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Heat engineering aspects of automatic control of the heat-moisture state of the heat carrier in shaft-type grain dryers

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Article info

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The article considers the heat engineering aspects of automatic regulation of the heat-moisture state of the heat carrier in shaft-type grain dryers. The purpose of the study is to substantiate the features of formation and stabilization of the temperature and humidity parameters of the heat carrier under conditions of automated control of the grain drying process. The study is based on methods of analysis and generalization of scientific and technical literature, system analysis, heat engineering analysis of heat and mass transfer processes, as well as mathematical modeling of dynamic control processes in grain drying systems. The physical model of the grain drying process in shaft-type grain dryers was analyzed, and the main factors affecting the formation of the heat-moisture state of the heat carrier were identified. It was established that the efficiency of the drying process largely depends on the stability of the temperature and humidity parameters of the heat carrier, the initial grain moisture content, the airflow rate, and the thermal inertia of the drying system. Based on the heat balance equation and mathematical models of moisture removal from grain material, the relationship between the heat carrier parameters and the intensity of heat and mass transfer in the grain layer was substantiated. A dynamic model of the drying system was proposed, taking into account the inertia of thermal processes and the delay between the control action and the response of the drying chamber. The study substantiates the expediency of using a closed-loop automatic control system based on PID regulation for simultaneous stabilization of the temperature and humidity parameters of the heat carrier. The proposed approach provides continuous monitoring of the heat carrier parameters and adjustment of the operating modes of the heat generator and ventilation system according to changes in the thermal state of the grain mass. The constructed graphical dependences in Cartesian coordinate systems showed that automatic regulation makes it possible to reduce fluctuations in the heat carrier temperature, improve the stability of drying modes, decrease unnecessary heat losses, and increase the energy efficiency of the drying process. It was established that multiparameter control of the heat-moisture state of the heat carrier contributes to more uniform moisture removal from grain material and reduces the risk of local overheating of grain. The practical significance of the obtained results lies in the possibility of using the proposed approaches in the design and improvement of automated control systems for shaft-type grain dryers in order to increase the stability and energy efficiency of grain drying technologies.

Keywords: grain drying, shaft-type grain dryer, heat carrier, heat-moisture state, automatic control, PID regulation, heat and mass transfer.

Теплотехнічні аспекти автоматичного регулювання тепловологісного стану теплоносія у зерносушарках шахтного типу

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У статті розглянуто теплотехнічні аспекти автоматичного регулювання тепловологісного стану теплоносія у зерносушарках шахтного типу. Метою дослідження є обґрунтування особливостей формування та стабілізації температурно-вологісних параметрів теплоносія в умовах автоматизованого керування процесом сушіння зерна. Дослідження базується на методах аналізу та узагальнення науково-технічної літератури, системного аналізу, теплотехнічного аналізу процесів тепло- і масообміну, а також математичного моделювання динамічних процесів керування у зерносушильних системах. Проаналізовано фізичну модель процесу сушіння зерна у шахтних зерносушарках та визначено основні фактори, що впливають на формування тепловологісного стану сушильного агента. Установлено, що ефективність процесу сушіння значною мірою залежить від стабільності температурно-вологісних параметрів теплоносія, початкової вологості зерна, витрати повітряного потоку та теплової інерційності сушильної системи. На основі рівняння теплового балансу та математичних моделей видалення вологи із зернового матеріалу обґрунтовано взаємозв'язок між параметрами теплоносія та інтенсивністю тепло- і масообміну у зерновому шарі. Запропоновано динамічну модель сушильної системи, яка враховує інерційність теплових процесів і затримку між керуючим впливом та реакцією сушильної камери. У роботі обґрунтовано доцільність використання системи автоматичного керування із замкненим контуром на основі PID-регулювання для одночасної стабілізації температурних і вологісних параметрів теплоносія. Запропонований підхід забезпечує безперервний моніторинг параметрів сушильного середовища та коригування режимів роботи теплогенератора і вентиляційної системи відповідно до зміни теплового стану зернової маси. Побудовані графічні залежності у декартових системах координат показали, що автоматичне регулювання дозволяє зменшити коливання температури теплоносія, підвищити стабільність режимів сушіння, знизити непродуктивні теплові втрати та підвищити енергоефективність процесу сушіння. Установлено, що багатопараметричне регулювання тепловологісного стану теплоносія сприяє більш рівномірному видаленню вологи із зернового матеріалу та зменшує ризик локального перегріву зерна. Практичне значення отриманих результатів полягає у можливості використання запропонованих підходів під час проєктування та вдосконалення автоматизованих систем керування зерносушарками шахтного типу з метою підвищення стабільності та енергоефективності технологій сушіння зерна.

