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A cellular dynamic mathematical model of a conveyor dryer as an object of automatic control

Avtandil Bardavelidze, Khatuna Bardavelidze, Otari Sesikashvili

ABSTRACT

In the paper, based on the analysis of the technological process of fruit drying in a conveyor-type dryer, the major regime parameters, control effects of the object, control variables and disturbing factors are determined. Considering the equations of the kinetics of heat and mass transfer of the dried product, control diagrams, certain standard assumptions and initial conditions, a system of ordinary differential equations for the convective drying of fruit in a conveyor-type dryer has been developed. In the system of equations of heat and mass transfer of the process, the drying coefficient in the first and second periods and the heat transfer coefficient were determined due to identification. The solution of the problem of determining the above parameters is reduced to solving the problem of minimising the criterion for assessing the degree of the mean square deviation of the difference between the solutions of the system of experimental and heat-mass transfer differential equations of the plum drying process. During the drying of blue plums, we have obtained the following values of unknown parameters: drying rate coefficient in the first period – $K_1=0.8309\cdot10^{-4}$ $kg\cdot(m^2\cdot s\cdot{}^oC)^{-1}$; drying rate coefficient in the second period–$K_2=0.3413\cdot10^{-4}$ $kg\cdot(m^2\cdot s\cdot{}^oC)^{-1}$ and heat transfer coefficients: $\alpha_2\cdot\phi_2=0.0794$ $kW\cdot(kg\cdot{}^oC)^{-1}$, $\alpha_3\cdot F_3=0.0245$ $kW\cdot(kg\cdot{}^oC)^{-1}$ and critical moisture content of blue plums $w_{CR}=71\%$. The energy reduction spent on the drying process is 4%. The "cellular" dynamic characteristics of the relative humidity and temperature of the drying agent during blue plum drying, obtained as a result of the experimental and theoretical study of the conveyor drying unit, allow us to judge the 96% - 98% adequacy of the developed dynamic mathematical model. The research found that the dynamic characteristics of the residual moisture content of blue plums at the dryer outlet were 11%.

Keywords: conveyor dryer, identification, cellular mathematical model, drying rate, drying agent, moisture content

INTRODUCTION

Drying is one of the most complex and widely used methods for preserving agricultural products. It helps increase product shelf life, improve product quality, and reduce losses during storage. Dried products are relatively lightweight, with their characteristics being convenient for storage conditions and transportation, making them easy to consume. Canning and pasteurisation of products are achieved through drying (dehydration), allowing the product to become suitable for long-term storage and consumption. Dehydration results in residual moisture, during which the unique vital activity of the microflora associated with a given type of product becomes complicated or impossible. The standard regulates the required residual moisture or various products. For example, fruits are dried to 20%-25%, and sometimes down to 3%. Such residual moisture ensures product storage by preventing microbiological damage, though it cannot always protect against other undesirable physicochemical and biochemical processes. Food products are often dried to 6% - 8% and even to 4%-5% to halt microbiological spoilage **[1]**, **[2]**, **[3]**.

The industrial drying process is energy-intensive, requiring a lot of thermal energy to heat and dehydrate the products. In developed countries, about 10% to 20% of the total energy consumed in the industrial sector is spent on thermal drying processes **[2]**, **[3]**, **[4]**.

Based on the above, processing and preserving agricultural products with lower energy costs to provide quality and affordable products to consumers is an urgent issue.

The significant parameters of the drying process must be consistently controlled to enhance the quality of agricultural products, reduce losses in the final product, and minimize the energy used during drying. Accurate control of such parameters is achieved using automatic control systems, the design of which relies on the development of a mathematical model. By solving the model, the relationship between the final moisture content of the product, the temperature of the air leaving the dryer, and other parameters can be established, which can be easily implemented in the automatic control system of the dryer. Thus, the fast, accurate, and much cheaper measurement of the relative humidity and temperature of the drying agent in the drying unit (which can be achieved using modern digital sensors) will, thanks to the sought-after relationships, replace the moisture measurement in the automatic control system of the drying process **[5]**.

Aleksanyan et al. **[6]** recommended using biodegradable polymer containings to preserve jackfruit and increase the shelf life while maximizing the preservation of nutritional value. This work aims to develop rational drying parameters for jackfruit slices with a protective coating and to model heat and mass transfer. To achieve this goal, kinetic patterns of the convective drying process for jackfruit slices, treated as a two-layer object, were established, and curves of the water removal rate were constructed. By varying the parameters that affect the dehydration intensity within the technological limitations framework, the process's specific productivity and its optimal value were determined based on their values.

The authors, Abdulla et al., in their work **[7]**, investigated fruit drying systems. They studied the influence of operating parameters on product quality and system efficiency. The method is based on a new model developed to examine the fruit drying system's performance, considering the fruit's equilibrium moisture content, humidity of the dryer atmosphere, temperature of the dryer atmosphere, and airflow. The results revealed that operating parameters significantly control dryer efficiency, while an increase in air temperature dramatically reduces the energy required and enhances dryer efficiency. However, high temperatures can damage the fruit, which worsens its quality. Therefore, air temperature plays a crucial role in controlling the quality of dried fruit. In the paper by Kiran et al. **[8]**, the authors describe a controlled environment suitable for small-scale fruit drying processes within a closed chamber using a Microcontroller (89s52). To begin, infrared light is used to heat the fruit to remove moisture content internally. Then, air is blown inside the chamber to maintain humidity below a specified level and exhaust humid air. The Microcontroller (89s52) controls the functions of heating, air blowing, and time indication, maintaining a constant environment throughout the chamber.

We consider the convective drying of fruits and vegetables in a conveyor-type drying device because it offers several advantages over other types of convective dryers: they are used for drying various unit materials (fruits and vegetables), the device's simplicity, ease of installation, and repair, sufficiently high efficiency, compact dimensions, reliable operation, and relatively low cost. This is why it has been widely utilized in production conditions **[5]**, **[9]**, **[10]**, **[11]**, **[12]**, **[13]**, **[14]**, **[15]**, **[16]**, **[17]**.

Due to the significant number of conveyors in the conveyor-type drying device, we consider it expedient to divide the drying space into cells and develop a "cellular" mathematical model to enhance the completeness of the mathematical model of heat-mass exchange during the convection drying process of the product (in our case, each conveyor is represented by two cells).

Scientific novelty

Based on the analysis of the scientific papers presented above, the scientific novelty of the research lies in the development of an adequate analytical-experimental dynamic "cellular" mathematical model of the heat-mass transfer occurring during the technological process of convective drying of fruits in a conveyor-type dryer, represented in vector-matrix form. This model describes the drying process along the conveyors by recording the transient (dynamic) experimental characteristics of air temperature, relative humidity, and moisture content of plums at the outlet of the conveyor dryer within the "cells" of the dryer. It also involves determining the coefficients of drying and heat-mass transfer while changing the pressure in the calorifiers and solving the problem of minimizing the criterion for assessing the quality of the mean square deviation between the data obtained from experimental and theoretical studies of the fruit drying process.

Objectives

The study aims to develop a mathematical model of the dynamic mode of a conveyor-type fruit drying machine, according to each conveyor cell, that will be suitable for the actual convection drying process and meet the requirements for the quality of the optimal automatic control system of the dynamic technological drying mode. This, in turn, will increase the machine's productivity, enhance the quality of dried fruit, and reduce energy consumption during drying.

Scientific Hypothesis

A dynamic mathematical model of a conveyor-type dryer, developed based on the theory of heat and mass transfer between the drying agent and the product, provides reliable predictions of the drying rate and temperature distribution within the product, as well as the potential distribution of temperature and humidity of the drying agent along the conveyors-in each "cell. " Furthermore, a dynamic mathematical model of the fruit drying process can be utilized to study the kinetics of the drying process, determine the coefficients of heat transfer and drying rate (in the first and second periods) for different high-moisture fruits, and address the challenge of designing optimal automatic control systems for fruit drying equipment.

