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OPTIMIZATION OF GRAIN DRYER FUNCTIONING MODES AS A COMPLEX DYNAMIC SYSTEM

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ABSTRACT

Drying of capillary-porous colloidal materials, including grain, is a complex technological process, which is implemented in installations of various design and principal designs. The method of grain dryers engineering calculation is based on material and thermal balances, because of which the amount of moisture to be removed from the material, the flow rate of the heat carrier, and the duration of the drying process are determined. However, to intensify and automate the processes of grain post-harvest processing, new technological approaches and circuit solutions based on digital platforms are needed. When optimizing the modes of grain dryers' operation as complex dynamic systems, it becomes necessary to formulate and solve a control problem that takes into account the restrictions imposed on the allowable ranges of changes in the coordinates of the technological process quality multidimensional space and its regulation. These restrictions are determined by the given regulation of the kinetic processes course, when thermal effects approach the maximum allowable values. Taking into account the limitations in the process of synthesis of control systems allows reasons to implement the conditions for product quality and improve the reliability of the grain dryer. On synthesizing an effective control system for a carousel-type grain dryer, a difficult task arises - the fulfillment of engineering requirements set for the quality of the technological process functioning in transient and steady-state modes. The development and implementation of an optimization model that ensures the stabilization of the grain dryer leads technological parameters to an increase in the reliability of the post-harvest grain processing system functioning as a whole.).

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1. INTRODUCTION

Ensuring the quality of technical equipment functioning in agricultural production is an urgent problem. An objective assessment of the technological reliability of post-harvest grain processing complexes is an important aspect of this problem, which is the initial prerequisite for its practical solution. During the operation of a production line for post-harvest processing of grain, the drying unit is the limiting section. The rate of grain harvesting and the quality of the production process as a whole depend on the efficiency of its work (Krichevsky et al., 1980; Volkhonov et.al., 2018).

The main requirement for the design of the drying unit is to ensure its productive operation due to the uniform effect of the heat carrier on the entire volume of the material being dried in the drying chamber. The solution of this problem is connected with the rationalization of the grain dryer design parameters and provides for the intensification of its work processes. Another group of tasks is aimed at optimizing the regime parameters of grain dryers, which affect the problem of process control.

When analyzing grain dryers as dynamic systems, the influence of control parameters on various performance indicators is evaluated. In particular, when optimizing operating modes, it is important to obtain a trajectory that describes the vector of output (dependent) parameters when the vector of input (independent) variables changes. Determining the statistical characteristics of grain dryers is reduced to assessing the sensitivity of the output parameters vector to the vector of input parameters, i.e.

$$\Delta Y=|dy/dx|\Delta X \tag{0}$$

Function (0) depends on the parameters of the grain dryer, such as heat transfer coefficients and moisture conductivity.

The main condition for the rational control of the drying process is the need to identify the factors that affect the specified process and determine the heat and mass transfer and hydrodynamic characteristics of the unit. To characterize the stability of the system quality controlled parameters, it is necessary to develop an adequate mathematical model that establishes a relationship between these parameters and the factors influencing them, which determine the need to change the operating modes of the drying process (Kerimov et al., 2020; Kerimov et al., 2021). To create a holistic theoretical picture of the processes occurring in the dryer it is necessary to formalize the kinetic regularities that take place in this case. The number of factors also determines the number of bonds that provide a closed system of kinetic equations.

The purpose of this study is a theoretical study of a grain dryer as a multidimensional kinetic-dynamic system and the development of an optimization model aimed at solving an applied problem - the control of the drying process and, ultimately, its intensification, taking into account the probabilistic nature of the operating conditions.

2. METHODS

Carousel universal dryer is designed for drying seeds of cereals, leguminous crops with an initial moisture content of up to 35% in seed and food modes. The drying technology is as follows (Figure 1).