Ключові слова: сушіння зерна, зерносушарка шахтного типу, теплоносій, тепловологісний стан, автоматичне регулювання, PID-регулювання, тепло- і масообмін.

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Introduction

Grain drying is one of the most energy-intensive technological processes in the post-harvest treatment of agricultural products, as it requires significant heat consumption to ensure the required moisture content of grain material. The efficiency of grain drying units is largely determined by the stability of the heat carrier parameters, particularly its temperature and humidity, which directly affect the intensity of heat and mass transfer, drying duration, energy consumption, and the quality of the final product [1, 2]. Violation of the heat-moisture drying regime may lead to local overheating of grain, non-uniform moisture removal, increased specific energy consumption, and deterioration of the seed and technological properties of grain products [3].

Modern studies pay considerable attention to improving the energy efficiency of grain drying units through the optimization of heat engineering regimes and the implementation of automated drying process control systems [4]. One of the promising approaches is the automatic regulation of heat carrier parameters, which makes it possible to stabilize the temperature and humidity state of the drying medium depending on changes in technological and environmental factors [5]. Contemporary research addresses mathematical modeling of heat and mass transfer processes during grain drying, the application of PID controllers, intelligent control systems, and digital monitoring of heat carrier parameters [6, 7]. Considerable attention is also devoted to the optimization of grain dryer energy consumption, improvement of heat carrier supply systems, and the application of modern sensor technologies for process parameter control [8, 9].

Despite the large number of scientific studies devoted to the automation of grain drying processes, the heat engineering aspects of automatic regulation of the heat-moisture state of the heat carrier in shaft-type grain dryers remain insufficiently studied. In particular, insufficient attention has been paid to the relationship between heat carrier parameters, the thermal inertia of the drying system, and the efficiency of automated control of the drying process [10]. In addition, modern approaches to the stabilization of temperature and humidity parameters of the heat carrier from the standpoint of energy efficiency and uniform grain drying require further generalization.

The relevance of the study is determined by the need to improve the efficiency of heat utilization in grain drying systems, reduce energy consumption, and ensure stable grain drying regimes through the improvement of automatic control systems for heat carrier parameters.

The aim of the study

The purpose of the study is to substantiate the heat engineering features of automatic regulation of the heat-moisture state of the heat carrier in shaft-type grain dryers.

To achieve this purpose, it is necessary to analyze the heat engineering features of the grain drying process in shaft-type grain dryers. Particular attention should be paid to the factors influencing the formation of the heat-moisture state of the heat carrier and the principles of its automatic control. In addition, it is necessary to substantiate the relationship between the heat carrier parameters, drying process stability, and the energy efficiency of grain dryers.

Materials and methods

The object of the study is the process of automatic regulation of the heat-moisture state of the heat carrier in shaft-type grain dryers. The subject of the study is the heat engineering regularities of the formation and stabilization of the temperature and humidity parameters of the heat carrier under conditions of automated control of the grain drying process.

The study employed a set of general scientific and specialized methods, including analysis and generalization of scientific and technical literature, system analysis, structural and functional analysis, and methods of heat engineering analysis of heat and mass transfer processes in grain drying units. The theoretical basis of the study is formed by the principles of heat engineering, the theory of heat and mass transfer, and the fundamentals of automatic regulation of technological processes.

The analysis of heat engineering processes in shaft-type grain dryers was carried out taking into account the influence of the temperature, humidity, and flow rate of the heat carrier on the intensity of heat and mass transfer processes, the stability of drying regimes, and the energy efficiency of the drying unit. Particular attention was paid to the investigation of the relationship between the heat carrier parameters and the conditions of formation of the heat-moisture state of the drying medium.

During the study of automatic regulation principles, the operational features of closed-loop control systems were taken into account, in which stabilization of heat carrier parameters is ensured through the use of temperature and humidity sensors, controllers, and actuating mechanisms. The analysis was performed from the standpoint of the influence of automated control on the stability of the heat-moisture state of the heat carrier, the uniformity of grain drying, and the reduction of energy consumption in shaft-type grain dryers.