MATERIAL AND METHODS

To achieve the set goal, we selected ripe fruits suitable for drying as the research object, such as dense green plums, apricots, cherries, pears, sweet cherries, blue plums, and apples, which are products with high moisture content, purchasing them from farms in Gori (Georgia). Their dehydration is associated with considerable problems because each type of fruit possesses special properties and varying compositions, depending on origin, growing conditions, and degree of ripeness. These properties also determine the nutritional value and taste.

Samples were collected and temporarily stored at a temperature of 7 °C.

Samples preparation: Samples were unpacked, and 100 g was taken from each sample for examination.

Number of samples analyzed : We analyzed six different samples (Table 2).

Number of repeated analyses: All measurements of instrument readings were performed nine times.

Number of experiment replications: The number of repetitions of each experiment to determine a single value was three. The experiment was repeated three times on different days. On other days, we bought various fruits of the same origin from different batches. The average values of the results are provided in the article.

Chemicals

We do not use chemicals for experiments.

Animals, Plants and Biological Materials

The use of plants is not included.
No animal species are used in the experiments.
Microorganisms are not included in the study.

Instruments

To determine the product's mass, we used an electronic digital analytical balance SF-400C model (Toms, Qilin, China) with a weighing accuracy of 0.01 g.

Equipment

We estimated the parameters of the mathematical model of the fruit drying process for an industrial conveyor-type dryer, type G4-KSK-15 (Belgorod region, Shebekino, Russia), which is equipped with:

- Electric drives, fans, and heaters;
- Linear velocity sensors of the conveyors and rotating sensors of heater fans;
- Steam press and temperature sensors in heaters;
- Air temperature and relative humidity sensors of EE211 type at the beginning and end of the conveyors (in each cell).

Structurally, all conveyor dryers are essentially the same and differ from one another only in size: steam supply and condensate removal systems, exhaust air suction systems, and conveyor belt drive devices. Figure 1 illustrates the scheme of the conveyor drying device. The dryer is a rectangular chamber in which three mesh conveyor belts moving in opposite directions are positioned one beneath the other. The chamber is open from below for airflow, regulated by a plug. The side chamber is tightly closed with a lid, which can be removed for inspection, repair, cleaning, and sampling. The design of the belt's electric drive allows for its movement at different velocities; either each belt is equipped with an individual drive (in large-scale dryers), or different speeds of the belts are achieved using appropriate variations.

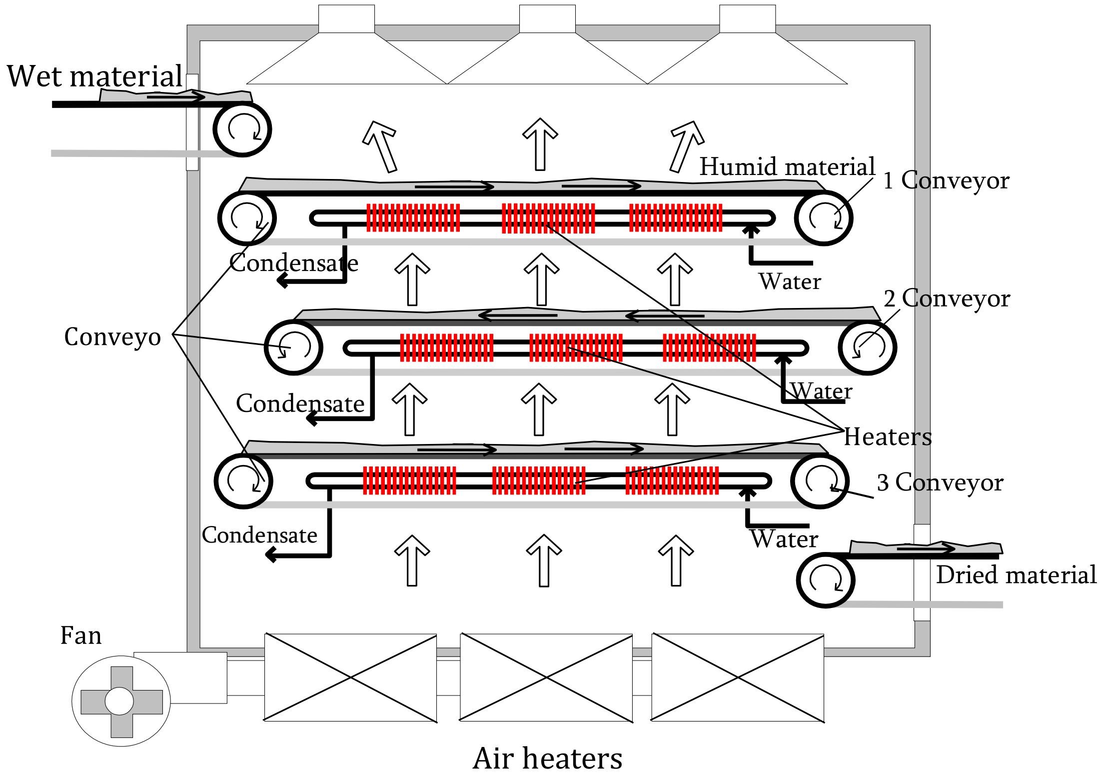

Figure 1 The principal scheme of the conveyor drying device.

A battery of heaters is positioned between the belts. Steam enters with the heaters and condensate exits. In large-scale dryers, individual steam inlets are supplied for each heater. Such a system for providing steam to the heaters enables us to establish the necessary temperature regime on each belt **[1]**.

A conveyor is installed at the side end of the dryer to deliver raw materials to the first belt, which moves toward the side end opposite the drying chamber, where the raw materials are discharged onto the next belt, and so on, sequentially passing through all the belts and exiting the dryer. During the time the raw materials pass through the dryer, they are dried due to the heat and moisture exchange between the drying agent and the moist air. The air moves from bottom to top, sequentially passing through the heaters, heats up, and blows on the product layer placed on the belt, where heat and moisture exchange and evaporation occur.

The standard operating mode and productivity of conveyor-type dryers depend on the type of air supply system and the method of selecting the belt movement mode.

- To increase the efficiency of conveyor-type dryers, it is advisable to use **[2]**, **[3]**:
- A supply and exhaust ventilation system that provides an air velocity of 0.45 $m \cdot s^{-1}$ to 0.5 $m \cdot s^{-1}$ and is
- balanced to ensure there is no excess pressure or condensation in the dryer;
- Individual steam supply and condensate discharge for each tier of the heater;
- An individual drive for each belt.

Technological control of conveyor dryers is typically provided with the following main positions **[1]**, **[2]**:

- Air temperature on each belt and beneath the belt;
- Temperature and relative humidity of the drying agent supplied to the dryer;
- Steam consumption on each tier of heaters;
- Pressure inside the dryer;
- Air movement in the exhaust pipe and the speed of the conveyor belt movement.

The drying technological process aims to achieve the desired moisture content of the dried product by removing moisture.

Conveyor dryers are primarily used for drying fruits and vegetables. In conveyor dryers, fruit and vegetable drying is performed in sufficiently large batches, ensuring that each batch of raw materials is dried continuously:

after the dryer is removed from the operating mode, raw materials are continually supplied to it, and dried material is continuously discharged from the dryer **[3]**, **[4]**, **[5]**.

During the operation of conveyor dryers, unique mechanical means ensure a uniform supply of raw materials, maintain a constant speed of movement of the conveyor belts, ensure a steady flow of drying agent (air) in the dryer, and regulate the temperature beneath the conveyor belts according to the drying regions by adjusting the steam pressure in the heaters.

