assumption that the energy state of the machine is formed under the influence of a set of structural, kinematic, power and technological parameters. For a mathematical description of the process, it is advisable to consider the technological machine as an energy system in which the drive power is transformed into useful technological work and a set of energy losses [10] .

The main indicator that characterizes the energy efficiency of a technological machine is the specific energy consumption. (1). This indicator is determined by the ratio of the power consumed by the machine to its productivity:

$$e_p = \frac{P}{Q} \tag{1}$$

where $e_p$ – specific energy consumption, kWh/t; P – power consumption, kW; Q – machine productivity, t/h.

At the same time, the power consumed by a technological machine consists of the useful power required to perform a technological operation and the power spent on overcoming various losses ( Fig . 1.). The overall energy balance can be represented by the dependence (2):

$$P = P_k + P_0 + P_m + P_t \tag{2}$$

where $P_k$ – useful technological power, kW; $P_0$ – idle power, kW; $P_m$ – mechanical losses in the drive and gears, kW; $P_t$ – additional technological losses associated with the peculiarities of the interaction of working bodies with the material, kW.

The useful technological power can be determined through the technological resistance and the speed of the work operation (3):

$$P_k = F_t * \frac{v}{1000} \tag{3}$$

where $F_t$ – technological resistance, N; v - operating speed, m/s.

For machines with rotating working bodies, it is advisable to use the relationship between torque and speed (4):

$$P = M * \Omega \tag{4}$$

where M is the torque on the shaft of the working body, Nm; omega is the angular velocity, rad/s.

The angular velocity is determined by expression (5):

$$\Omega = pi * \frac{n}{30} \tag{5}$$

where n is the speed of rotation of the working element, $min^{-1}$.

Taking this into account, the power consumption can be represented in the form (6):

$$P = M * pi * \frac{n}{30} \tag{6}$$

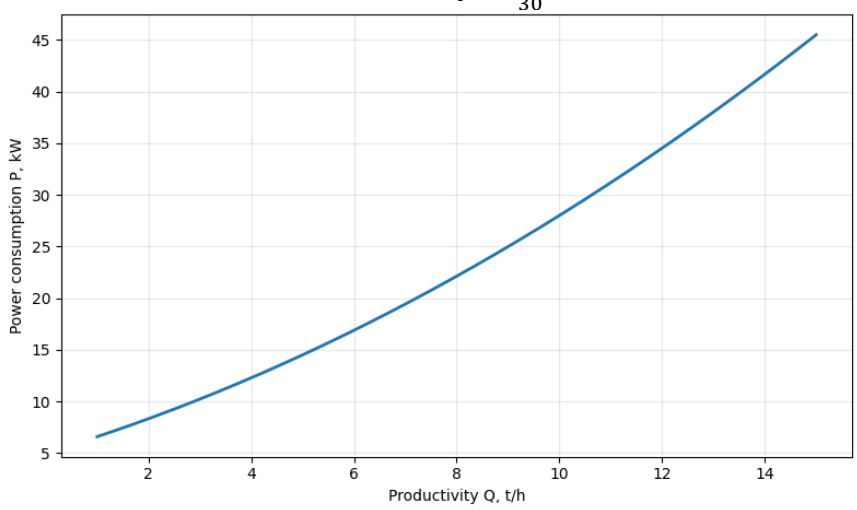


***Fig. 1. Power consumption vs productivity***

The obtained dependence shows that an increase in the frequency of rotation of the working body at a constant torque leads to a proportional increase in the consumed power. However, in real technological systems, the torque also depends on the frequency of rotation, productivity, physical and mechanical properties of the processed material and other factors. Therefore, to establish a rational regime, it is necessary to analyze not a separate parameter, but their combined effect.

For theoretical study, we assume that the idle power of the machine is relatively stable within the operating range, and the technological component of power depends on the productivity (Fig. 2.). Then the general dependence can be represented in the form (7):

$$P(Q) = P_0 + a * Q + b * Q^2 \quad (7)$$

where a and b are coefficients characterizing the linear and nonlinear components of energy costs, respectively.

