При вивченні кінетики високотемпературного сушіння пшениці встановлено, що в кінці постійного періоду сушіння відбувається різке зростання температури нагрівання зерна. Температурний стрибок відбувається через зневоднення поверхні зерна, коли його середня відносна вологість знаходиться близько до кондиційної і становить – 15...16 %. Грунтуючись на цій закономірності, розроблений спосіб управління експозицією сушіння зерна в високотемпературних сушарках без використання поточних вологомірів.

Спосіб заснований на одночасному контролі температури нагрівання матеріалу температурними датчиками на всій довжині сушильної камери. Виміряні значення з температурних датчиків передаються в мікроконтролер з метою їх періодичної апроксимації поліномом третього ступеня і знаходження похідної функції другого порядку.

Мікроконтролер запрограмований на визначення критичної точки другого порядку – місцезнаходження зерна, що має кондиційну вологість. Отриманий результат порівнюється з максимальною довжиною шляху зерна по сушильній камері з метою подальшого впливу на продуктивність випускного пристрою.

Розроблений спосіб управління експозицією сушіння зерна в високотемпературних сушарках забезпечує необхідний час температурного впливу агента сушіння на зерно, якість процесу, зниження енерговитрат на сушіння зерна. На основі цього способу автоматизований процес сушіння без використання дорогих, поточних вологомірів зерна, що працюють з високою похибкою вимірювань

Ключові слова: сушіння зерна, управління сушінням, експозиція сушіння, кінетика сушіння

UDC 631.171
DOI: 10.15587/1729-4061.2018.133607

DEVELOPMENT OF THE METHOD OF EXPOSURE CONTROL OF GRAIN DRYING IN HIGH-TEMPERATURE DRYERS

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1. Introduction

Grain production has a great impact on the economy and food security of the country. China, India, Russia, the USA, France, Canada produce 55.4 % of the world's grain volume [1]. In humid areas, drying is usually required for 50–55% of the grain yield. With a moisture decrease from 20 % to standard, in rainy years in some regions the whole crop is subjected to drying. The importance of drying grows with increasing volumes of grain production [3].

Grain drying is the most energy-intensive and expensive operation in post-harvest processing, which requires large amounts of fuel and electric energy to operate dryers [4]. In the grain production, direct energy consumption for drying is up to 35 % and in the cost of drying – 70–75 % [2].

At the moment, there is a problem all over the world in the accurate determination of grain moisture during both continuous-flow drying and on portable devices. The problem lies in the accuracy of determination, design complexity and price of the device. Technical implementation of continuous-flow grain moisture meters in order to automate the grain drying exposure control requires the development of direct measurement methods implemented by automatic devices – moisture meters.

All moisture meters have the same drawbacks, such as high measurement error, difficulty of fitting into the process flow sheet of the dryer and high cost.

High measurement errors are caused by the peculiarities of the drying process. The physicomechanical properties of the grain heap coming for drying have stochastic nature, strongly depend on environmental parameters, especially in humid areas. When operating dryers equipped with conductivity or dielcometric continuous-flow moisture meters, a variation of grain moisture from 11 to 17 %, with standard 14 %, due to measurement inaccuracy is observed at the dryer outlet. Grain overdrying leads to wasting of a large amount of thermal energy, about 58.3 MJ per 1 % of the excessively evaporated moisture of a ton of dried grain. In case of underdrying, the operator is forced to re-pass the grain through the dryer, while significantly reducing its

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performance and increasing the damage of damp grains from their excessive interaction with the working bodies of conveyors and dryers. Therefore, at present, the use of existing continuous-flow moisture meters in grain dryers inevitably leads to a decrease in quality and an increase in the cost of finished products.

2. Literature review and problem statement

At present and the last not less than half a century, the methods based on changes in the physical characteristics of grain with a change in its moisture have been applied to measure grain moisture [5]. There is a dependence of grain temperature change on moisture during drying, which is confirmed by the results of the studies given in [6]. Mathematical modeling of drying has been also given in [7], where the theoretical background for the dependence of the material drying rate on temperature has been confirmed experimentally.

The kinetics of soybean seed drying has been given in [8]. The obtained Wang and Singh mathematical model confirms the dependence of the soybean heating temperature on changes in moisture during drying.

The results of the study of the drying kinetics of a dense layer of grain materials in a microwave field have been presented in [9]. It has been shown that moisture and temperature changes over time correspond to the curves characteristic of drying of colloidal capillary-porous bodies with other methods of heat supply.

Mathematical modeling of the seed drying kinetics has been presented in [10]. Statistical results have shown that the Henderson-Pabis model can also be applied to the kinetics of drying of a thin seed layer.

Modeling of drying curves has been also carried out for basil leaves at temperatures of 50, 60, 70 and 80 ^{o}C to assess the effect of drying temperature on the color of dried leaves. It has been found that the behavior of drying curves of basil leaves was similar to most agricultural products [11].

The revealed regularities indicate the dependence of temperature changes of capillary-porous colloidal bodies on moisture during drying. Today, however, no one suggests using these regularities for the material heating temperature dependence to control dryers without expensive, faulty continuous-flow moisture meters.