The major parameters of the operating mode of conveyor dryers are **[1]**, **[2]**, **[3]**, **[4]**, **[5]**:

1. The speed of the conveyor belts, which is maintained for each belt individually using variations;
2. The working load on the surface of the belts, which is determined by the ratio of the raw material supply to the speed of the belts;
3. The temperature of the drying agent in the regions under the belts;
4. The relative humidity of the air leaving the dryer;
5. The air flow rate within the dryer.

Laboratory Methods

We chose the convection drying method for our fruit drying research, as well as the mathematical modeling method and the experimental research method, which are based on determining the drying and heat transfer coefficients and solving the system of differential equations that describe heat and moisture transfer.

The measurements of the changes in air temperature and relative humidity in the dryer were performed synchronously in each cell using an industrial humidity and air temperature sensor. The experimental data were recorded every 50 seconds for a total of 700 seconds.

We monitored the product moisture at both the inlet and outlet of the drying chamber.

Description of the Experiment

When controlling conveyor dryers, for each batch of raw materials, the required speed of the belts is specified and established based on their initial moisture content (through experimentation). Subsequently, the air temperature is regulated according to the drying regions during the drying process. At this time, the air beneath the 3rd belt is heated to 50 °C to 55 °C, beneath the 2nd belt to 60 °C to 80 °C, and beneath the 1st belt to 90 °C to 100 °C. Such a temperature distribution is selected to avoid loss of product quality while ensuring that the process is carried out sufficiently intensively. A temperature higher than that of the 1st belt is not detrimental to product quality, as drying occurs at a high speed during the initial period, causing the product temperature to be close to the wet bulb temperature, usually 40 °C to 45 °C. Conversely, low temperatures can result in the oxidation of the product in the dryer (as the product remains in the conveyor dryer for 2-4 hours), so the temperature within it should not be too low **[3]**, **[4]**, **[5]**, **[9]**.

The main technological parameter is the residual moisture of the dried product, which is controlled under industrial conditions through periodic sampling and laboratory analysis according to ISO 1446:2001 **[10]**.

Quality Assurance

Number of repeated analyses: Nine

Number of experiment replications: Nine

Reference materials: We have reviewed references **[1]**, **[2]**, **[3]**, **[4]**, **[5]**, **[6]**, **[7]**, **[14]**, **[15]** to verify the laboratory equipment, methods, tests, and kits used.

Laboratory accreditation: The experiments were performed in an industrial enterprise that has a laboratory accredited according to the international standard ISO 17025.

Data Access

The data supporting this study's results will be openly available at the Akaki Tsereteli State University Library (info@atsu.edu.ge) after the article is published.

Statistical Analysis

To analyze the test parameters of the product, a statistical analysis of the obtained data is conducted, and the reliability of the received data is evaluated using the T-test method of mathematical statistics with the Windows IBM SPSS Statistics version 20.0 program (IBM, Armonk, New York, USA). We utilized the statistical functions for the arithmetic mean and the standard error to describe the ordered sample. We selected a reliability value of $p<0.05$.

RESULTS AND DISCUSSION

The mathematical description of conveyor-type drying devices, as with other types of dryers, consists of a system of material and heat balance equations, formulated by considering the interconnection of all heat and mass storage capacities.

In the paper by Pavlushin et al. **[9]**, the authors developed a grain conveyor-type dryer. The drying mode was implemented based on the example of drying oats. As a result of the experiments, the regression equation was obtained in the independent factors' natural and encoded values. The research established that the amount of heat spent on drying in the developed device is 1.5 times less than in mass-produced drying devices.

In the paper by Alexander et al. **[11]**, the authors developed a static mathematical model of the pasta conveyor drying process. This model allows us to define the curves of temperature and humidity gradients for tube-shaped pasta. Additionally, the model helps select the best parameters to reduce thermal energy costs while maintaining the high quality of the dried product.

In the paper by Hany et al. **[12]**, the authors developed a static mathematical model of convective drying of apple slices obtained from experimental curves. They found the optimal value of the moisture diffusion coefficient and determined the average activation energy.

The paper by García-Moreira et al. **[13]** described the experimental data by presenting five different experimental mathematical models of peach convective drying.

The papers of Friso **[14]** and **[15]** presented recommendations for the rational design of conveyor-type dryers with tangential airflow concerning products. A mathematical model of the conveyor dryer was developed for the specific case when the moisture content of the final product XF is lower than the critical moisture content - XC (XF < XC) and vice versa, XF > XC, which is obtained by differentiating the drying rate equation and integrating it along the drying belt.

In the paper by Druzhinina et al. **[16]**, the authors developed a mathematical model of the belt conveyor dryer based on the material's weight difference during loading and unloading, representing material balance. The model considers uneven load distribution and control actions. A control algorithm has been developed, and a qualitative effect has been identified in the control model.

In the paper **[17]**, Agustín Bottaria and Lautaro Bracciab presented the problem of choosing the control structure for the grain conveyor-type dryer. A corresponding mathematical programming problem has been formulated. Experimental modeling results show that a linear combination of control variables and a hierarchical management structure can enhance the economic performance of closed and open structures.

In the paper by Rani Puthukulangara Ramachandran et al. **[18]**, the authors presented a detailed overview of the computing power of computational fluid dynamics (CFD) packages and their use in simulating the drying process. The overview also discusses various mathematical approaches used in drying models.

In the paper by Bagheri et al. **[19]**, the authors calculated the dryer's current and optimized efficiency using a conveyor dryer control program, and the fan speed was adjusted accordingly to maintain the optimized efficiency.

In the paper by Mutumba et al. **[20]** and Abdussamad et al. **[21]**, the authors developed an automatic control system for the efficient operation of the conveyor dryer, which manages the movement of the conveyor belt. This automatic control system comprises a central control unit -ARDUINO. The controlled system for automatic humidity regulation during fruit drying was designed based on experimental results without developing a mathematical model.

In the paper by Atykhanov and Kassymbayev **[22]**, the authors determined the period of the fruit drying process experimentally, and the drying rate was described by a third-degree polynomial, which allowed for the investigation of only the second period of the drying process.

The paper by Reppich et al. **[23]** presented the experimental mathematical model for drying a thin layer of apple. A regression analysis was conducted to determine the model's parameters, which cannot adequately describe the drying heat and mass exchange process.

In the paper by Akter et al. **[24]**, the authors developed a mathematical model describing the kinetics of the drying process of apple and banana samples using a laboratory method. Adequacy between the results obtained from the experiment and those predicted by the mathematical model has been established.

The papers **[25]**, **[26]**, and **[27]** mainly present only experimental mathematical models of fruit and vegetable drying obtained under laboratory conditions. These models are insufficient for analyzing the heat-mass exchange process and optimally conducting the drying process.

When compiling a system of material and heat balance equations, we introduce a linear coordinate ℓ along the working surface of the conveyor belt. The starting point is the position of the material to be dried as it enters the dryer, and the measurement of the coordinate ℓ continues to the point of transition of the material from one conveyor to another in the direction of material movement.

Let us divide the working volume (space) of the drying chamber into equal cells, in particular one belt into two cells, which are numbered in the direction of material movement (in the direction of increase in ℓ), with the index $m = 1,2, \ldots,$ M, where M - is the total number of cells. We assume that the cell size is chosen so that the number of cells on one conveyor equals k (in our case, k = 2). Figure 2 illustrates the principle scheme of the cell of a conveyor drying belt.

In a given cell m, air enters from the cell numbered **m + k**, while material enters from the cell numbered **m - 1**. We determine the material and heat balance equation for drying, considering the relationship between the material to be dried and the drying agent in the cells.

Let us make the following basic assumptions regarding the conditions of the drying process in the cells:

1. The parameters of the material and the drying agent at any point in the cell are the same over time.
2. The quantity of material that has exited the cell per unit of time is proportional to the amount of material within it and the linear velocity of the conveyor.
3. Drying occurs in the first and second periods, with its rate in the first period being proportional to the difference between the moisture contents of the drying agent and the air, at which the air humidity in the cell is in equilibrium with the wet material.
4. The heat and mass transfer coefficients between the material and the drying agent are considered. Additionally, the specific heat capacity of the material remains constant.