Substituting this dependence into the equation of specific energy costs, we obtain (8):

$$e_{p(Q)} = \frac{P_0}{Q} + a + b * Q \quad (8)$$

This dependence has fundamental theoretical significance. The first term characterizes the decrease in the specific share of constant losses with increasing productivity, the second - the conditionally proportional component of energy consumption, and the third - the increase in specific costs due to the increase in technological resistance and nonlinear losses.

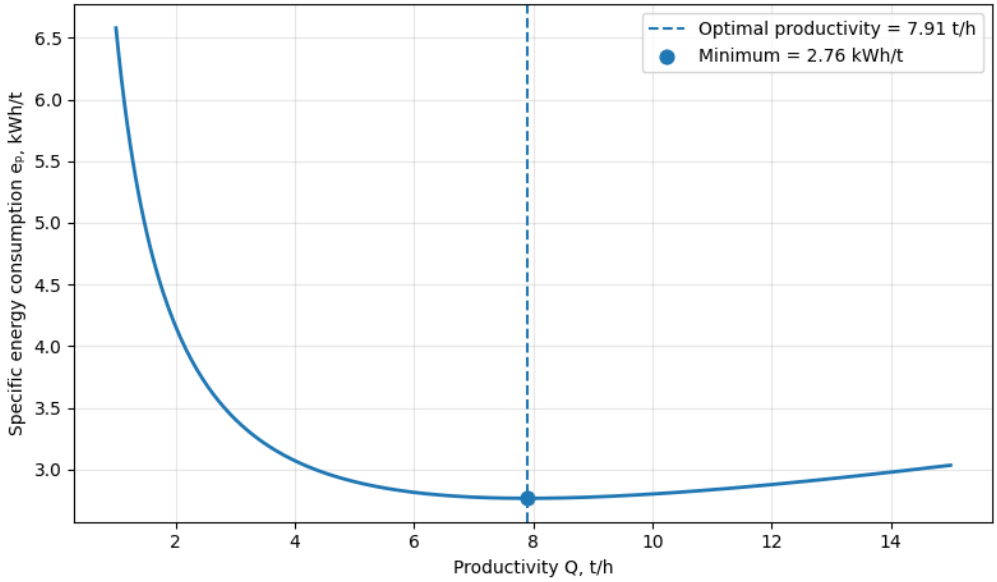


***Fig. 2. Specific energy consumption vs productivity***

To determine the optimal productivity, we differentiate the obtained dependence (9):

$$\frac{d(e_p)}{dQ} = -\frac{P_0}{Q^2} + b \quad (9)$$

The condition for minimum specific energy costs has the form (10):

$$\frac{d(e_p)}{dQ} = 0 \quad (10)$$

from where we get (11):

$$Q_{opt} = sqrt\left(\frac{P_0}{b}\right) \quad (11)$$

where $Q_{opt}$ is the theoretically optimal productivity of the technological machine, t/h.

The obtained result shows that the optimal productivity is determined by the ratio of constant energy losses and the nonlinear component of technological costs. With an increase in idle power, the optimal mode shifts to the region of higher productivity. At the same time, an increase in the coefficient b, which characterizes the intensity of the growth of technological losses, leads to a decrease in optimal productivity.

One of the most important operating parameters of a technological machine is the speed of rotation of the working body (Fig. 3.). For theoretical analysis, the dependence of torque on speed can be taken as (12):

$$M(n) = M_0 + k_n * n^2 \quad (12)$$

where $M_0$ is the base torque, N·m; $k_n$ is the coefficient characterizing the increase in resistance with increasing rotational speed.