Generally, conductivity and dielcometric grain moisture meters are the most common for rapid analysis in terms of physical principles of work. Thus, in conductivity meters, the functional dependence of electric conductivity of the material on moisture is used. Dry grain is a dielectric, and becomes conductive when damp. Specific resistance of grain depends on the moisture content and varies in a fairly wide range. Using conductivity sensors for accurate measurement of grain moisture is problematic. It is especially difficult to control small values of grain moisture by conductivity meters. In this case, electric resistance is large, and additional external factors increase the measurement error. In the most important moisture range of 5–17 %, even a single grain has tens of MΩ resistance. For the grain sample, the order of resistance values will be even greater. It is technically difficult to measure the resistance of hundreds of MΩ with a small error and, accordingly, to obtain an accurate moisture value. The conductivity method of measurement is quite suitable for materials having low initial resistance, but it is difficult to implement for continuous-flow grain sensors [12].

Capacity dielcometric sensors are strongly dependent on grain properties, since it is impossible to take into account all properties of grain and flow only in terms of dielectric permeability. To obtain accurate moisture values from such sensors in the continuous-flow measurement conditions, it is necessary to ensure the reproducibility of the factors affecting the measurement results. As a rule, it is necessary to stabilize the flow density in the measuring space of the sensing element and to ensure the stability of the measuring cell, especially under possible contamination, varying water hardness. In the production environment, this forces one to use additional devices or to introduce hardware error corrections. At least after each change of one grain grade to another or after changing the composition of the milling blend, it is necessary to carry out a new calibration of the moisture sensor to achieve the required measurement accuracy. This entails the need for laborious laboratory measurements. At the same time, this means certain limitations for existing moisture meters based on dielcometric properties of grain [12]. Practice shows that during grain drying there is a redistribution of moisture from the inner layers outside. For this reason, conductivity or dielcometric sensors operate with an error of 0.5 % to 3 % or higher, since they measure mainly "external" moisture. The accuracy of measurement is strongly influenced by the physicomechanical properties of the grain heap coming for drying, environmental parameters that are stochastic, especially in the non-chernozem zone of the Russian Federation. When operating dryers equipped with such sensors, an increase in the cost and decrease in the quality of grain drying are inevitable, since if underdried, the grain should be re-passed through the dryer, which leads to additional damage by the transporting devices.

Grain overdrying entails energy overexpenditure, while the quality of seeds decreases from excessive dehydration.

There is a model of intelligent control of the grain drying process [13], based on automatic control of parameters of the drying agent and grain moisture in real time. This scheme uses a microcontroller, temperature and moisture sensors, a data acquisition system and an industrial control computer. The drawback of this model is the absence of an automatic system of grain temperature control in real time, which can lead to overheating of seeds, as well as the high cost of the continuous-flow moisture meter.

The studies [14] of the grain drying control process provided a relationship between the high-temperature drying parameters: initial moisture, grain heating temperature and time of subsequent ventilation. The disadvantage of this model is unsuitability for dryers with a stochastically moving grain layer, since this study only deals with a fixed layer.

The system of automated determination of grain drying parameters is known [15]. The drawback of this system is the use of industrial grain moisture sensors, which have a high cost and need constant calibration when changing the dryer operating modes.

In [16], the authors use the least-squares method to calibrate the data of the resistance sensor for determining grain moisture in real time. The use of the resistance sensor is associated with an increase in the measurement error due to the formation of surface moisture when drying the grain with moisture above 20 %, which is characteristic of harvesting conditions in humid areas.

Thus, the known automatic control systems of the high-temperature drying process use conductivity, dielcometric or resistance sensors for continuous-flow measurement of grain moisture. Due to the measurement error of the sensors, variation in the relative moisture of grains from 11 % – overdrying, up to 17 % – underdrying is observed at the dryer outlet. Grain overdrying leads to wasting of a large amount of thermal energy, about 58.3 MJ per 1 % of the excessively evaporated moisture of a ton of dried grain. In case of underdrying, the operator is forced to re-pass the grain through the dryer, while significantly reducing its performance and increasing the damage of damp grains from their excessive interaction with the working bodies of conveyors and dryers. To date, no methods and devices for timely grain removal from the drying chamber of high-temperature continuous-flow dryers at the end of the constant drying rate period have been developed.

3. The aim and objectives of the study

The aim of the study is to develop a method and a device for timely grain removal from the drying chamber of high-temperature continuous-flow dryers based on the kinetics of drying without the use of continuous-flow moisture meters.

To achieve the aim, the following objectives were set:

– to justify the method of exposure control of high-temperature grain drying based on the nature of temperature changes during dehydration;

– to develop an algorithm of the grain drying exposure control automation system based on the developed method;

– to obtain analytical expressions for determining the grain path through the drying chamber, after which it reaches a standard moisture, and use them in the microcontroller programming.