Results and discussion

The grain drying process in shaft-type grain dryers represents a complex heat and mass transfer system in which heat is transferred from the heat carrier to the grain mass simultaneously with moisture evaporation from the grain. The efficiency of the drying process is determined by the heat-moisture state of the heat carrier, characterized by its temperature, humidity, and airflow velocity.

During the passage of the heat carrier through the grain layer, its temperature gradually decreases, while its humidity increases due to the absorption of evaporated moisture. The intensity of heat and mass transfer depends on the initial grain moisture content, the temperature difference between the grain mass and the heat carrier, the airflow rate, and the residence time of grain within the drying shaft.

A characteristic feature of shaft-type grain dryers is the non-uniform distribution of temperature and humidity parameters along the height of the drying shaft, as well as the significant thermal inertia of the system. This determines the dynamic nature of the formation of the heat-moisture state of the heat carrier and necessitates its stabilization during the grain drying process.

Further analysis of the drying process requires a mathematical description of the relationship between the heat engineering parameters of the grain drying unit and the heat-moisture state of the heat carrier. To evaluate the energy state of the drying system, the heat balance equation was used:

$$Q_{in} = Q_{gr} + Q_{ev} + Q_{loss}, \tag{1}$$

where Q_{in} is the heat supplied by the heat carrier;
Q_{gr} is the heat consumed for heating the grain mass;
Q_{ev} is the heat used for moisture evaporation;
Q_{loss} represents heat losses to the environment.

The presented relationship shows that the efficiency of heat utilization in a grain dryer is determined by the ratio between useful heat consumption and thermal losses of the system. Changes in the temperature or humidity of the heat carrier alter the intensity of heat and mass transfer, which directly affects the energy efficiency of the drying process.

The intensity of moisture removal from the grain mass can be described by the following relationship:

$$\frac{dW}{d\tau} = -k\left(W - W_e\right), \tag{2}$$

where W is the current grain moisture content;
W_e is the equilibrium moisture content;
k is the drying coefficient;
τ is the drying time.

According to the presented model, the drying rate is determined by the difference between the current and equilibrium moisture content of the grain, as well as by the conditions of heat and mass transfer within the drying zone. An increase in the heat carrier temperature intensifies moisture evaporation; however, excessive temperature elevation may lead to non-uniform drying and local overheating of the grain mass.

To evaluate the dynamics of changes in the thermal state of the system, a first-order inertial model was used:

$$T\frac{dy(t)}{dt} + y(t) = Ku(t), \tag{3}$$

where T is the system time constant;
$y(t)$ is the controlled parameter;
$u(t)$ is the control action;
K is the system gain coefficient.

The presented relationship characterizes the inertial nature of changes in the heat-moisture state of the heat carrier in shaft-type grain dryers and makes it possible to take into account the time delay between changes in the operating mode of the heat generator and the response of the drying system.

To ensure the stability of the heat-moisture state of the heat carrier, a shaft-type grain dryer should be considered as a multiparameter automatic control object with a closed-loop regulation system. In such a system, the main controlled parameters are the temperature and humidity of the heat carrier, while the control actions are the intensity of airflow heating and the performance of the ventilation system.

Structurally, the automatic control system includes temperature and humidity sensors, a signal processing unit, a controller, a heat generator, and actuating mechanisms of the heat carrier supply system. During operation, the sensors continuously record the current parameters of the drying medium, after which the signal is transmitted to the controller, where the deviation of the actual parameters from the specified values is determined. Based on the obtained error, a control signal is generated to change the operating mode of the heat generator or the ventilation system.

The mathematical description of the automatic control process can be represented by the PID controller equation:

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{de(t)}{dt}, \tag{4}$$

where $u(t)$ is the control signal;
$e(t)$ is the control error;
K_p, K_i and K_d are the coefficients of the proportional, integral, and derivative components of the controller, respectively.

The proportional component ensures a rapid system response to changes in the heat carrier parameters, the integral component eliminates the steady-state control error, while the derivative component compensates for rapid changes in the drying medium parameters and reduces overshoot. The combined application of these components makes it possible to improve the stability of the temperature-humidity drying regime.