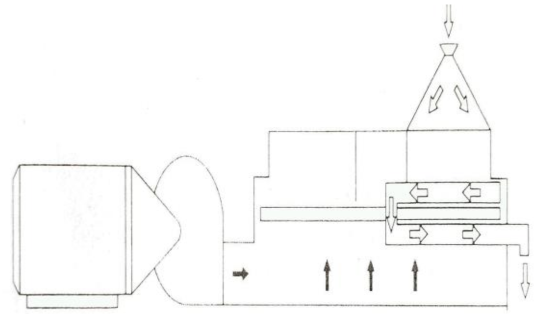

Figure 1. Technological scheme of the dryer operation

A grain layer 0.5 m high on a lattice carousel platform is blown from below with a powerful flow of coolant. Loading, drying and unloading of the material occurs simultaneously during the operation of the dryer. The grain in the lower part of the layer is separated as it dries and is removed from the dryer. A new portion of wet grain is automatically fed as the already dried one is removed.

The grain mass is in the zone of elevated temperature for the minimum required time, and the drying agent (heat carrier) passes through the dried grain layer and completely gives it excess heat. During the operation of the rotary dryer, the heating temperature of the grain layer doesn’t exceed the values allowed by agrotechnical requirements, thereby ensuring a gentle drying mode.

The heat received by the grain from the coolant is used to heat (Qheat) the grain material and evaporate the moisture (Qunit) contained in it:

$$Q_{\text{warm.}} = Q_{\text{heat.}} + Q_{\text{unit}} \tag{1}$$

Germination and viability of seeds depend not only on temperature, but also on the initial moisture content of the heated grain, heating time and other factors. This dependence is described by the formula:

$$T_{add} = \frac{2350}{0{,}37(100-W)+W} + 20 - 10lg\tau \tag{2}$$

where T - is the time the grain stays in the heated state, min;
W – initial moisture content of grain, %.

Considering the drying process in dynamics, it is possible to present in a formalized form each of the heat balance equation components: the amount of heat used to evaporate moisture per unit time:

$$Q_{us.} = r\frac{dM}{d\tau} \tag{3}$$

the amount of heat used to heat the grain layer

$$Q_{heat.} = G \cdot C_{\text{м}}\frac{dT}{d\tau} \tag{4}$$

Where r – desorption heat equal to the latent heat of vaporization, J;

$\frac{dM}{d\tau}$– amount of moisture evaporated per unit time, kg/g;
G – mass of heated grain layer, kg/h;
$C_{\text{м}}$–heat capacity of the heated grain mass, J/kg · C°;
$\frac{dT}{d\tau}$– grain layer heating rate, °C/h.

After simple transformations, expression (1) is reduced to the form:

$$(\frac{F\cdot\alpha}{G_{dr}}(T_{tr.tem.} - T_m) = \left(C_{dr} + \frac{W_a}{100}\cdot C_{hew}\right)\frac{dT}{d\tau} + r\frac{dW_a}{d\tau}\cdot\frac{1}{100} \tag{5}$$

Where:
α –heat transfer coefficient;
$T_{tr.tem..}$– heat transfer temperature, °C;
$T_{\text{м}}$– material temperature, °C;
F – heating surface area, m^2;
C_{dr} – heat capacity of dry grain, J/kg · °C;
W_{em}– amount of evaporated moisture, kg/h;
C_{hcw}– heat capacity of water, J/kg · °C;
G_{dr} – mass of dried grain, kg.

The temperature of the coolant within certain limits can be controlled by the gas dynamics of the process. Fluctuations in the temperature of the coolant are permissible within the limits determined by the heat resistance of grain crops seeds (Table 1).

Table 1. Heat resistance of seeds of grain crops, ° C

Time of seeds stay in a heated state, min	**Initial seed moisture**		
	30	25	20
120	40,5	43,5	45,5
90	42,0	45,0	47,0
60	43,5	46,5	48,5
30	46,5	49,5	51,5

The grain drying time τ depends on the steam pressure above its surface. When the grain is heated, the pressure increases and the drying rate increases. Therefore, drying is carried out at the maximum allowable heating temperature of the grain. It is unacceptable to intensify the drying process by using higher coolant temperatures, since the grain germ receives thermal damage before the seeds are heated to an acceptable temperature. To avoid protein denaturation, it is not recommended to heat wheat grain (seed purpose) above 55°C.

Depending on the structure, chemical composition and other factors, the grain has an unequal moisture-releasing capacity. When drying grain of various crops, it is necessary to take into account such features as heat resistance, permissible moisture removal, etc. (Morais S. J. D. S., et al., 2013).

In this study, the grain dryer is considered as a set of interconnected units that ensure the consistent implementation of technological operations: grain loading, drying and unloading. The model of functioning of the grain dryer is shown in Figure 2.