4. Materials and methods of the study of the method of exposure control of grain drying in high-temperature dryers

To explain the idea, let us consider the kinetics of the drying process typical for damp capillary-porous colloidal bodies, including grain, grass and oil seeds in their interaction with air [18]. It is obvious that the drying curves (Fig. 1) are correlated, which, when analyzing changes in one curve, makes it possible to objectively judge changes in the others. We suggest using these regularities for control and management of the process of moisture changes in the material based on the nature of temperature changes, which has distinctive features in each drying period [19]. The method is based on simultaneous control of the material heating temperature by temperature sensors installed over the entire length of the drying chamber. The measured temperature values from the sensors are transmitted to the microcontroller in order to periodically approximate them with the cubic polynomial and find the derivative of the second-order function. The microcontroller is programmed to determine the second-order critical point – the location (grain path) of the grain, having standard moisture. The result is compared with the length of the drying chamber in order to subsequently affect the discharger performance.

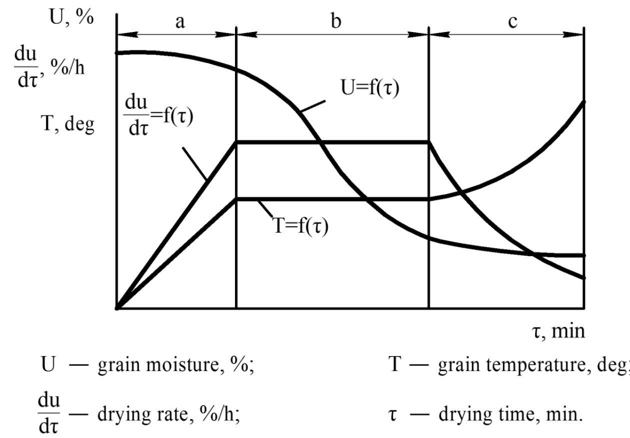

Fig. 1. Typical drying curves of capillary-porous colloidal materials, a — warm-up period; b — constant drying rate period; c — falling drying rate period

The device based on the developed method is made. It consists of a housing with a display for selecting the grain type, microprocessor, correction unit, measuring circuit of the display unit, remote optical temperature sensors, return communication lines of the microprocessor with the dryer drive.

The device for grain drying exposure control automation sends the command to perform measurements to measuring sensors (Fig. 2). After the time required to convert the temperature into a digital code, the controller alternately reads the measurement results from the sensors. The data obtained are subjected to mathematical processing, the results of which are used for a control action on the dispenser, which regulates the rate of grain displacement in the drying chamber – the time of temperature action of the drying agent on grain. Then, after a certain time, the process is repeated.

The operation algorithm of the dryer with the developed exposure control system of grain drying is as follows. In order to bring the dryer (Fig. 3) to the continuous-flow – steady-state mode, it is necessary to warm it up to the set temperature. For this, the conditioning and heating system is switched on, and damp grain is filled in. At the end of filling, when the hopper is full, the grain low level sensor 3 is triggered. At the same time, the command is given to activate the automated drying exposure control system, which at a frequency of 1–5 Hz interrogates temperature sensors and operates according to the algorithm shown in Fig. 2. In the transitional mode – before the dryer is brought to the steady-state mode, the readings of grain temperature sensors in the dryer will change according to the kinetics – drying periods (Fig. 4–7).