The analysis established that, for shaft-type grain dryers, the most significant factor affecting the quality of regulation is the thermal inertia of the system. The considerable volume of the grain mass and the duration of its residence within the drying shaft cause a time delay between changes in the heat carrier parameters and the response of the system. Under such conditions, the use of only proportional regulation may lead to fluctuations in the temperature and humidity parameters and instability of the drying regime.

Therefore, it is advisable to apply combined regulation of the temperature and humidity of the heat carrier, taking into account the current state of the grain mass and environmental conditions. Such an approach makes it possible to increase the accuracy of maintaining the heat-moisture state of the heat carrier and to ensure a more stable grain drying process.

Further analysis of the effectiveness of the proposed automatic regulation approach requires evaluation of the relationship between the heat carrier parameters and the main characteristics of the drying process. For this purpose, the dependences characterizing the influence of the temperature regime, the dynamics of changes in grain moisture content, and the inertial properties of the system on the operational stability of the shaft-type grain dryer were analyzed.

According to the heat balance equation, an increase in the temperature difference between the inlet and outlet heat carrier is accompanied by an increase in the heat flow transferred to the grain mass. The graphical dependence of the heat flow on the temperature difference has a nearly linear character, indicating a proportional increase in heat transfer intensity with increasing heat carrier temperature (***Fig. 1***).

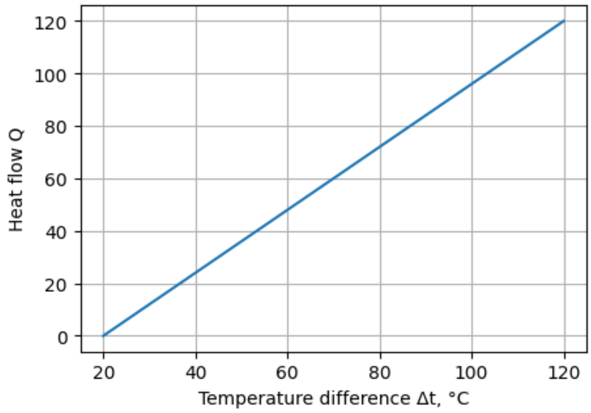

Fig. 1. Dependence of heat flow on the temperature difference of the heat carrier

At the same time, excessive increase in the heat carrier temperature is accompanied by an increase in unnecessary heat losses and the risk of local overheating of the grain mass, especially in the upper zones of the drying shaft where the initial grain moisture content is the highest. This confirms the necessity of maintaining a rational drying temperature regime.

The intensity of the drying process is determined by the rate of moisture removal from the grain mass. Analysis of drying kinetics showed that the change in grain moisture content over time has an exponential character (***Fig. 2***).

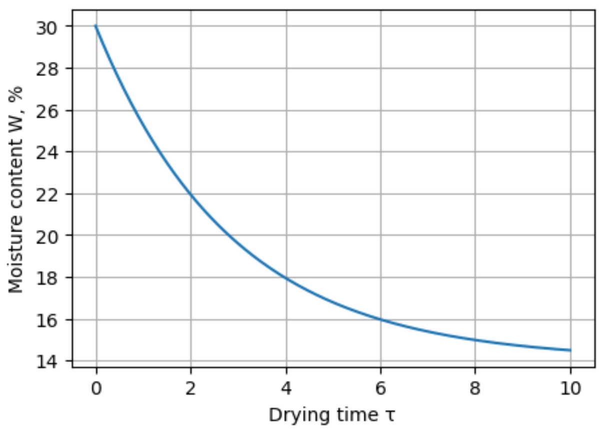

Fig. 2. Kinetics of grain moisture content change during the drying process

The highest moisture removal rate is observed at the initial stage of the process, when the difference between the current and equilibrium grain moisture content is maximal. Subsequently, the drying intensity gradually decreases due to the reduction of mass transfer between the grain and the heat carrier.

The obtained dependence indicates the expediency of changing the heat carrier supply parameters depending on the stage of the drying process. Maintaining a constant heat carrier temperature throughout all drying stages may result in excessive heat consumption and non-uniform moisture removal from the grain mass.

The conducted analysis also showed that the drying intensity depends nonlinearly on the heat carrier temperature. As the temperature increases, the rate of moisture evaporation rises; however, after reaching a certain temperature level, the increase in drying intensity gradually decreases (***Fig. 3***). This is explained by the reduction in the efficiency of heat and mass transfer and the increase in heat losses under excessive heating of the airflow.