The grain mass is characterized by three indicators: supply G_1, temperature θ_1, humidity W_1.

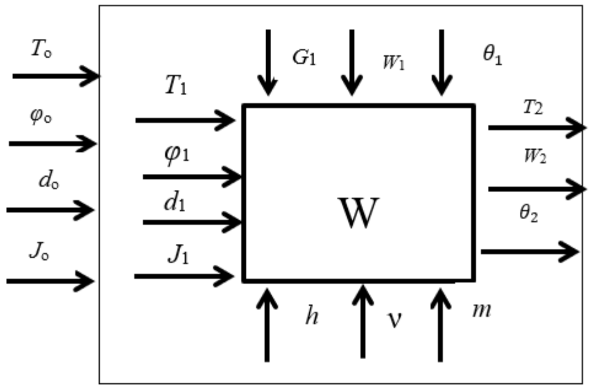

Figure 2. Model of rotary dryer type functioning

The following conventions are adopted in the model:
G1 – amount of grain fed into the dryer, kg/h;
W1 –grain moisture (initial), %;
θ_1–grain temperature at the entrance to the drying chamber, °C;
To –outdoor temperature, °C;
φo –relative humidity air, %;
do – moisture content of air, g/kg of dry air;
Jo – heat content (enthalpy), J/kg;
h –grain layer height, m;
ν –drum rotation speed, m/s;
m –bulk weight of material, kg;
G2 – productivity of the grain dryer, kg/h.

The main task of controlling grain drying is to provide the most favorable conditions in the drying chamber for the processes of moisture removal and their maximum use of energy resources (Reis, R. C. D. et al., 2012).

Features of the control object and high requirements for the accuracy of heat carrier temperature stabilization necessitate the adoption of sound technical solutions in the design and operation of temperature stabilization systems for a grain dryer, taking into account its technological and design features.

3. RESEARCH RESULTS

A grain dryer is a complex system in which the course of physical and chemical processes of removing moisture from grain is described by the equations of heat and mass transfer. The main factor determining the nature of the grain drying process is the thermal regime in the drying chamber. The kinetic-dynamic model of the grain dryer reproduces the real conditions of the removing moisture process from the material with the maximum approximation (figure 2).

Drying curves are a combined graphic representation of the main characteristics of grain drying: temperature, humidity and speed.

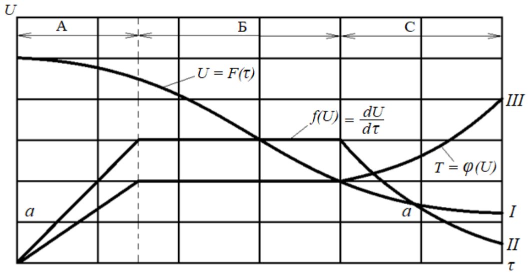

Figure 3. Curves of grain drying in a convective way

Figure 3 shows graphs expressing:

- I) $U = F(\tau)$– dependence between grain moisture content U and drying time τ;
- II) $f(U) = \frac{dU}{d\tau}$ – dependence between drying rate and moisture content of the grain layer;
- III) $T = \varphi(U)$ –dependence between temperature T and grain moisture content .

The straight line a-a characterizes the equilibrium moisture content. Here, drying stops, since the moisture-absorbing capacity of the coolant is exhausted. The temperature of the dried material must always be lower than the temperature of the spent drying agent, as otherwise, an increase in the moisture content of the material may occur due to the adsorption of water vapor from the coolant (Volkhonov et al., 2018; Volkhonov et.al., 2019; Kulikov et al., 2018).

Analyzing the curves in their totality, three stages of drying can be distinguished:

A - heating of the material;
B - section of constant drying rate;
C- time of the falling drying rate.

The main task of the dryer loading system is the uninterrupted supply of grain to the drum in an amount equal to the amount of finished material removed from the drying zone. If this condition is observed, it is possible to maintain the required productivity and achieve the quality of the resulting material in terms of moisture content (Figure 4).