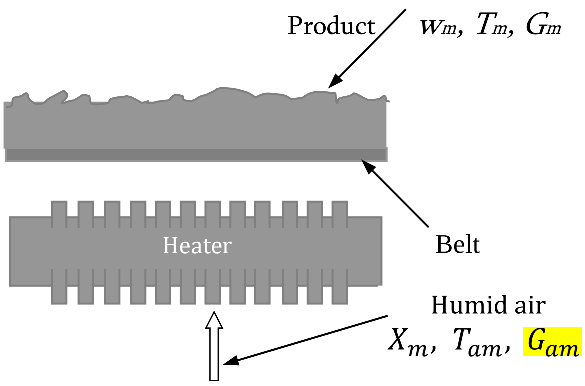

Figure 2 The principle scheme of the cell of a conveyor drier's cell.

Based on the aforementioned characteristics of conveyor-type dryers , the laws of physics , and the heat-mass transfer control diagrams, the changes in heat-mass transfer of the dried product, as well as the temperature and moisture content of the drying agent along the drying conveyors, depending on the cells and considering certain standard assumptions, can be described for cell m as a system of ordinary differential equations **[5]**, **[14]**, **[24]**, **[28]**, **[29]**, **[30]**:

$$\frac{dG_m}{d\tau} = \frac{G_{m-1} - G_m}{\tau_m} \tag{1}$$

$$\frac{dw_m}{d\tau} = \frac{w_{m-1} - w_m}{\tau_m} - \phi_1 N(w_m, T_m, X_m) \tag{2}$$

$$C_m \cdot \frac{dT_m}{d\tau} = \frac{C_{m-1}(T_{am}-T_m)}{\tau_m} + \phi_1 N(w_m, T_m, X_m)(\Delta H + C_{H_2O} T_m) + \alpha_2 \phi_2 (T_{am} - T_m) \quad (3)$$

Where:

Eq. 1 – reflects the change in the mass of the drying material in the cell m at time τ; Eq. 2 – reflects the change in the moisture content of the material in the cell m at time in cell m at time τ; Eq. 3 – reflects the change in the temperature of the material in the cell m at time τ.

The parameters presented in Eq.1 – 3 are as follows:

$G_m(\tau)$ - mass of material in the cell m (on dry matter basis) at time τ, kg;

$g_m(\tau)$ - mass of 1 linear meter of material (on dry matter basis) passing through the cell m at time τ, kg·m^{-1} ;

$w_m(\tau)$, $T_m(\tau)$ - moisture content (%) and temperature (°C) of material in the cell m at time τ;

$X_m(\tau)$, $T_{am}(\tau)$ - moisture content (%) and temperature (°C) of drying agent in the cell m at time τ;

T_{Hm} - temperature of the heaters in the cell m, °C;

ϕ_1, ϕ_2 - specific mass transfer and heat transfer surface areas of material per unit mass of dry matter, m^2·kg^{-1};

α_2 - heat transfer coefficient between the material and moist air, KW·(m^2·°C)$^{-1}$;

F_3 - heat exchange surface area of the heater, calculated per cell, m^2;

α_3 - heat transfer coefficient between the air and the heater surface, KW·(m^2·°C)$^{-1}$;

ΔH - specific heat of vaporization of water, kJ·kg^{-1};

$$C_m = C_X + C_{H_2O} \quad (4)$$

Where:

C_m - is the heat capacity of the moist material in the cell m (C_X is the heat capacity of the dry material);

C_{H_2O} - is the heat capacity of water, kJ·(m^2·°C)$^{-1}$;

$$\tau_m = k_g / \upsilon_m \quad (5)$$

Where:

τ_m - dead time of the material in the cell m;

υ_m - conveyers linear velocity, m·s^{-1};

kg^{-1} - is the coefficient of proportionality between the product of $G_m \upsilon_m$ and the amount of material leaving the cell at time τ, m^{-1} (which we introduce according to assumption 2).

The moisture content and the temperature T_{am} of the drying agent X_m in cell m from Eq. 1-3 are determined by the material and heat balance in Eq. 6 and Eq. 7 **[6]**, **[31]**:

$$\frac{dX_m}{d\tau} = \frac{X_{m+k} - X_m}{\tau_{am}} + \frac{G_{am}}{V_m} \phi_1 N(w_m, T_{am}, X_m) \quad (6)$$

$$\frac{dT_{am}}{d\tau} = \frac{T_{a(m+k)} - T_{am}}{\tau_{am}} + \frac{G_{am}(\alpha_2 \phi_2 (T_m - T_{am})) - \Delta H \phi_1 N(w_m, T_{am}, X_m) + \alpha_3 F_3 (T_{Hm} - T_{am})}{V_m \tilde{C}_{H_2O}} \quad (7)$$

Where:

$\tilde{C}_{H_2O}$ - the heat capacity of water vapor, kJ·(kg·°C)$^{-1}$;

V_m - the volume of air in the cell m, m^3;

τ_{am} - is the air delay time in the cell m, which is determined as the ratio of the air volume to the air flow rate in the cell:

$$\tau_{am} = \frac{V_m}{Q_{am}}, \quad (8)$$

$$Q_a = K_{VMax} \sqrt{\Delta P_a}, \quad (9)$$

Where:

K_{VMax} – air permeability coefficient per cell; ΔP_a – air pressure drop per cell.

In Eq. 1– 3 and Eq. 6, Eq. 7 $N(w_m, T_m, X_m, T_{am})$ – drying rate in the first (when $w_m > w_{CR}$) and the second periods (when $w_m \le w_{CR}$) has the following form **[6]**, **[31]**:

$$N(w_m, T_m, X_m, T_{am}) = \begin{cases} K_1(P_{aEQ}(T_{Mm}) - \phi P_{aEQ}(T_{am})), & w_m > w_{CR}, \\ K_2(w_m - w_{EQ}(\phi)), & w_m \le w_{CR}. \end{cases} \quad (10)$$

Where:
K_1 an K_2 are the drying process rates in the first and second periods, respectively.
w_{CR}– is the critical moisture content of the material, %, which is determined experimentally; ϕ – relative humidity of the drying agent, %;
$P_{aEQ}(T_M)$ - the tabular dependence of saturated water vapor pressure on temperature;
$w_{EQ}(T_M, P_a)$ - the relationship between the equilibrium moisture content of the material and the temperature of the material being dried and the partial pressure of water vapor in a humid drying agent environment.

On the right-hand side of Eq. 6 and Eq. 7, each m-th cell includes as parameters the air humidity and temperature entering the chamber from the m + k-numbered cell located below (k is the number of cells on one belt of the conveyor).

Equations 1-3, 6, and 7, taken together for all m=1, 2, ..., M (5M equations in total), generate a mathematical description of the dynamics of the conveyor dryer. In addition to Equations 1-3, 6, and 7, the equations connecting the cells belong to the mathematical description of the process:

$$G_m^{in} = G_{m-1}, \quad w_m^{in} = w_{m-1}, \quad T_m^{in} = T_{m-1}, \quad X_m^{in} = X_{m+S}, \quad T_m^{in} = T_{am+S} \quad (11)$$

with clear “border” conditions:

At the entrance of the wet material in the dryer, in the first cell with parameters G_0, w_0, and T_0:

$$G_1^{in} = G_0, \quad w_1^{in} = w_0, \quad T_m^{in} = T_0, \quad (12)$$

and with external air with parameters X_0, T_{a0}, for all cells from the last series

$$X_k^{in} = X_0, \quad T_k^{ain} = T_{a0}. \quad (13)$$

Thus, when modelling Eq. 1 – 3 and Eq. 6, Eq. 7 must be solved with the following initial conditions

$$G_m(0) = G_{m0}, \quad w_m(0) = w_{m0}, \quad T_m(0) = T_{m0}, \quad X_m(0) = X_{m0}, \quad T_{am}(0) = T_{am0}, \quad (14)$$

which represents the state distribution of the cell variables at the initial time τ=0. In addition, the moisture content, temperature, and quantity of the material should be provided; that is, the feed rate of raw material to the dryer, the volumetric flow rate , and the parameters of air supplied from the heaters, as well as control effects:

- linear velocity of conveyors;
- temperature of the heaters;
- capacity of fans (air flow rate).

