

Mathematical model of the static mode of tunnel dehydrator for fruits as a controlled object

AVTANDIL BARDAVELIDZE – KHATUNA BARDAVELIDZE – OTARI SESIKASHVILI

Summary

In the study, based on the analysis of technological process of drying apricots in a tunnel-type dehydrator, the main mode parameters, control variables of the object and disturbing factors were determined. With the heat-mass exchange equations and control charts of the dried product, with established distribution of the temperature and moisture content of the drying agent, taking into account certain assumptions and initial conditions, a system of ordinary differential equations with distributed parameters for convective drying of fruits in a tunnel-type dehydrator was established. In the system of process heat-mass exchange equations, the drying coefficient in the first and second periods and heat exchange coefficient were determined as a result of identification. The solution of the problem of determining these parameters was reduced to the solution of the minimization problem of the criterion for evaluating the quality of the mean square deviation between the solutions of experimental and heat-mass exchange equations results of the apricot drying process. The dependence curves between the equilibrium moisture content of apricots and relative moisture content of the working agent as well as the temperature obtained as in experimental and theoretical studies of the drying process allowed us to judge the adequacy of the developed mathematical model at 95–98 %.

Keywords

tunnel dehydrator; mathematical model; drying rate; drying agent; moisture content

Tunnel-type dehydrators are among the most powerful consumers of energy, but they enable to preserve the high nutritional value of food products. The main requirements during the implementation of the technological process are the reduction of energy consumption for drying, maximum performance and compliance with the standard regulated value of the final (residual) moisture content of the dried product at the outlet of the dehydrator, which determines the shelf-life of the dried product. Controlling the residual moisture content of the product is very important, since overdrying leads to significant overconsumption of energy and lower quality, while improper dehydration leads to microbiological spoilage of the product [1–3].

Fruits and vegetables are saturated with microelements, rich in vitamins and plant fibres, which can help people to compensate for an unhealthy diet and thereby improve their health. It is estimated that one-third of the world food stocks is lost each year due to poor post-harvest treatment practices. This is thought to be a major source of the damage to the country's economy. Because of this, it is necessary to find and study the best methods of food processing and preservation in order to reduce food losses. Due to seasonal changes, it is impossible to access a variety of fruits and vegetables throughout the year, which is why the processing and preservation of agricultural products with less energy costs, in order to maintain a continuous cycle of providing high-quality

Avtandil Bardavelidze, Department of Computer Technology, Faculty of Exact and Natural Sciences, Akaki Tsereteli State University, 59 Tamar Mepe Str., 4600 Kutaisi, Georgia.

Khatuna Bardavelidze, Department of Interdisciplinary Informatics, Faculty of Informatics and Control Systems, Georgian Technical University, 77 Merab Kostava Str., 6th Building, Tbilisi, Georgia.

Otari Sesikashvili, Department of Mechanical Engineering, Faculty of Engineering – Technical, Akaki Tsereteli State University, 59 Tamar Mepe Str., 4600 Kutaisi, Georgia.

Correspondence author:

Otari Sesikashvili, e-mail: otar.sesikashvili@atsu.edu.ge

and low-cost products to consumers, is a pressing problem [4, 5].

The most common method of storing fruits and vegetables is dehydration, because bacteria multiply rapidly in fruits with high moisture content. Removing moisture from fruits is a way to prevent them from spoilage, for which more than 85 % of industrial enterprises use the heat convective drying method. Dehydration of fruits can increase their shelf-life and reduce production costs, food weight as well as transport costs. The drying process not only helps to increase the shelf-life of the product, but also creates an opportunity to improve the quality of the product. However, to ensure the high quality of dried fruits, it is necessary to develop new methods of drying or to improve the drying process effectively. The improved technologies reduce drying energy costs by 20 % and improve drying efficiency by 26.5 % in terms of dehydration time reduction [6, 7].

The aim of the study of COSME-DE VERA et al. [8] was to review the drying kinetics studies conducted on common tubers. Of particular interest was the influence of the parameters of the drying process such as temperature and speed of the heating air medium, the method of physico-chemical pre-treatment and sample preparation on the rate and time of drying. The various most appropriate drying kinetics for specific tubers were also extensively studied. The role of dehydration process parameters and the most appropriate model equations in the design of drying equipment were. Other study of FIGIEL and MICHALSKA [9] mentioned that vacuum-microwave drying was the best combined dehydration method that provided high quality of the product and low energy consumption. This method requires further research in terms of preserving the physical-chemical characteristics of the dried product. The paper of IQBAL et al. [10] highlighted that the calculations of heat and mass transfer during convective drying of fruits will significantly contribute to the optimization of the dehydration process.