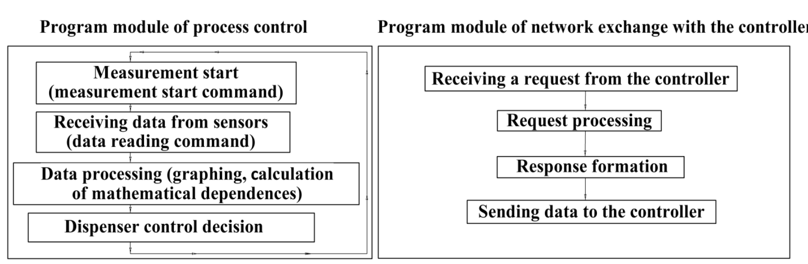

Fig. 2. Algorithm of the drying exposure control automation system

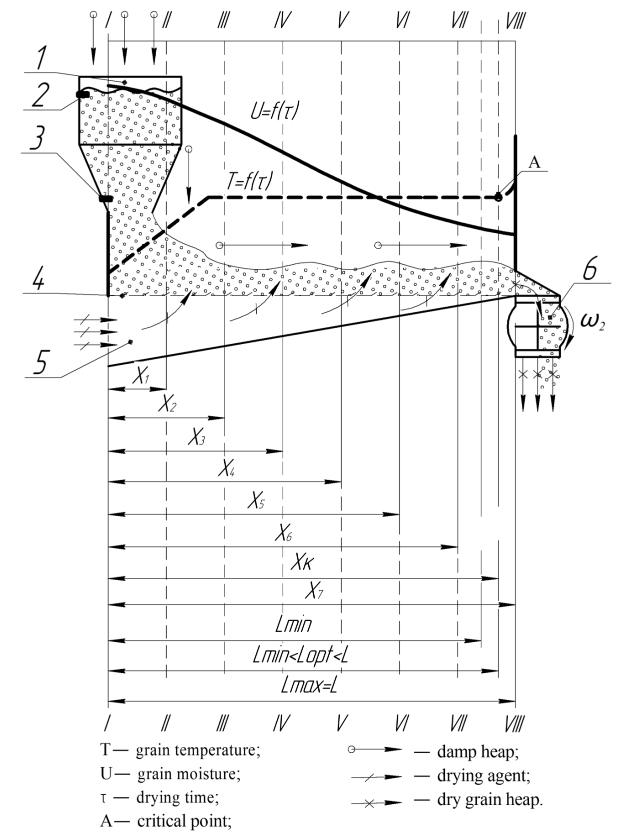

Fig. 3. Grain drying kinetics, the flowchart of the drying box and the section with temperature sensors: 1 — over-the-drier hopper; 2 —upper grain level sensor; 3 —lower grain level sensor; 4 — load-bearing perforated partition; 5 — box; 6 — discharge dispenser; X_1, X_2, X_3, X_4, X_5, X_6, X_7 — grain path from the beginning of the drying chamber to sections with temperature sensors; *Xк* — grain path from the beginning of the drying chamber to the section where the grain reaches standard moisture

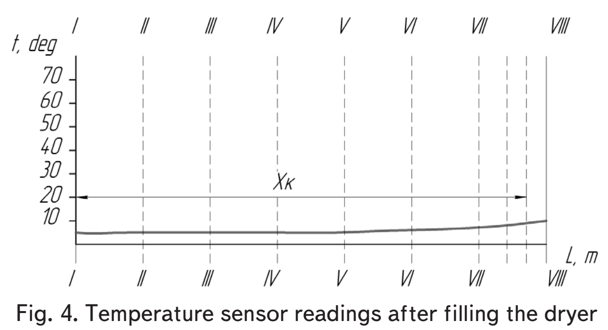

Fig. 4. Temperature sensor readings after filling the dryer with fresh, damp grain

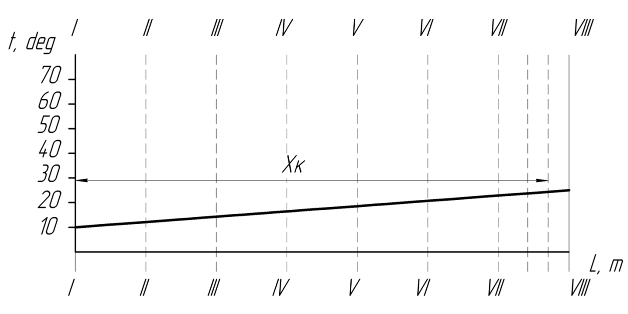

Fig. 5. Temperature sensor readings — all grain in the warm-up period

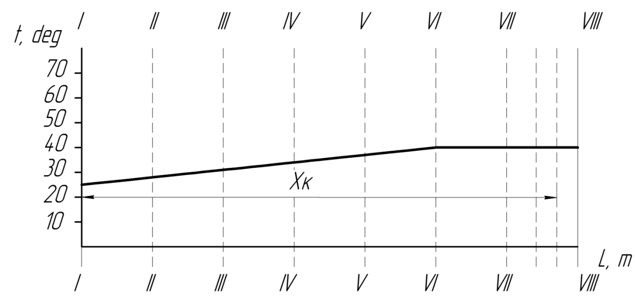

Fig. 6. Temperature sensor readings during grain transition from the warm-up period to the constant drying rate period

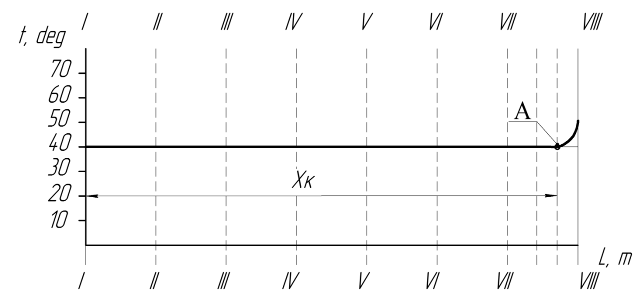

Fig. 7. Temperature sensor readings during grain transition from the constant drying rate period to the falling drying rate period

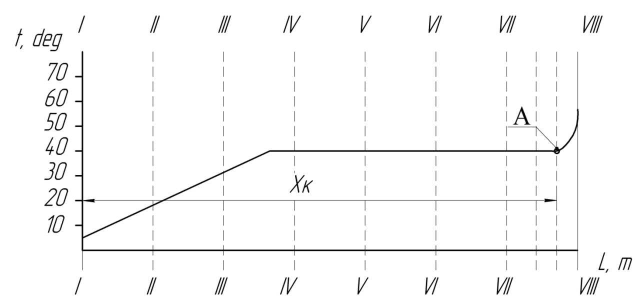

Fig. 8. Temperature sensor readings in the continuous-flow mode of the dryer — grain passes all drying periods

When grain reaches a standard moisture, the grain surface is dehydrated – a temperature jump occurs at point A (Fig. 7, 8) due to the lack of moisture on the surface of the grains that cools them. The grain drying exposure control system compares the location of the grain, having moisture close to standard, – its path (distance to point A) with the length of the drying chamber (Fig. 3). If it is less than Lmin, the discharge dispenser 6 is activated. The system automatically selects the rotor speed of the dispenser so that the grain path (to point A) is in the range from Lmin to Lmax. In the absence of an inflection point, the dispenser is switched off.