The heater temperature for each conveyor cell (each conveyor has its own heater) is directly included in Eqs . 6 and 7. In all cells of the dryer, the capacity of the fans simultaneously determines the value of a coefficient τ_a that appears in Eqs . 6 and 7. Similarly, the linear velocity of the conveyors determines τ_m , which appears in Eqs . 1-3. At this time, according to the second assumption, the approximation of the dynamic characteristic of the conveyor dryer is introduced into Eq. 1 regarding the movement of the product, with the control channel for the linear velocity of the conveyors, while the dynamic operator of the transport delay is approximated by a first-order aperiodic ring with a constant time τ_m. Moreover, the dynamic characteristic of the dryer as a whole is approximated using a high-order aperiodic ring concerning the movement of the material (the chain equations of product movement for cells m = 1, 2, ... , M). This type of approximation is widely used in the theory and practice of automatic control (in our case, M = 6) **[7]**, **[8]**, **[32]**.

The dynamics of the drying agent's movement in Eqs. 6 and 7 are not considered, as the relaxation time of air pressure and flow in the drying chamber is much shorter than the relaxation time of air heating and material drying processes.

The conveyor dryer is a complex multi-profile and multi-connected control object. The main variables that characterize the state of drying include **[33]**:

1. The amount of product, its temperature, and moisture content in different regions of the drying chamber (in the cell m);
2. Cost of the drying agent (wet air);
3. Temperature and moisture content of the drying agent in the entire volume of the drying chamber.

The main control variables of the conveyor dryer are as follows:

1. Air flow rate at the inlet of the drying chamber;
2. The linear velocity of movement of the conveyors, which determines the quantity of raw materials and the delay time in the drying chamber;
3. The temperature of the heated heaters.

The main concerns when controlling the drying machine are the quantity and moisture content of raw materials and the moisture content and temperature of the air supplied to the chamber inlet, which are influenced by the uncontrolled state of the environment.

The controlled variables of the conveyor dryer are the output values from the object. The air temperature and relative humidity in different regions of the drying chamber can be among them.

The main output parameter, whose magnitude of change is characterized by the quality of automatic control, is the final moisture content of the dried product. As there is currently no reliable automatic measuring device for dry products **[4]**, **[5]**, **[8]**, **[34]**, moisture is measured only by the laboratory method of periodic sampling; that is, non-operational control is taking place.

When creating and identifying the mathematical model of the dryer, it is necessary to develop a scheme that defines the division of the drying chamber into cells. For concreteness, we consider the drawing of the model using the 4Г-КСК-15-type dryer, whose technical characteristics are presented in Table 1.

Table 1 Technical characteristics of the 4Г-КСК-15-type dryer.

No.	Mode parameters	Values
1	Productivity with evaporated moisture, ($kg \cdot h^{-1}$)	100
2	Conveyor belt working area, (m^2)	15
3	Number of conveyor belts, (pieces)	3
4	Belt width, (mm)	1600
5	Conveyor velocity change limit, ($m \cdot s^{-1}$)	0.1÷0.6
6	Surface area of the heaters, (m^2)	180.0
7	Steam consumption, ($kg \cdot h^{-1}$)	120.0
8	Electric drive capacity, (kW)	8.00

The working cells of the drying chamber are divided (Figure 1) according to the number of conveyors (3 conveyors), with horizontal rows of cells; each row (on each conveyor) has 2 cells. The numbering of cells coincides with the direction of movement of the material (see Figure 3). With this numbering method, air enters cell m from the cell numbered m + 3, and material enters from the cell numbered m - 1.

Based on the above, the mathematical description of the conveyor dryer can be represented as a system of equations: Eq. 1 -3, Eq. 6, Eq. 7, and Eq. 10, which are considered together with the inter-cell connection equations Eq. 11 under the "boundary" conditions of Eq. 14.

Thus, the mathematical description of the six cells of the conveyor dryer (five differential equations in each cell) forms a system comprising 30 ordinary differential equations, the right-hand side of which depends only on four undefined parameters:

1. K_1 and K_2 parameters of the drying rate equation;
2. The heat exchange coefficients $\alpha_2\phi_2$ and α_3F_3.

The other coefficients of Eq. 1 – 3, Eq. 6, Eq. 7, and Eq. 10 were determined by reference and technical documentation data.

Thus, the work aims to estimate the values of cap K sub 1, cap K sub 2, alpha sub 2, phi sub 2, and alpha sub 3d α_3F_3.

In convection drying, there is no need to fundamentally determine the drying and heat transfer coefficients separately since, during the experiment, the state of the drying agent is controlled, and the moisture content of the product and the drying agent are unambiguously related. It should be noted that conducting an industrial experiment on a conveyor dryer is associated with specific difficulties. In practice, measuring the airflow rate at different points in the drying chamber is very challenging. In reality, the flow rate is measured only in the exhaust pipe by calculating the air velocity at the cross-section of the drying chamber **[32]**.

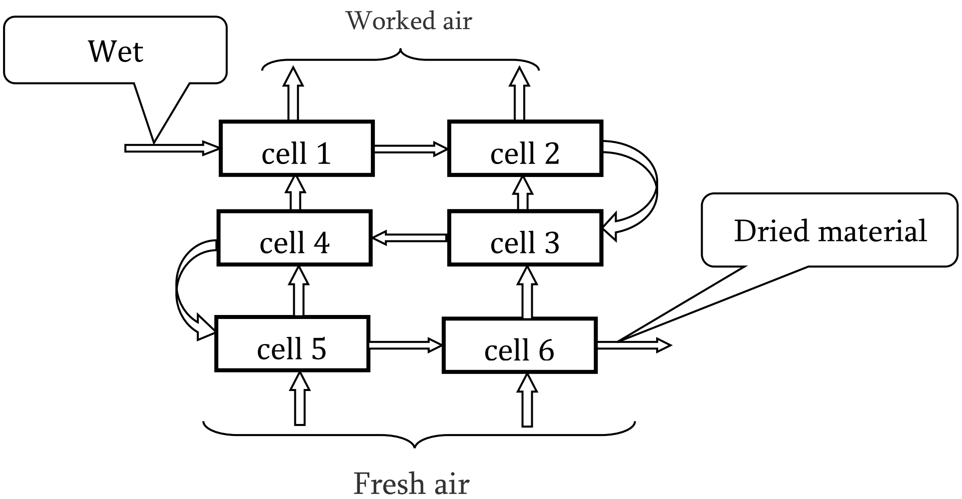

Figure 3 Flow chart of product and air movement between the cells on conveyors in a dryer.

Today, with the advent of modern microprocessor technology, the issues of developing and identifying a mathematical model of the convection drying process have translated into practical demand. Installing digital sensors at various points in the drying chamber allows us to reliably control air temperature and relative humidity for the experimental evaluation of the parameters of a conveyor dryer model **[8]**, **[20]**, **[21]**, **[34]**.

The collection of necessary experimental data is carried out using the following methodology:

1. The dryer exits the stationary mode, characterised by the cessation of changes in temperature and relative humidity of the air in the working volume of the drying chamber, after setting the required constant velocity of the conveyors and the temperature of the heaters.
2. The temperature of one of the heaters (by changing the steam pressure) or the fan speed of one of the heaters undergoes a step change in a jump by a given value and then, after a while, returns to its original value.