Then the power of the working body is determined by (13):

$$P(n) = \left(pi * \frac{M_0}{30}\right) * n + \left(pi * \frac{k_n}{30}\right) * n^3 \quad (13)$$

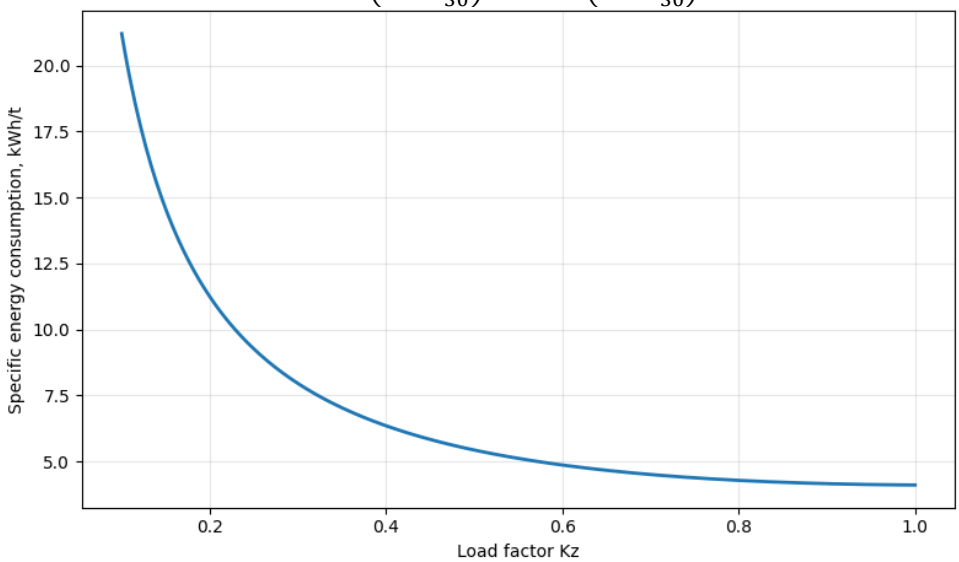


***Fig. 3. Specific energy consumption vs load factor***

The dependence shows a nonlinear nature of the power increase with increasing speed. The influence of speed becomes especially significant in the upper part of the operating range, where the cubic component begins to dominate.

To take into account the simultaneous influence of energy and technological indicators, it is proposed to use a complex criterion (14):

$$J = w_1 * \frac{e_p}{e_p}, min + w_2 * \frac{Q_{min}}{Q} + w_3 * \frac{R}{R_{max}} \quad (14)$$

where J is a complex optimization criterion; $w_1$, $w_2$, $w_3$ are weighting factors; $e_p$ is the current specific energy consumption; $e_p$, min is the minimum specific energy consumption; Q is the current productivity; $Q_{min}$ is the minimum permissible productivity; R is the current level of technological load; $R_{max}$ is the maximum permissible load.

The proposed model allows us to move from a single-criteria determination of energy efficiency to a multi-criteria selection of the machine operating mode (Fig. 4.). This is especially important for agro-industrial technologies, where minimization of energy consumption should not be carried out at the expense of an unacceptable decrease in productivity or quality of the technological process.

The theoretical study demonstrates the nonlinear nature of the formation of the energy characteristics of a technological machine. It has been established that specific energy consumption cannot be considered as a monotonic function of productivity. At low productivity, constant and idle losses have a dominant influence, while at high load, technological resistance and nonlinear losses become decisive.

This provision is of fundamental importance for determining energy-efficient operating modes of machines. Increasing productivity to a certain level contributes to a decrease in specific energy costs, since the constant component of energy consumption is distributed over a larger volume of products. However, a further increase in productivity is accompanied by an intensive increase in the technological component of power, as a result of which specific energy costs begin to increase.

The established patterns also indicate the feasibility of adaptive control of the operating modes of technological machines. If the actual technological load changes due to the heterogeneity of the raw material, changes in its moisture content, density or fractional composition, a fixed operating mode cannot ensure minimal energy consumption throughout the entire technological cycle.

In this regard, it is promising to create an adaptive control system that will determine the actual load of the machine in real time and adjust the rotation frequency, material feed rate or other operating parameters. The general algorithm of such control can be represented by the sequence: measurement of parameters → determination of current load → calculation of specific energy consumption → comparison with the optimal value → adjustment of the operating mode.