5. Results of studies on the possibility of using analytical expressions to determine the drying end

The nature of the mathematical dependences obtained as a result of laboratory studies of processing of experimental data on high-temperature drying of wheat grain [19] confirms the information available in the literature on the kinetics of drying of capillary-porous colloidal bodies. The obtained temperature dependences on the drying time have inflection points and are well approximated by the cubic polynomial. Obviously, a sharp increase in temperature occurs due to surface dehydration of the material, its average relative moisture is close to standard and makes 15...16 %. Therefore, grain at the beginning of the intense temperature increase must be discharged from the dryer and brought to standard moisture as it is cooled in the cooler. In this case, grain quality is preserved and the possibility of energy overexpenditure resulting from material overdrying is excluded.

As mentioned above, the experimental dependence of grain temperature on drying time has the form of a cubic polynomial. In this case, this polynomial has an inflection point. The entire drying process is carried out by the microcontroller. To program the microcontroller, it is necessary to find analytical expressions of the approximating function, its derivatives, and also the inflection point. To ensure the necessary accuracy of determining the moment of grain removal from the drying chamber, the derivatives and the inflection point must be found at least once a minute during the drying process. That is, there is no one standard cubic polynomial suitable for all cases. Therefore, we present the analytical expressions obtained. They are used in the program in C++ to program the microcontroller.

The initial experimental data for the calculation example are presented in Table 1.

Table 1

Dependence of temperature *Y* (degrees) on the grain path along the drying chamber *X* (meters)

X	$X_0=0$	$X_1=0.143$	$X_2==0.268$	$X_3==0.429$	$X_4==0.596$	$X_5==0.739$	$X_6==0.882$	$X_7=1$
Y	15	26	35	41	47	50	53	56

We look for the approximating function in the form [20]:

$Y=F(X)$.

This function $F(X)$ at points X_1, $X_1 ... X_n$ should take values as close as possible to the table values Y_1, $Y_1 ... Y_n$.

We look for the approximating cubic function in the form:

$$F(x,a,b,c)=a\cdot x^3+b\cdot x^2+c\cdot x+d. \tag{1}$$

According to the least-squares method, we write down the sum of the squared differences [20]:

$$\sum_{i=1}^{n}\left(y_i-F\left(x_i,a,b,c\right)\right)^2=\Phi(a,b,c,d). \tag{2}$$

We find the derivatives of (1) with respect to the parameters a, b, c, d:

$$\frac{\partial F}{\partial a}=x^3,\ \frac{\partial F}{\partial b}=x^2,\ \frac{\partial F}{\partial c}=x,\ \frac{\partial F}{\partial d}=1. \tag{3}$$

To find the deviation minimum $\Phi(a, b, c, d)$, we equate the derivatives to zero and obtain the system of equations:

$$\frac{\partial \Phi}{\partial a}=0,\ \frac{\partial \Phi}{\partial b}=0,\ \frac{\partial \Phi}{\partial c}=0,\ \frac{\partial \Phi}{\partial d}=0. \tag{4}$$

From (4), taking into account (2), we obtain the equations:

$$\begin{cases}\sum_{i=1}^{n}\left(y_i-ax_i^3-bx_i^2-cx_i-d\right)\cdot x_i^3=0,\\ \sum_{i=1}^{n}\left(y_i-ax_i^3-bx_i^2-cx_i-d\right)\cdot x_i^2=0,\\ \sum_{i=1}^{n}\left(y_i-ax_i^3-bx_i^2-cx_i-d\right)\cdot x_i=0,\\ \sum_{i=1}^{n}\left(y_i-ax_i^3-bx_i^2-cx_i-d\right)\cdot 1=0.\end{cases} \tag{5}$$

We transform (5):

$$\begin{cases}\sum_{i=1}^{n}(y_i\cdot x_i^3-ax_i^6-bx_i^5-cx_i^4-dx_i^3)=0,\\ \sum_{i=1}^{n}(y_i\cdot x_i^2-ax_i^5-bx_i^4-cx_i^3-dx_i^2)=0,\\ \sum_{i=1}^{n}(y_i\cdot x_i-ax_i^4-bx_i^3-cx_i^2-dx_i)=0,\\ \sum_{i=1}^{n}(y_i-ax_i^3-bx_i^2-cx_i-dx)=0.\end{cases} \tag{6}$$

We transform (6):

$$\begin{cases}\sum_{i=1}^{n}y_i\cdot x_i^3=\sum_{i=1}^{n}(ax_i^6-bx_i^5-cx_i^4-dx_i^3),\\ \sum_{i=1}^{n}y_i\cdot x_i^2=\sum_{i=1}^{n}(ax_i^5-bx_i^4-cx_i^3-dx_i^2),\\ \sum_{i=1}^{n}y_i\cdot x_i=\sum_{i=1}^{n}(ax_i^4-bx_i^3-cx_i^2-dx_i),\\ \sum_{i=1}^{n}y_i=\sum_{i=1}^{n}(ax_i^3-bx_i^2-cx_i-d).\end{cases} \tag{7}$$