The experimental data are characterised by a large volume and represent a synchronous record of the linear velocity of the conveyors, the temperature of the heaters, and the changes in air temperature and relative humidity in the cells of the drying chamber. In addition, during the experiment, the moisture content of the material at the inlet and outlet of the dryer is measured using the laboratory method of periodic sampling.

The algorithm for processing experimental data, the solution to the problem of determining the unknown parameters of the heat-mass transfer system Eq. 1-3, Eq. 6, Eq. 7, and Eq. 10, is reduced to solving the problem of minimising the criterion that assesses the quality of the mean square deviation of the difference between the solutions to the experimental and the given system of equations and its performance Eq. 15.

$$\Phi(K_1, K_2, \alpha_2\phi_2, \alpha_3F_3) = \sum_k \sum_\mu [(\omega_X (X_{ak}(\tau_\mu) - \hat{X}_{ak}(\tau_\mu))^2 + \omega_T (T_{ak}(\tau_\mu) - \hat{T}_{ak}(\tau_\mu))^2) + \sum_v (w_6(\tau_v) - \hat{w}_6(\tau_v))^2] \rightarrow \min \quad (15)$$

Where:

τ_μ and τ_v - respectively, the moment of measurement of the air condition (temperature and moisture content) at the points $\mu,\ v$ of the sensor installation in the cell numbered as k and the moisture content of the material at the dryer outlet (from the 6th cell of the 3rd belt); $X_{ak}(\tau_\mu)$, $\hat{X}_{ak}(\tau_\mu)$ - respectively, the air moisture content obtained by solving the system of Eq. 1 – 3, Eq. 6, Eq. 7 and Eq. 10 and through the experiment in the cell k at a time τ_μ; $T_{ak}(\tau_\mu)$, $\hat{T}_{ak}(\tau_\mu)$ - the air temperature obtained by solving the system of Eq. 1 – 3, Eq. 6, Eq. 7 and Eq. 10 and through the experiment in the cell k at a time τ_μ; $w_6(\tau_v)$, $\hat{w}_6(\tau_v)$ - respectively, the moisture content of the product obtained by the corresponding calculation and experiment at the dryer outlet (in the 6th cell) at a time τ_v; the weighting coefficients ω_X ($\omega_T > 0$) are introduced in (15), reflecting the relative value of various data in Eq.1 – 3, Eq. 6, Eq. 7 and Eq. 10 when solving the parameter estimation problem **[35]**, **[36]**.

The problem of minimizing the criterion for estimating the degree of the mean square deviation of the difference between the experimental data and the solutions of the system Eq. The Nelder-Mead direct search method solved 1-3, Eq. 6, Eq. 7, and Eq. 10. This was done after processing the experimental data on an IBM computer with MS Excel (Microsoft Corporation, Redmond, Washington, USA) and the Optimization Toolbox package of the dynamic systems modeling program Matlab/Simulink (MathWorks, Natick, Massachusetts, USA) **[37]**, **[38]**. When drying plums in a conveyor-type dryer, we were able to obtain the following values of the unknown parameters: drying rate coefficient in the first period K_1 =0,8309.10^{-4} $kg \cdot (m^2 \cdot s \cdot {}^{o}C)^{-1}$; the drying rate coefficient in the second period K_2 = 0,3413.10^{-4} $kg \cdot (m^2 \cdot s \cdot {}^{o}C)^{-1}$ and the heat transfer coefficient: $\alpha_2\phi_2$=0,0794 $kW \cdot (kg \cdot {}^{o}C)^{-1}$, α_3F_3=0,0245 $kW \cdot (kg \cdot {}^{o}C)^{-1}$ and the critical moisture content of plums w_{CR}= 71%.

In the case of convection drying of plums in a conveyor-type dryer, we can assess the adequacy of the mathematical model using the coefficient values obtained from the study results with an accuracy of 95% - 98%, as clearly illustrated from Figure 4 to Figure 8 (the experimental data were recorded synchronously).

Figure 4 illustrates the transient (dynamic) characteristics of the air temperature at the beginning (cell 3) and at the end (cell 4) of the second conveyor belt in the conveyor drying chamber. These characteristics were obtained through calculations and actual measurements during plum drying when the drying chamber operates in nominal mode, with a change in the temperature of the second belt heater (instantaneous change in vapor pressure). From this, it can be observed that with an instantaneous change in pressure (disturbance), the air temperature in cell 3 increases from 79 °C to 82 °C. After 350 s, when the disturbance stops and the pressure decreases to the set value, the air temperature decreases with a certain inertia to 79 °C. Meanwhile, the air temperature in cell 4 increases from 65 °C to 79 °C with a certain inertia. When the disturbance is removed, after 350 s, and the pressure decreases to the initial value, the air temperature decreases with a certain inertia to 65 °C.

Figure 5 illustrates the transient (dynamic) characteristics of the air temperature at the beginning (cell 5) and at the end (cell 6) of the third (last) conveyor belt of the conveyor drying chamber, obtained through calculations and actual measurements during plum drying, when the drying chamber operates in nominal mode with a change in the temperature of the second belt heater (instantaneous change in vapor pressure). It can be observed that with an instantaneous change in pressure (disturbance), the air temperature in cell 5 increases from 77 °C to 80 °C. After 350 s, when the disturbance stops , and the pressure drops to the set value, the air temperature decreases with a certain inertia to 75 °C. At the same time, the air temperature in cell 6 increases with a certain inertia from 63 °C to 78 °C. When the disturbance is removed, after 350 s, and the pressure drops to the set value, the air temperature decreases with a certain inertia to 63 °C.

Figure 6 illustrates the transient (dynamic) characteristics of the relative humidity of the air at the beginning (cell 3) and at the end (cell 4) of the second conveyor belt of the drying chamber. These were obtained through calculations and actual measurements during plum drying, when the drying chamber operates in nominal mode with a change in the temperature of the second belt heater (instantaneous change in vapor pressure). It can be seen that with an instantaneous change in pressure (disturbance), the relative humidity of the air in cell 3 decreases instantly from 78% to 65%. After 350 seconds, when the disturbance stops , and the pressure decreases to the set value, the relative humidity of the air increases with significant inertia to 86%. At the same time, the relative humidity of the air in cell 4 decreases from 74% to 41% with some inertia. When the disturbance is removed after 350 seconds, and the pressure drops to the set value, the relative humidity of the air instantly increases to 55%.