An important result of the theoretical study is the establishment of the principle possibility of determining the optimal mode without the need for a complete search of all possible mode parameters. The use of a mathematical model allows first to determine the region of rational values, and then to experimentally clarify its boundaries for a specific machine design [11].

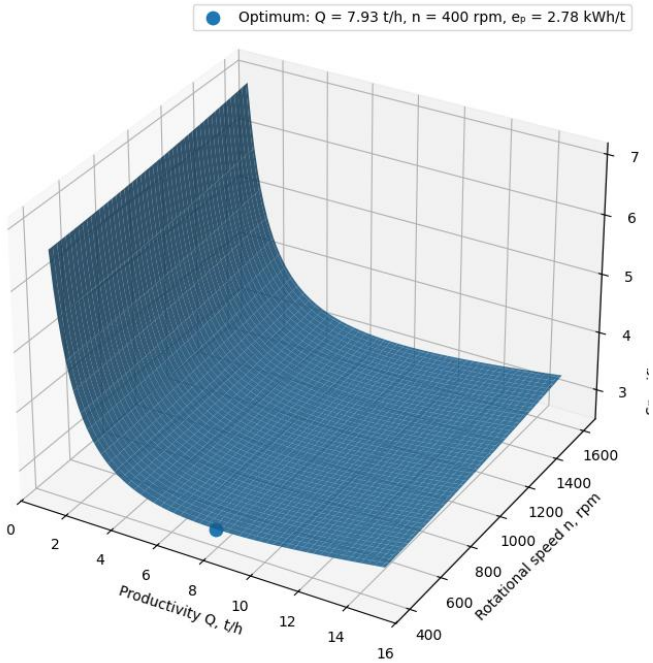


***Fig. 4 . 3D optimization surface of specific energy* consumption**

Thus, the results of the theoretical analysis confirm the feasibility of optimizing technological machines not by one parameter, but by a set of indicators - specific energy consumption, productivity, technological load and quality of operation. The proposed approach can be used as a theoretical basis for further experimental research of specific technological machines of the agro-industrial complex and the development of automated control systems for their operating modes.

## 5. Conclusions

As a result of the theoretical study, the feasibility of considering a technological machine of the agro-industrial complex as a complex energy-technological system, the efficiency of which is determined by the interaction of structural, kinematic, power, technological and energy parameters, has been substantiated. It has been established that assessing energy efficiency only by the value of installed capacity or absolute energy consumption does not allow objectively determining the rational mode of operation of the machine.

A theoretical approach to determining the energy characteristics of a technological machine has been developed based on the decomposition of the total power into a useful technological component and a set of constant, mechanical and technological losses. This approach allows us to establish the physical content of the main components of the energy balance and determine their impact on the overall efficiency of the technological process.

The mathematical dependence of specific energy costs on the productivity of a technological machine is obtained in the form $e_p(Q) = P_0/Q + a + bQ$. Theoretical analysis of this dependence has shown that specific energy costs are nonlinear and are characterized by the presence of a region of minimum values. At low productivity, constant energy losses have a dominant influence, while at excessive productivity increase, the nonlinear growth of the technological component of energy consumption becomes decisive.

The theoretical dependence of optimal productivity on the parameters of the energy characteristic of the machine has been established: $Q_{opt} = sqrt(P_0/b)$. This makes it possible to determine the preliminary area of rational productivity without conducting a complete search of operating modes and creates a basis for further experimental refinement of the optimal parameters of a specific technological machine.

The influence of the working body rotation frequency on the energy characteristics of the machine is theoretically substantiated. It is shown that with increasing rotation frequency, the power required to drive the working body increases, and with a nonlinear nature of the torque change, energy consumption can grow faster

than productivity. Therefore, the maximum rotation frequency cannot automatically be considered the most energy-efficient mode.

A three-dimensional mathematical model $e_p = f(Q,n)$ *has been developed*, which establishes the relationship between productivity, working element rotation frequency and specific energy consumption. The construction of a 3D optimization surface and a two-dimensional contour map allows us to determine the area of rational machine operating modes and visually assess the impact of simultaneous changes in two main operating parameters.