We transform (7):

$$\begin{cases}a\sum_{i=1}^{n}x_i^6+b\sum_{i=1}^{n}x_i^5+c\sum_{i=1}^{n}x_i^4+d\sum_{i=1}^{n}x_i^3=\sum_{i=1}^{n}y_ix_i^3,\\ a\sum_{i=1}^{n}x_i^5+b\sum_{i=1}^{n}x_i^4+c\sum_{i=1}^{n}x_i^3+d\sum_{i=1}^{n}x_i^2=\sum_{i=1}^{n}y_ix_i^2,\\ a\sum_{i=1}^{n}x_i^4+b\sum_{i=1}^{n}x_i^3+c\sum_{i=1}^{n}x_i^2+d\sum_{i=1}^{n}x_i=\sum_{i=1}^{n}y_ix_i,\\ a\sum_{i=1}^{n}x_i^3+b\sum_{i=1}^{n}x_i^2+c\sum_{i=1}^{n}x_i+d\cdot n=\sum_{i=1}^{n}y_i.\end{cases} \tag{8}$$

We transform (8):

$$\begin{cases}a\cdot M1+b\cdot M2+c\cdot M3+d\cdot M4=M5,\\ a\cdot M2+b\cdot M3+c\cdot M4+d\cdot M6=M7,\\ a\cdot M3+b\cdot M4+c\cdot M6+d\cdot M8=M9,\\ a\cdot M4+b\cdot M6+c\cdot M8+d=M10,\end{cases} \tag{9}$$

which denote:

$$M1=\frac{1}{n}\sum_{i=1}^{n}x_i^6,\quad M2=\frac{1}{n}\sum_{i=1}^{n}x_i^5,$$

$$M3=\frac{1}{n}\sum_{i=1}^{n}x_i^4,\quad M4=\frac{1}{n}\sum_{i=1}^{n}x_i^3,$$

$$M5=\frac{1}{n}\sum_{i=1}^{n}y_ix_i^3,\quad M6=\frac{1}{n}\sum_{i=1}^{n}x_i^2,$$

$$M7=\frac{1}{n}\sum_{i=1}^{n}y_ix_i^2,\quad M8=\frac{1}{n}\sum_{i=1}^{n}x_i,$$

$$M9=\frac{1}{n}\sum_{i=1}^{n}y_ix_i,\quad M10=\frac{1}{n}\sum_{i=1}^{n}y_i. \tag{10}$$

We write (9) in the matrix form:

$$\begin{bmatrix} M1 & M2 & M3 & M4 \\ M2 & M3 & M4 & M6 \\ M3 & M4 & M6 & M8 \\ M4 & M6 & M8 & 1 \end{bmatrix} \cdot \begin{bmatrix} a \\ b \\ c \\ d \end{bmatrix} = \begin{bmatrix} M5 \\ M7 \\ M9 \\ M10 \end{bmatrix}. \quad (11)$$

We denote:

$$M = \begin{bmatrix} M1 & M2 & M3 & M4 \\ M2 & M3 & M4 & M6 \\ M3 & M4 & M6 & M8 \\ M4 & M6 & M8 & 1 \end{bmatrix} \quad Mo = \begin{bmatrix} M5 \\ M7 \\ M9 \\ M10 \end{bmatrix}. \quad (12)$$

Then from (11), taking into account (12), we obtain the required coefficients a, b, c, d:

$$\begin{bmatrix} a \\ b \\ c \\ d \end{bmatrix} = M^{-1} \cdot Mo. \quad (13)$$

We denote the inverse matrix:

$$P = M^{-1}. \quad (14)$$

After transformations (14), we obtain the elements of the matrix P:

$$P11 = \frac{1}{D}\begin{pmatrix} 2M4 \cdot M6 \cdot M8 - M4^2 - \\ -M6^3 + M3 \cdot M6 - M3 \cdot M8^2 \end{pmatrix},$$

$$P12 = \frac{1}{D}\begin{pmatrix} M4 \cdot M6^2 - M4^2 \cdot M8 + M3 \cdot M4 - \\ -M3 \cdot M6 \cdot M8 - M2 \cdot M6 + M2 \cdot M8^2 \end{pmatrix},$$

$$P13 = \frac{1}{D}\begin{pmatrix} M8 \cdot M3 \cdot M4 - M3^2 + M3 \cdot M6^2 - \\ -M4^2 \cdot M6 + M2 \cdot M4 - M2 \cdot M8 \cdot M6 \end{pmatrix},$$

$$P14 = \frac{1}{D}\begin{pmatrix} M8 \cdot M3^2 - 2M3 \cdot M4 \cdot M6 + \\ +M4^3 - M2 \cdot M8 \cdot M4 + M2 \cdot M6^2 \end{pmatrix},$$

$$P21 = P12,$$

$$P22 = \frac{1}{D}\begin{pmatrix} 2M3 \cdot M4 \cdot M8 - M3^2 - \\ -M6 \cdot M4^2 - M1 \cdot M8^2 + M1 \cdot M6 \end{pmatrix},$$