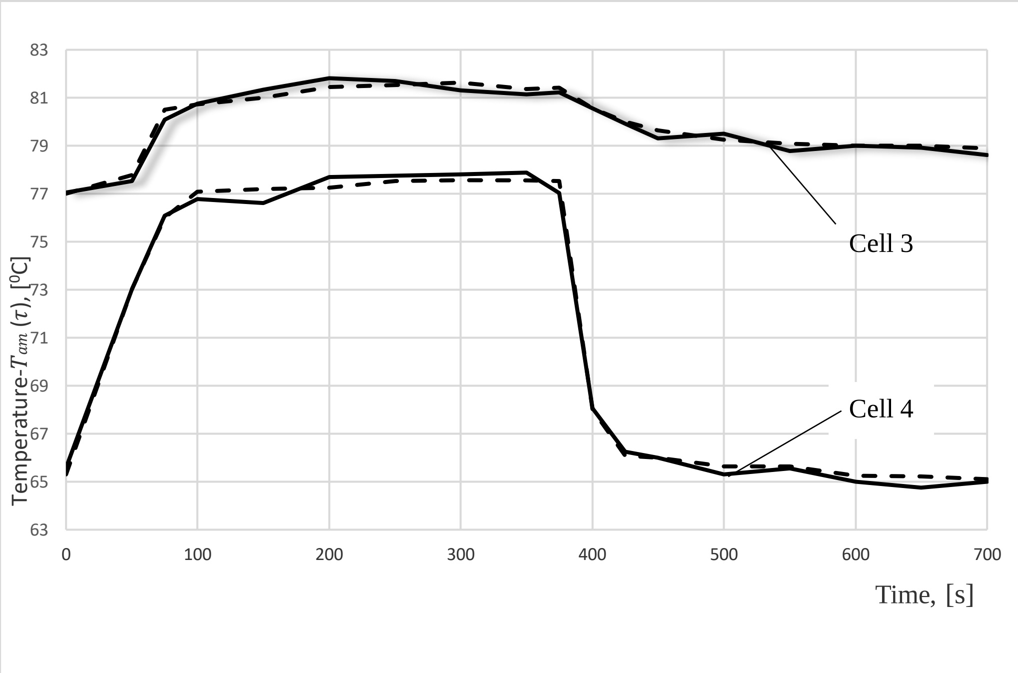

Figure 4 Transient characteristics of air temperature during plum drying on the second belt of the conveyor dryer (in cells 3 and 4).
Note: Model (solid line), Experiment (dashed line).

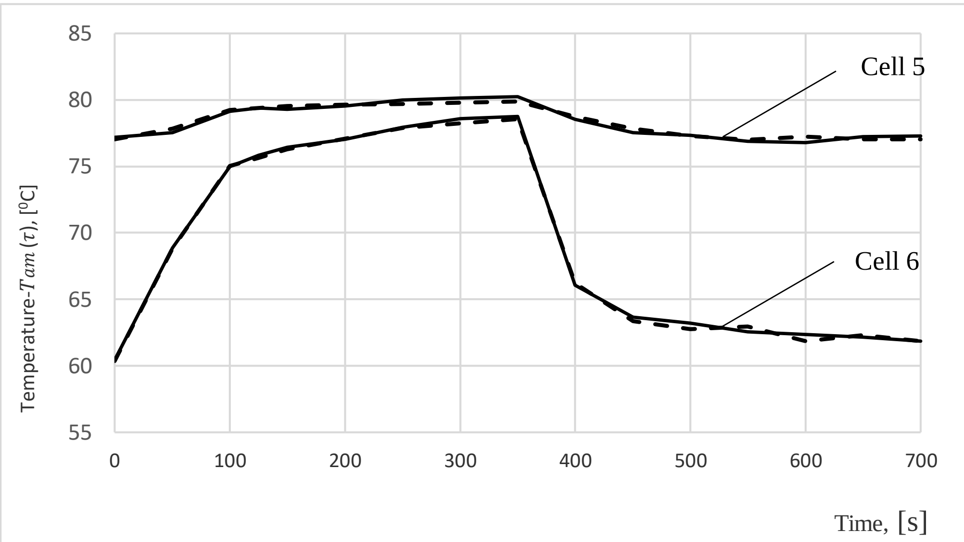

Figure 5 Transient characteristics of air temperature at the outlet of the conveyor dryer (on the third belt – in cells 5 and 6) during plum drying.
Note: Model (solid line), Experiment (dashed line).

Figure 7 illustrates the transient (dynamic) characteristics of the relative humidity of the air at the beginning (cell 5) and at the end (cell 6) of the third (last) conveyor belt of the drying chamber, obtained through calculations and actual measurements during plum drying, when the drying chamber operates in nominal mode with a change in the temperature of the second belt heater (instantaneous change in vapor pressure during disturbance). From this, it can be seen that with an instantaneous change in pressure (disturbance), the relative humidity of the air in cell 5 decreases from 78% to 60%. At the same time, the relative humidity of the air in cell 6 decreases from 57% to 48% with a certain inertia.

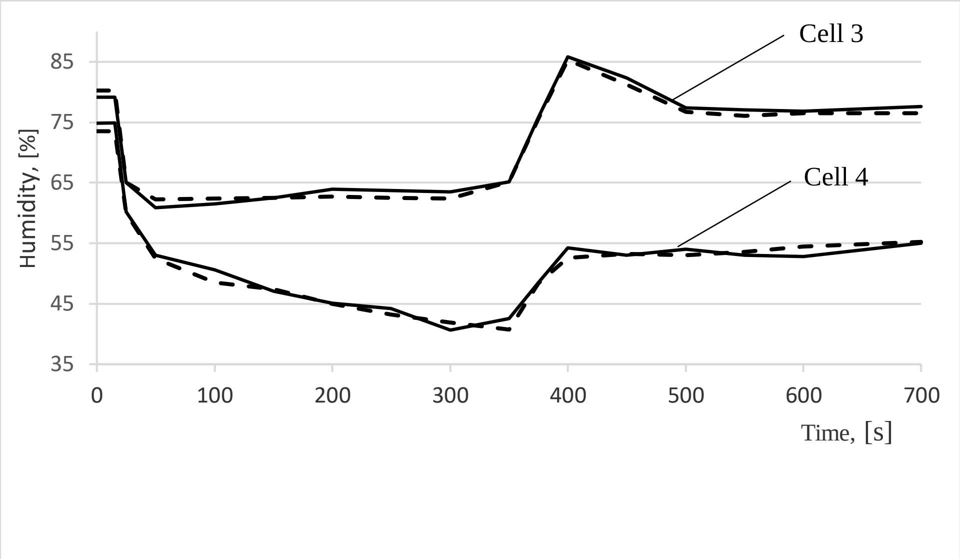

Figure 6 Transient characteristics of relative air humidity during plum drying on the second belt of the conveyor dryer (in cells 3 and 4).
Note: Model (solid line), Experiment (dashed line).

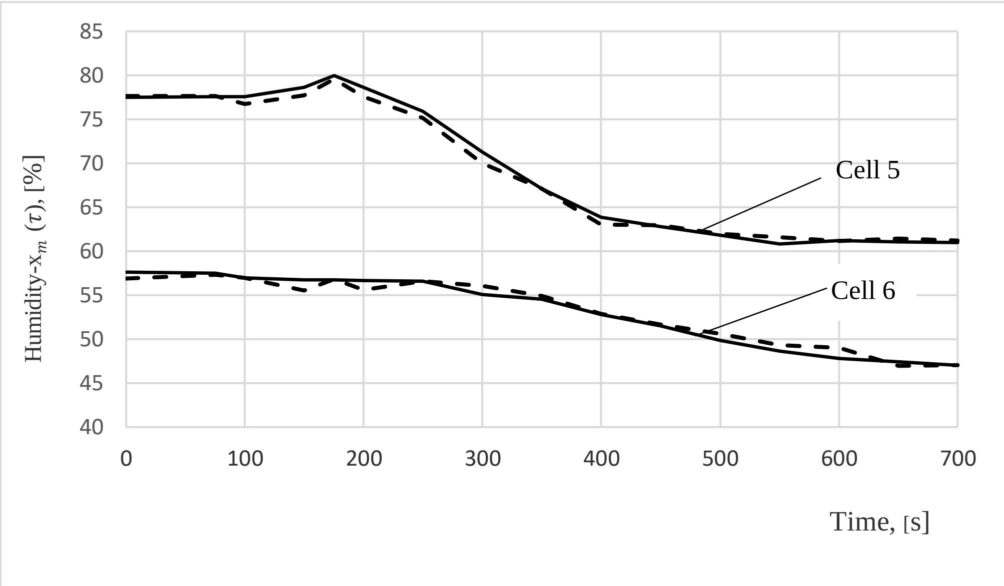

Figure 7 Transient characteristics of relative air humidity at the outlet of the conveyor dryer (on the third belt – in cells 5 and 6) during plum drying.
Note: Model (solid line), Experiment (dashed line).