Let us formulate an optimization problem for a rotary dryer as a dynamic system. Such systems are characterized by relationships between state variables x(t), control variables b(t) and parameters a in the format of ordinary differential equations. The instantaneous efficiency of the process fo depends on the same variables x, b, a:

$$x_\vartheta = f_\vartheta(x, b, a);\ \vartheta = \overline{1, m}.$$

In this case, restrictions are imposed on the set of admissible solutions: $x \in V_x$; $b \in V_b$; $a \in V_a$.

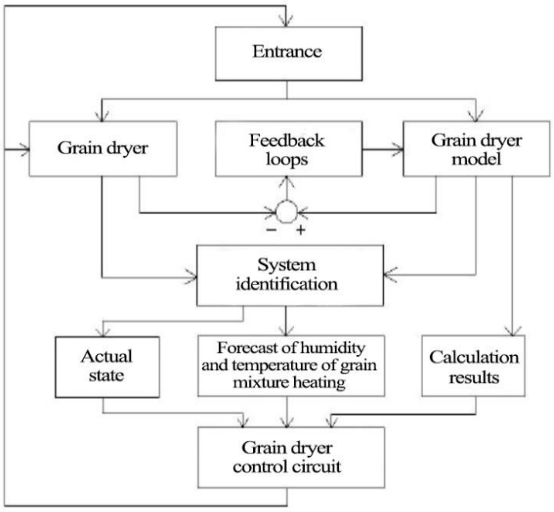

Figure 4. Scheme of a rotary dryer using a mathematical model automated control

Let us assume that the unloading and loading of grain into the dryer occur simultaneously, so that the working volume of the drum remains unchanged. For simplicity, we take this volume equal to unity. The optimality conditions for such controls as the temperature of the coolant, the moisture content of the grain in the drying chamber, and the pressure have the usual form. Therefore, we will consider only the features of the problem related to the control of the process of loading grain into the drum. Let's us denote by u(t) the intensity of grain loading and unloading, by xp- the vector that characterizes the composition of the loaded portion, taking into account its quality indicators (initial moisture content, contamination, temperature), and by x(t) the composition of the grain portion removed from the dryer (taking into account the final moisture content, contamination, temperature). We denote by u the price vector, so that the cost of drying a unit of product (planned ton) is equal to the scalar product (c, x) = Σicixi. We formulate the optimization problem.

$$I = \frac{\sum_{i=1}^{m} \mathrm{c}_i \int_0^T u(t)(x_i(t) - x_i(t) - x_i^{\text{п}} dt}{T} \tag{6}$$

The change in the characteristics of grain in the drying chamber, taking into account its uninterrupted feeding with grain, is described by the equation:

$$x_i = f_i(x) - u\left(x_i - x_i^p\right); i = \overline{1, m} \tag{7}$$

The control is subject to restrictions u(t)≥0. The absence of upper bounds on u(t) and the linearity of the problem with respect to u lead to the possibility of implementing cyclic impulse feeds. Let's write down the conditions for the optimality of the problem, the variables in which, along with u(t), are the cycle time T and the composition of the loaded grain portion xp (Boyko. et al., 2015; Bhesh Bhandari et al., 2012). To use the technique associated with the transfer of the phase coordinates one to the category of controls, we pass to the new variables

$$y_i = \ln(x_i - x_i^{\text{п}}) - y_1; i \ = \overline{2, m};\ y_1 = \ln(x_1 - x_1^{\text{п}}) \tag{8}$$

The purpose of such a replacement is that only one of the new variables [in this case y1(t)] depends on the control u, which is transferred to the category of controls. We rewrite the conditions in new notation:

$$I = \int_0^T \frac{u(t) e^{y_1(t)} [c_1 + \sum_{i=2}^{m} c_i e^{y_i(t)}] dt}{T} \to max \tag{9}$$

$$y_1 = \varphi_1(y, x^p) - u \tag{10}$$

$$y_i = \varphi_i(y, x^p) - \varphi_1(y, x^p); y_i(0) = y_i(T); i \ = \overline{2, m} \tag{11}$$

Here $\varphi_1(y, x^p)$ functions obtained after replacement in expressions $f_i(x)$and $(x_i - x_i^p)$ components of the vector x according to dependencies (8) as

$$x_1 = e^{y_1} + x_1^{\text{п}}; x_i = e^{y_i + y_1} + x_1^{\text{п}}; i \ = \overline{2, m} \tag{12}$$