$$P23 = \frac{1}{D}\begin{pmatrix} M4^3 - M1 \cdot M4 + M2 \cdot M3 - M3 \cdot M4 \cdot M6 - \\ -M2 \cdot M4 \cdot M8 + M1 \cdot M6 \cdot M8 \end{pmatrix},$$

$$P24 = \frac{1}{D}\begin{pmatrix} M3^2 \cdot M6 - M3 \cdot M4^2 - M2 \cdot M8 \cdot M3 + \\ +M2 \cdot M4 \cdot M6 + M1 \cdot M8 \cdot M4 - M1 \cdot M6^2 \end{pmatrix},$$

$$P31 = P13, \quad (15)$$

$$P32 = P23,$$

$$P33 = \frac{1}{D}\begin{pmatrix} 2M2 \cdot M4 \cdot M6 - M2^2 - \\ -M3 \cdot M4^2 - M1 \cdot M6^2 + M1 \cdot M3 \end{pmatrix},$$

$$P34 = \frac{1}{D}\begin{pmatrix} M8 \cdot M2^2 - M6 \cdot M2 \cdot M3 - M2 \cdot M4^2 + \\ +M3^2 \cdot M4 - M1 \cdot M8 \cdot M3 + M1 \cdot M6 \cdot M4 \end{pmatrix},$$

$$P41 = P14,$$

$$P42 = P24,$$

$$P43 = P34,$$

$$P44 = \frac{1}{D}\begin{pmatrix} 2M2 \cdot M3 \cdot M4 - M6 \cdot M2^2 - \\ -M3^3 + M1 \cdot M6 \cdot M3 - M1 \cdot M4^2 \end{pmatrix}.$$

That is, the matrix P has the form:

$$P = \begin{bmatrix} P11 & P12 & P13 & P14 \\ P21 & P22 & P23 & P24 \\ P31 & P32 & P33 & P34 \\ P41 & P42 & P43 & P44 \end{bmatrix}. \quad (16)$$

In this case, the determinant of the matrix is:

$$\begin{aligned} D = {} & M2^2 \cdot M8^2 - M2^2 \cdot M6 + 2M2 \cdot M3 \cdot M4 - \\ & -2M2 \cdot M3 \cdot M6 \cdot M8 - 2 \cdot M2 \cdot M4^2 \cdot M8 + \\ & +2M2 \cdot M4 \cdot M6^2 - M3^3 + 2M3^2 \cdot M4 \cdot M8 + M3^2 \cdot M6^2 - \\ & -3M3 \cdot M4^2 \cdot M6 + M1 \cdot M3 \cdot M6 - M1 \cdot M3 \cdot M8^2 + \\ & +M4^4 - M1 \cdot M4^2 + 2M1 \cdot M4 \cdot M6 \cdot M8 - M1 \cdot M6^3. \end{aligned} \quad (17)$$

Then from (13), taking into account (14) and (16), we obtain the coefficients of the approximating cubic polynomial (1):

$$\begin{aligned} a &= P11 \cdot M5 + P12 \cdot M7 + P13 \cdot M9 + P14 \cdot M10, \\ b &= P21 \cdot M5 + P22 \cdot M7 + P23 \cdot M9 + P24 \cdot M10, \\ c &= P31 \cdot M5 + P32 \cdot M7 + P33 \cdot M9 + P34 \cdot M10, \\ d &= P41 \cdot M5 + P42 \cdot M7 + P43 \cdot M9 + P44 \cdot M10. \end{aligned} \quad (18)$$

That is, the cubic approximating polynomial with regard to (18) is:

$$PL(x) = a \cdot x^3 + b \cdot x^2 + c \cdot x + d. \quad (19)$$

As mentioned, the cubic function of grain temperature dependence on drying time has an inflection point. When this temperature reaches the corresponding inflection point, it is necessary to stop the drying process and discharge grain from the dryer. Thus, it is necessary to find this inflection point and the corresponding grain path and grain temperature. To do this, we use the condition that at the inflection point of the function its second derivative is zero [21].

We find the first derivative of (19).

$$PL' = 3 \cdot a \cdot x^2 + 2 \cdot b \cdot x + c. \quad (20)$$

We find the second derivative of (19).

$$PL'' = 6 \cdot a \cdot x + 2 \cdot b. \quad (21)$$

We equate the second derivative (21) to zero and find the grain drying time Xp corresponding to the inflection point.

$$Xp = -\frac{b}{3 \cdot a}. \quad (22)$$

We find the temperature value Yp corresponding to the inflection point at Xp. To this end, we substitute the expression (22) in (19) and make transformations.

Then we get:

$$Yp = a \cdot \left(\frac{-b}{3 \cdot a}\right)^3 + b \cdot \left(\frac{-b}{3 \cdot a}\right)^2 + c \cdot \left(\frac{-b}{3 \cdot a}\right) + d$$

or

$$Yp = \frac{b \cdot \left(2 \cdot b^2 - 9 \cdot c \cdot a\right)}{27 \cdot a^2} + d. \quad (23)$$

In order to make sure that the point (Xp, Yp) is the inflection point, we use the condition that the third derivative should not be zero.