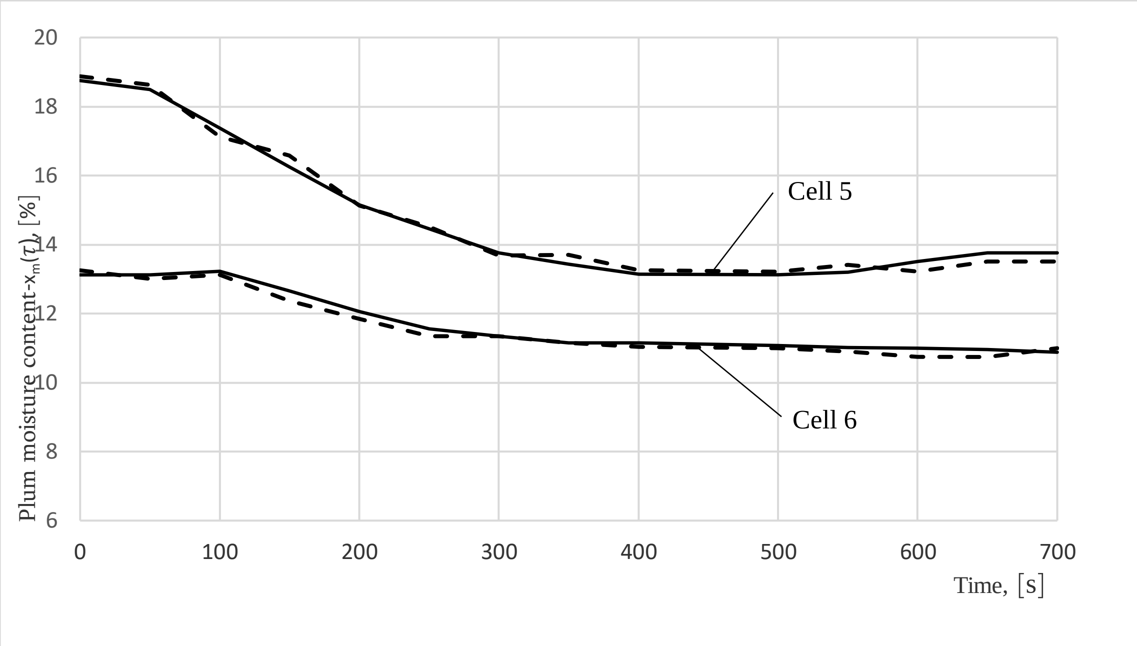

Figure 8 Transient characteristics of plum moisture content at the outlet of the conveyor dryer (on the third belt – in the 5th and 6th cells).
Note: Model (solid line), Experiment (dashed line).

Figure 8 illustrates the transient (dynamic) characteristics of the final moisture content of plums obtained through calculations and actual measurements at the beginning (cell 5) and the end (cell 6) of the third (last) conveyor belt of the drying chamber, when disturbed by a change in the temperature of the second belt heater (instantaneous change in vapor pressure) during the nominal operation of the drying chamber. Figure 8 shows that with an instantaneous increase in the vapor pressure in the heater (disturbance), the moisture content of the product in cell 5 decreases from 19% to 13%. At the same time, the moisture content of the product in cell 6 decreases from 13% to 11% with a certain inertia.

Table 2 Parameters of a mathematical model of conveyor drier for several types of fruit products.

Product type	**Drying rate coefficients (kg·(m^2· s · ^{o}C)$^{-1}$)**		**Heat transfer coefficients (kW· (kg · ^{o}C)$^{-1}$)**		**Critical moisture content (%)**
	$K_1 \cdot 10^{-4}$	$K_2 \cdot 10^{-4}$	$\alpha_2\phi_2$	$\alpha_3 F_3$	w_{CR}
Green plum	0.8163	0.3073	0.0854	0.0383	62
Cherry	0.9587	0.4201	0.0873	0.0412	66
Blue plum	0.8309	0.3413	0.0794	0.0245	71
Apricot	0.7710	0.2639	0.0651	0.0390	74
Pear	0.7952	0.2822	0.0685	0.0280	72
Apple	0.7234	0.2058	0.0671	0.0305	59

Note: Table 2 presents the values of the unknown coefficients found in the study of Eq.1 – 3, Eq. 6, Eq.7, and Eq. 10 for various fruit products.

CONCLUSION

A dynamic mathematical model of conveyor-type drying, developed based on the heat-mass exchange between the drying agent and the product, can reliably predict the drying rate and temperature distribution in the product, as well as the temperature and moisture content distribution of the drying agent along the conveyors (by cells). The model reflects the equilibrium moisture content relationship between the drying agent and the product.

The "cellular" dynamic mathematical model of the plum drying process developed in this paper can be used to study the kinetics of the drying process, determine unknown parameters, solve optimal automatic control problems, identify the heat transfer coefficients for drying various high-moisture fruits during the first and second periods of drying, respectively, as well as to develop an optimal automatic control system for the dynamic mode of the conveyor-type drying process. This ensures a reduction in the energy expended on the drying process and maintenance of the moisture content of fruit products established by the standards for fruits. For example, when drying plums, we have obtained the following values of unknown parameters: drying rate coefficient in the first period – $K_1=0.8309\cdot10^{-4}$ kg·(m²·s·°C)$^{-1}$; drying rate coefficient in the second period–$K_2=0.3413\cdot10^{-4}$ kg·(m²·s·°C)$^{-1}$ and heat transfer coefficients: $\alpha_2\cdot\phi_2=0.0794$ kW·(kg·°C)$^{-1}$, $\alpha_3\cdot F_3=0.0245$ kW·(kg·°C)$^{-1}$ and critical moisture content of plums $w_{CR}=71\%$. The energy reduction spent on the drying process is 4%.

The research found that the dynamic characteristics of the residual moisture content of plums at the dryer outlet were 11%.

The "cellular" dynamic characteristics of the relative humidity and temperature of the drying agent during blue plum drying, obtained as a result of the experimental and theoretical study of the conveyor drying unit, allow us to assess the 96% - 98% adequacy of the developed dynamic mathematical model.

The algorithm for developing a "cellular" dynamic mathematical model of a conveyor-type dryer is universal and helpful in obtaining a mathematical model of any conveyor dryer type. This will provide practical assistance to designers of fruit preservation industrial technology and automatic or automated control systems and managers in this field during the decision-making process.

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Contact Address:
Avtandil Bardavelidze
Affiliation: Akaki Tsereteli State University, Faculty of Exact and Natural Sciences, Department of Computer Technology, 59 Tamar Mepe Str., 4600, Kutaisi, Georgia
Tel.: +995 558 82 99 82
E-mail: avtandil.bardavelidze@atsu.edu.ge
ORCID: https://orcid.org/0000-0002-9873-4402
Author contribution: conceptualization, methodology, software, validation, formal analysis, investigation, writing – original draft, project administration.

Khatuna Bardavelidze
Affiliation: Georgian Technical University, Faculty of Informatics and Control Systems, Department of Interdisciplinary Informatics, 77, Merab Kostava Str., 6th Building, 0117, Tbilisi, Georgia
Tel.: +995 598 15 62 09
E-mail: bardaveli@yandex.ru
ORCID: https://orcid.org/0000-0001-7972-4711
Author contribution: formal analysis, investigation, resources, data curation, writing – review & editing, visualization.

Otari Sesikashvili
Affiliation: Akaki Tsereteli State University, Faculty of Engineering – Technical, Department of Mechanical Engineering, 59 Tamar Mepe Str., 4600, Kutaisi, Georgia
Tel.: +995 593 96 62 42
E-mail: otar.sesikashvili@atsu.edu.ge
ORCID: https://orcid.org/0000-0003-1229-4141
Author contribution: software, validation, formal analysis, data curation, writing – review & editing, project administration, funding acquisition.

Correspondence author: **Otari Sesikashvili**