Let's take $r = -1, l = \varphi_1(y, x^p)$ then the function $r_0$is equal to the multiplier at u in the integrand of the functional I, and the function l0 is formed taking into account the connections (11), we obtain the optimality conditions for this problem in the form

$$y_1^*(t) = \arg\max_{y_1} H_1 = \arg\max_{y_1} \left\{ \frac{e^{y_1}[c_1 + \sum_{i=2}^{m} c_i e^{y_i}]}{T} \varphi_1(y, x^p) + \sum_{i=2}^{m} \lambda_i [\varphi_i(y, x^p) - - \varphi_1(y, x^p)] \right\} \tag{13}$$

$$\left. \begin{array}{l} \lambda_j = -\frac{\partial H_1}{\partial y_j}; j = \overline{2, m}; \\ \lambda_j(0) = \lambda_j(T). \end{array} \right\} \tag{14}$$

Note that under impulsive control, we could not write down the cyclicity conditions for the variables xi, since these variables were discontinuous. After the change, the variables $yj(j = \overline{2, m})$, except for y1*, are continuous, and the cyclicity conditions are valid for them. When calculating y1* according to (13), it is necessary to take into account the limitations arising from equation (10) and the non-negativity of the control *u(t).*

Optimality conditions with respect to the cycle time T in problem (9) – (11) are derived according to the general rule and have the form

$$H_1(\lambda(T), y^*(T), x^{p*}) = I^*(T) \tag{15}$$

The optimality condition for the loaded portion of grain will be written in the form

$$\left[\int_0^T \nabla_{x^p} H_1(y^*, x^p, \lambda) dt\right] \delta x^p \le 0 \tag{16}$$

Here $\delta x^p$are variations allowed by the constraints $x_i^p \ge 0;\ \sum_{i=1}^{m} x_i^p == 1$

Having obtained the optimal solution of problem (9) - (11), we calculate the initial variables x* using dependencies (12). In this case, the variables xi*(t)) experience a jump at the time of the jump change y1*(t).

4. DISCUSSION

Various systems are used to control the drying process in grain dryers of various types (Liu. et al., 2001). Studies conducted on dryers 5XCZ-30 indicate that the use of this system in the control loop helps to stabilize the drying process, increase the likelihood of maintaining a technological tolerance for grain moisture fluctuations when leaving the unit. The technological scheme of the 5XCZ-30 dryer is shown in figure 5.

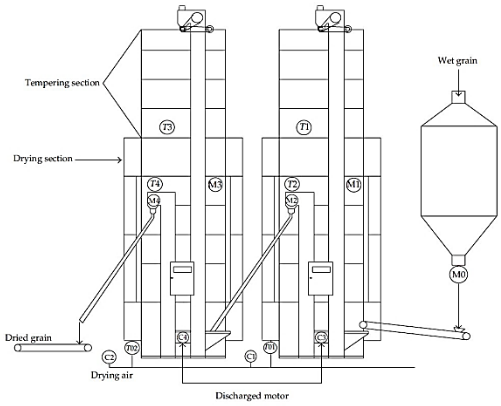

Figure 5. Technological scheme of the dryer brand 5XCZ-30

T1-T4 - temperature sensors; M0-M4 - in-line grain moisture meters; T01-T02 - devices for measuring and controlling temperature; C1-C4 - humidity measurement devices and control drives

A schematic diagram of the drying section is shown in Figure 6.

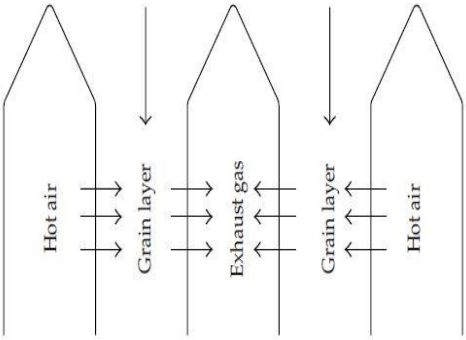

Figure 6. Diagram of the drying section in the dryer brand 5XCZ-30

However, the method for optimizing the technological parameters of the grain dryer functioning presented in the study (Liu et al., 1998; Yan et al., 2006) does not consider it as a kinetic-dynamic system and does not take into account the random nature (in the probabilistic-statistical sense) of changing the conditions for its operation. These factors include fluctuations in humidity and contamination of the grain mass at the entrance to the grain dryer, as well as fluctuations in its operating parameters. The results obtained by the authors are graphically presented in Figures 7 and 8.