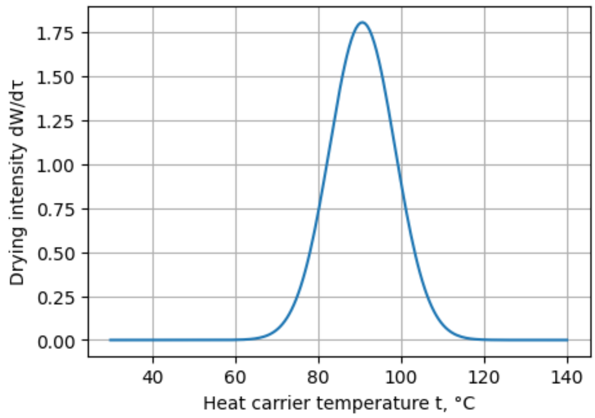

Fig. 3. Influence of heat carrier temperature on grain drying intensity

The presented dependence makes it possible to determine the rational operating temperature range of the grain dryer, within which the most efficient heat utilization is ensured without deterioration of grain product quality.

The dynamic properties of the automatic control system are of particular importance for the stability of the drying process. Analysis of the transient process showed that changes in the operating mode of the heat generator do not result in instantaneous stabilization of the heat carrier parameters, since the system is characterized by considerable thermal inertia (***Fig. 4***). As a consequence, a time delay occurs between the control action and the response of the drying system.

As the system inertia increases, the risk of fluctuations in the temperature and humidity parameters of the heat carrier and overshoot also increases. The application of PID regulation makes it possible to reduce the fluctuation amplitude and shorten the time required for the system to reach a steady-state operating mode.

Improving the stability of the temperature regime directly affects the energy efficiency of the drying process. Analysis of the dependence of specific energy consumption on the amplitude of heat carrier temperature fluctuations showed that an increase in temperature regime instability leads to higher unnecessary heat losses (***Fig. 5***).

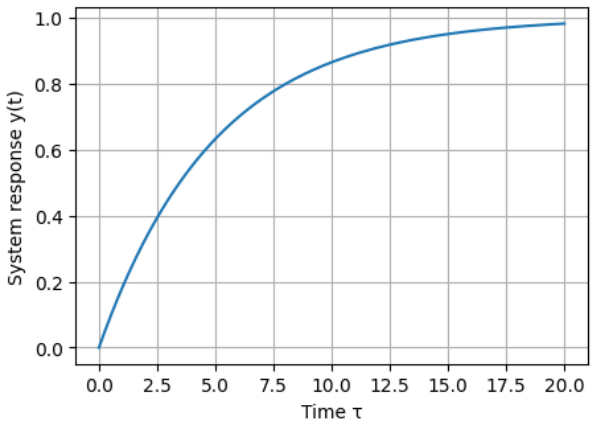

Fig. 4. Transient response of the automatic heat carrier temperature regulation system

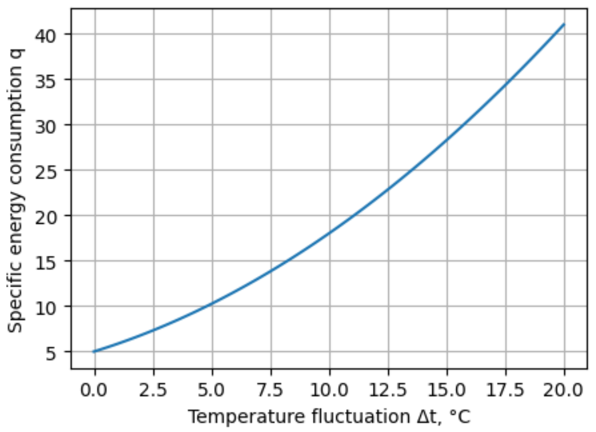

Fig. 5. Influence of heat carrier temperature fluctuations on the specific energy consumption of the grain dryer

The obtained graphical dependences confirm that the efficiency of the drying process in shaft-type grain dryers is determined by the complex interaction of the temperature and humidity parameters of the heat carrier, as well as by the dynamic characteristics of the automatic control system. This indicates the expediency of using multiparameter control systems capable of stabilizing the heat-moisture state of the heat carrier according to changing drying process conditions.