A complex optimization criterion is proposed, which involves simultaneous consideration of specific energy costs, productivity, and technological load. This approach allows avoiding single-criteria optimization, in which minimizing energy consumption may be accompanied by an unacceptable decrease in productivity or deterioration of the quality of the technological process.

The feasibility of adaptive regulation of the operating parameters of technological machines depending on the actual technological load and the properties of the processed raw materials has been established. Changes in humidity, density, fractional composition and other physical and mechanical characteristics of the material lead to changes in technological resistance, and therefore, optimal energy modes.

The practical value of the results obtained lies in the possibility of using the proposed mathematical approach for preliminary selection and optimization of operating modes of crushing, mixing, transport, drying, pressing and other technological equipment of the agro-industrial complex. The results can be used when designing new machines, modernizing existing equipment and developing automated control systems.

Further research should be directed at experimental verification of the proposed theoretical dependencies for a specific type of technological machine, determination of the actual coefficients of the mathematical model, establishment of the influence of the physical and mechanical properties of the processed material, and development of an algorithm for adaptive control of operating modes based on the criterion of minimum specific energy consumption.

Thus, the results of the theoretical study confirm that it is advisable to ensure the increase in energy efficiency of technological machines of the agro-industrial complex not by simply reducing the power consumption, but by optimizing the interrelated parameters "productivity - speed - technological load - energy consumption". The proposed approach forms the theoretical basis for the further development of energy-saving technological machines and intelligent systems for controlling their operating modes.

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## ТЕОРЕТИЧНЕ ОБҐРУНТУВАННЯ ЕНЕРГОЕФЕКТИВНИХ РЕЖИМІВ РОБОТИ ТЕХНОЛОГІЧНИХ МАШИН АГРОПРОМИСЛОВОГО КОМПЛЕКСУ

*Статтю присвячено теоретичному обґрунтуванню енергоефективних режимів роботи технологічних машин агропромислового комплексу в умовах необхідності підвищення продуктивності, зниження питомих енергетичних витрат та забезпечення стабільності технологічних процесів. Актуальність дослідження зумовлена зростанням вартості енергетичних ресурсів, необхідністю скорочення експлуатаційних витрат і підвищення ресурсоефективності машин та обладнання. Значна частина технологічних машин експлуатується за номінальними режимами, які не завжди відповідають фактичному навантаженню, властивостям сировини та умовам виконання операції, що спричиняє надлишкові енергетичні витрати.*

*Сформовано теоретико-методологічний підхід до визначення енергоефективних режимів функціонування технологічних машин на основі встановлення взаємозв'язку між конструктивними, кінематичними, силовими, технологічними та енергетичними параметрами. Технологічну машину розглянуто як енергетико-технологічну систему, у якій взаємодіють привод, робочі органи, оброблюваний матеріал та зовнішнє середовище. Визначено основні складові енергетичного балансу та запропоновано систему взаємопов'язаних параметрів, що включає продуктивність, частоту обертання, крутний момент, потужність привода, коефіцієнт корисної дії та питомі енергетичні витрати.*

*Теоретично обґрунтовано використання питомих енергетичних витрат як одного з основних критеріїв ефективності технологічної машини. Встановлено, що залежність енергетичних витрат від продуктивності та режимних параметрів має нелінійний характер і характеризується областю раціональних режимів. За недостатнього навантаження зростає частка холостих втрат, тоді як надмірне навантаження спричиняє збільшення силового опору, механічних втрат та енергоспоживання. Запропонований підхід створює теоретичну основу для визначення оптимальних режимів роботи технологічних машин та подальшої розробки систем адаптивного керування.*

***Ключові слова:*** *технологічна машина, агропромисловий комплекс, енергоефективність, енергетичні витрати, режим роботи, математичне моделювання, оптимізація, продуктивність, технологічний процес, потужність привода, питомі енергетичні витрати.*

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