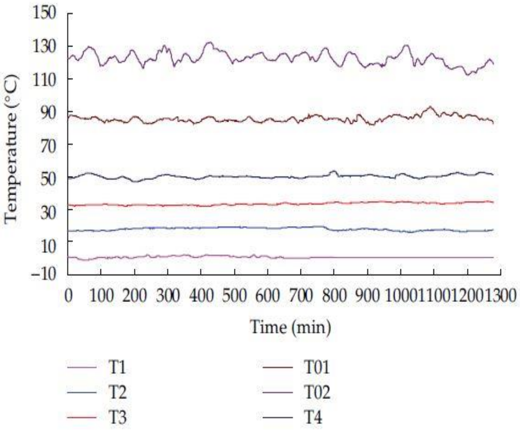

Figure 7. Temperature graphs of the coolant and grain with automatic process control

As mentioned above, compliance with the required technological parameters in the drying chamber is an urgent issue when drying seed grain.

Figure 8 shows graphs of changes in seed germination for manual and automatic control.

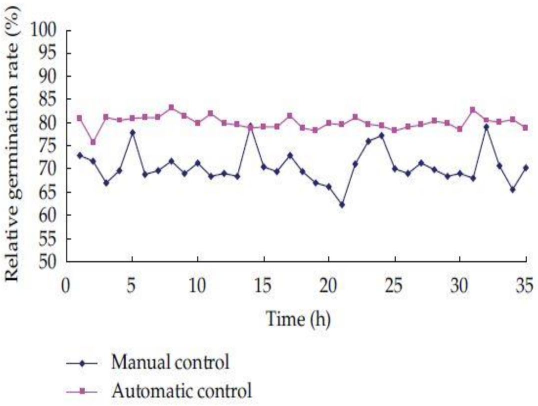

Figure 8. Graphs of the grain relative germination with manual and automatic control

Therefore, in order to intensify the technological process, it is necessary to formalize in the form of a kinetic-dynamic system the patterns that occur in a grain dryer, taking into account the multidimensionality of the quality space of its functioning (Parfenova et al., 2019; Parfenova et.al., 2020; Kerimov et al., 2022).

5. CONCLUSION

The main task of the loading system in rotary grain dryers is the uninterrupted supply of the drum with grain in an amount equal to the amount of finished material removed from the drying zone. If this condition is observed in the technological process, it is possible to maintain the specified productivity and achieve the required grain quality (in terms of moisture content) at the outlet of the dryer. The static characteristics of the loading processes are determined based on the material balances equations, assuming the continuity of the materials flow. Productivity as a determining criterion for the quality of the dryer functioning depends on the design and regime parameters: the height of the layer h of the grain material, the speed v of the drum and the bulk mass of the material. Under such conditions, limiting the change in the level of grain in the hopper is one of the main requirements for the dynamics of the automatic load control system.

The process of drying the material in a carousel-type grain dryer is characterized by the influence of various disturbing factors. The main perturbations that result in transient processes include a change in the height of the grain layer and the drum rotation speed. During the operation of the grain dryer, it becomes necessary to coordinate the speed of the drum rotation with the speed of drying in order to stabilize the completeness of the process. The indicated coordination must be carried out based on the kinetic-dynamic model shown in Figure 2.

For grain dryer control systems, the main requirement is the intensification of the technological process. This leads to the necessity of setting and solving control problems: taking into account the restrictions imposed on the allowable ranges of coordinate changes and regulation. These restrictions are determined by the given technological schedule for the flow of kinetic processes, when the thermal effects approach the maximum permissible values. Taking into account the limitations in the synthesis of control systems makes it possible to ensure the fulfillment of the requirements characterizing the quality of the final product, and to increase the reliability of the grain dryer.

On building an effective control system for a carousel-type grain dryer, a difficult problem arises to meet the set of engineering requirements for the quality of the technological process functioning in transient and steady-state modes. The development and solution of an optimization model ensure the stabilization of the grain layer level in the hopper, lead to a decrease in fluctuations in the thermal regime in the dryer drum and a decrease in the variation in the moisture content of the final product from the standard value.

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