The conducted study confirms that modern approaches to the automation of grain drying processes are focused on integrated regulation of drying medium parameters with consideration of the dynamics of heat and mass transfer within the grain layer. Unlike traditional systems, in which regulation is performed mainly according to the heat carrier temperature, modern grain drying units increasingly apply multiparameter control with simultaneous consideration of temperature, humidity, and airflow rate [11, 12]. This makes it possible to improve the stability of the drying process and reduce energy consumption through more accurate coordination of the operating modes of the heat generator and the ventilation system.

The results of the conducted analysis are consistent with contemporary studies devoted to improving the energy efficiency of grain drying units through stabilization of heat carrier parameters and optimization of drying regimes [13]. In modern grain drying systems, particular attention is paid to maintaining stable temperature and humidity parameters of the drying medium, since their fluctuations lead to increased heat losses and deterioration of grain drying uniformity [14].

The conducted study confirms that, for shaft-type grain dryers, one of the most significant factors affecting the efficiency of automatic regulation is the thermal inertia of the system. Under conditions of considerable drying process inertia, the use of only proportional regulation does not provide the required stability of the temperature-humidity regime, which is consistent with the results of studies in the field of heat engineering analysis of drying systems [15, 16].

In modern approaches to the automation of drying processes, multiparameter control systems capable of simultaneously considering temperature, humidity, and heat carrier flow rate are becoming increasingly widespread [17]. The use of sensor-based monitoring systems for drying medium parameters creates the possibility for prompt correction of the operating modes of the heat generator and ventilation system according to changes in the heat engineering state of the grain mass [18].

The obtained results also confirm the prospects of using adaptive control algorithms for shaft-type grain dryers. Unlike classical PID regulation, adaptive systems make it possible to account for changes in grain moisture content and environmental parameters in real time, thereby improving drying energy efficiency and reducing unnecessary heat losses [19].

Thus, the proposed approach to automatic regulation of the heat-moisture state of the heat carrier corresponds to current trends in the development of energy-efficient grain drying technologies and can be applied in improving automated control systems for shaft-type grain dryers. A promising direction for further development is the integration of mathematical modeling of heat and mass transfer processes with real-time monitoring systems of drying medium parameters to ensure more stable grain drying regimes [20].

Conclusions

As a result of the conducted study, it was established that the efficiency of the grain drying process in shaft-type grain dryers is largely determined by the stability of the heat-moisture state of the heat carrier, which is characterized by the temperature and humidity parameters of the drying medium. It was determined that the process of formation of the heat-moisture state of the heat carrier has a dynamic character and depends on the interaction of heat engineering and technological factors, including the initial moisture content of the grain mass, the airflow rate, and the operating mode of the heat generator.

Based on the analysis of mathematical models, the influence of the thermal inertia of the drying system on the stability of drying regimes was substantiated, and the regularities of changes in temperature and humidity parameters during heat and mass transfer processes were established.

The expediency of using multiparameter automatic regulation of the temperature and humidity of the heat carrier to improve the accuracy of maintaining drying medium parameters and reduce the amplitude of their fluctuations was proven. Analysis of the graphical dependences showed that stabilization of the temperature-humidity regime contributes to increased drying intensity, reduction of unnecessary heat losses, and improvement of the uniformity of moisture removal from the grain mass. It was established that the use of PID regulation ensures a reduction in system stabilization time and improves the operational stability of the grain dryer under conditions of variable heat engineering load.

The scientific novelty of the study lies in substantiating the relationship between the heat-moisture state of the heat carrier, the dynamic characteristics of the drying system, and the efficiency of automatic regulation of the grain drying process in shaft-type grain dryers.

The practical significance of the obtained results lies in the possibility of applying the proposed approaches for improving automated control systems of grain drying units in order to increase the energy efficiency and stability of technological drying regimes.

Prospects for further research. A promising direction for further research is the development of adaptive automatic control systems for the heat-moisture state of the heat carrier, taking into account changes in grain mass parameters and environmental conditions in real time. It is advisable to conduct studies aimed at integrating digital monitoring systems, intelligent control algorithms, and mathematical modeling of heat and mass transfer processes in shaft-type grain dryers. Particular attention should be paid to investigating the possibilities of applying predictive control algorithms to improve the energy efficiency of the grain drying process and reduce unnecessary heat losses.

DECLARATIONS

Ethical Statement

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Conflict of Interest

The author declares no conflict of interest.

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Declaration of AI and AI-assisted technologies

The author declares that no artificial intelligence or AI-assisted technologies were used in the preparation of this manuscript.

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