We find the third derivative of (19).

$$PL''' = 6 \cdot a. \quad (24)$$

It is seen from (24) that the third derivative is not zero. An exception is the point at a=0, when the cubic function turns into a quadratic function, and it has an extremum, and not an inflection point. Thus, the point (Xp, Yp) is exactly the inflection point.

To confirm the correctness of the presented mathematical calculations, we construct the approximating cubic polynomial and find its inflection point for the function from Table 1. The corresponding graph is shown in Fig. 9. In this figure, the curve PL(x) corresponds to the curve $T=f(\tau)$ in Fig. 1.

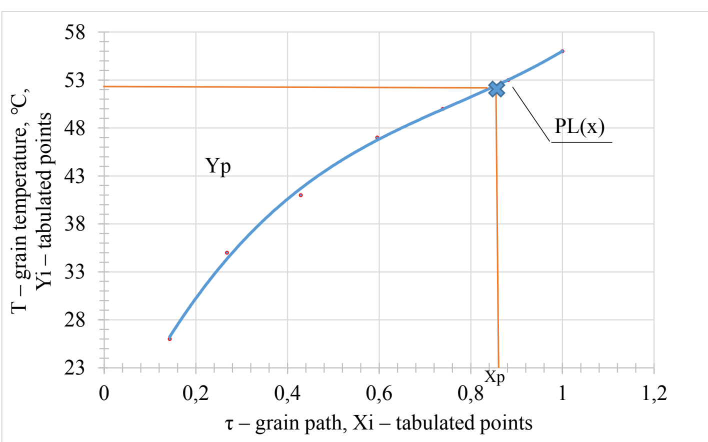

Fig. 9. Tabulated values *Xi* and *Yi*, the graph of the cubic polynomial *PL*(*x*), the inflection point *Xp* and *Yp*

From Fig. 9, it is seen that the cubic polynomial well approximates the given tabulated function and has an inflection point at Xp=0.849 and Yp=52.522 according to the expressions (22), (23). The coefficients of the polynomial (18), (19) are: a=31.906, b=–81.25, c=90.304, d=14.897.

That is, the critical point A in this case will be at a distance of 0.849 of the drying chamber length, while grain temperature will be 52.5 °C.

In order to detect the inflection point, a different approach can be used. In the transition through the inflection point, the sign of the second derivative of the function changes [21]. Thus, if grain temperature measurements are organized, then at each step "k" it is possible to compare the sign of the second derivative (21) at the given and previous steps. When the sign of the second derivative changes, the product of its values at "k" and "k–1" steps becomes negative. That is, the product PR can be controlled:

$$PR = PL''_{k-1} \cdot PL''_k. \quad (25)$$

When the product PR becomes less than zero, it is possible to stop the drying process – to switch on the discharger.

6. Discussion of the results of the study on the implementation of the developed method of exposure control of grain drying

The implementation of the developed method in grain drying exposure control systems will provide timely removal of material from the drying chamber, from the influence of the drying agent, when its temperature approaches a critical value. Constant temperature control by infrared sensors – without contact with the control object, improves the accuracy of temperature measurement, eliminates the germ death, protein denaturation, gluten weakening. Energy consumption in this case is minimum, because the drying process is carried out in the modes recommended by dryer developers, and there is no additional energy consumption resulting from overdrying or re-drying if grain is underdried. The disadvantages of the developed method include the fact that when applied in drying units, complex equipment will be used, and high qualification of maintenance personnel will be required in order to maintain its performance.

The obtained analytical expressions (18), (19), (22), (23), (25) allow the microcontroller programming and automatic control of grain drying exposure, as well as efficiency improvement of the drying process as a whole.

The results of this study can be used to automate the operation of all types of high-temperature continuous-flow dryers – shaft, tower, hopper, airslide, etc. At the same time, intervention in the existing automation systems is minimum. The control system of grain drying exposure – grain discharge, can operate as a separate device, remote sensors and the control unit of which are easily mounted in any design and electric circuit of the dryer.

The presented research results are a continuation – the next stage of the author's work in the field of automation of a very complex technological process of convective drying of capillary-porous colloidal bodies [22]. In the future, the results of these studies can be used to automate the drying process of low-temperature dryers, including batch ones.

7. Conclusions

1. The method of exposure control of high-temperature drying based on constant control of the temperature of moving grain along the drying chamber and search for the area of temperature jump due to dehydration is developed. The studies have shown that an intense increase in grain temperature occurs when it reaches a relative moisture of 15...16 %, close to standard. Therefore, grain at the beginning of the intense temperature increase must be discharged from the dryer and brought to the standard moisture when it is cooled in the cooler. In this case, grain quality is preserved and the possibility of energy overexpenditure resulting from the material overdrying is excluded.

2. The algorithm of the grain drying exposure control automation system, which, at a frequency of 1–5 Hz, interrogates temperature sensors, approximates the obtained values and calculates the derivative of the second-order function is developed. The obtained result is compared with the maximum length of the grain path along the drying chamber in order to subsequently influence the discharger performance.

3. Analytical expressions for determining the grain path along the drying chamber, after which it reaches a standard moisture are obtained. The derived analytical expressions allow the microcontroller programming and automatic control of grain drying exposure, as well as efficiency improvement of the drying process as a whole.

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