The paper of REPPICH et al. [11] discussed an experimental mathematical model of drying thin-layers of apples. A regression analysis was carried out to determine the parameters of the model, which cannot sufficiently describe the heat-mass exchange process of drying. In a further study of AKTER et al. [12], a mathematical model describing the kinetics of the ripening process of apple and banana samples by the laboratory method was developed. The analysis of the conducted research showed that the reduction of the volume of drying fruits had a significant effect on the effective diffusion coefficient and accordingly

changed the distribution of moisture and temperature inside the material. Finally, the adequacy between the results predicted by the mathematical model and the experimental results was established.

The paper of MABROUK et al. [13] presented a numerical model of heat and mass transfer of bulk products in a tunnel dryer with a fixed bed. A simplified numerical model of heat and mass transfer was developed on the basis of the constitutive equations and the drying rate of thin-layer bulk products. The resulting system of non-linear partial differential equations was solved numerically by the method, which was associated with great difficulties. The paper of MEWA et al. [14] focused on dehydration of beef in a solar tunnel dryer. As a result of the research, an experimental regression mathematical model of the drying process was obtained, which cannot describe the drying process with sufficient accuracy.

In this study, we considered convection drying of fruits in a tunnel-type dehydrator, because it has a number of advantages compared to other types of convective dryers at the use for drying of a large number of single-piece materials, drupaceous fruits, namely, simplicity, ease of installation and repair as well as sufficiently high efficiency. These advantages justify its wide application [13–15].

Due to the large longitudinal dimensions of the tunnel dehydrator, in order to increase the completeness of the mathematical model, we considered it appropriate to analyse the heat-mass exchange in the process of convective drying of fruits therein along the longitudinal coordinate of the drying chamber, that is, as a convective drying process with distributed parameters, which, based on our analysis of the existing literature review, has not been found in the last 7–10 years. We analysed several scientific studies of the early period of the tunnel dehydration process [1–4].

Based on the analysis of the scientific papers presented above and the necessary strategy for solving the problem, the scientific novelty of the research is the development of an adequate mathematical model of the technological process of convection drying with distributed parameters, because the existing mathematical models for the tunnel dehydrator do not reflect the change in the drying agent, product temperature and moisture content distribution in the drying channel along the machine's transverse coordinate as the controlled object, cannot fully meet the requirements of the optimal control system of the machine's static technological mode.

The aim of the study was to develop a mathematical model with parameters distributed on the

longitudinal coordinate of the static mode of the fruit tunnel dehydrator, which will be adequate for the real process and meet the requirements for the optimal control system of the static technological mode of the machine.

MATERIALS AND METHODS

Samples

In order to achieve the set goal, we selected as the research object ripe and dense apricots suitable for drying. These were obtained in the market of Kutaisi (Georgia). Apricot is a product of high humidity, whose dehydration is associated with considerable problems, because each type of apricots has specific properties and different composition, depending on the cultivar, origin, growing conditions and degree of ripeness. These properties determine also the nutritional value and taste.

Methods

The research methods were the convective drying method, the mathematical modelling method and the experimental research method. These were based on the determination of the drying and heat transfer coefficients together with the solution of the system of differential equations describing the transfer of heat and moisture in the wet fruit. We measured the moisture content of apricots at the inlet and outlet of the drying chamber by the gravimetric method.

Equipment

We estimated parameters of the mathematical model of the fruit drying process for the tunnel

dehydrator PR128T-3000/4 (FLAIT-M, Moscow, Russia), which is provided with automatic temperature measuring devices of the drying agent at the inlet and outlet of the drying chamber, and with automatic measuring devices of relative humidity of the wet and exhaust air. The tunnel dehydrator is presented in the form of a schematic diagram in Fig. 1. The dryer consists of two parallel channels located under each other. The lower channel represents the working chamber in which the drying process takes place, while the upper channel serves for the preparation of the drying agent and formation of circulation. Air is used as the drying agent.

In the upper channel, an axial fan, a diffuser and a sliding shutter are installed for air supply and equal distribution in the cross-section of the working channel. A heat generator working on liquid fuel is placed in the frontal part of the upper channel. Fuel is burned in an automatic burner. Combustion products pass through the heater, heat the air and pass through the exhaust pipes into the atmosphere. The product (e.g. fruits or vegetables) is laid in a single layer on the lattice plate, which is placed on a special drying car. The drying car is transported to the dryer and moved to the working chamber by means of a step feeder. In the working chamber, the flow of the drying agent moves in the direction opposite to the movement of the drying car loaded with the dried product, gradually losing heat and gaining moisture, while the moving product, on the contrary, is heated and loses moisture.

Several drying cars are located in the chamber simultaneously, the number of which is determined by the design of the dryer. Periodically,

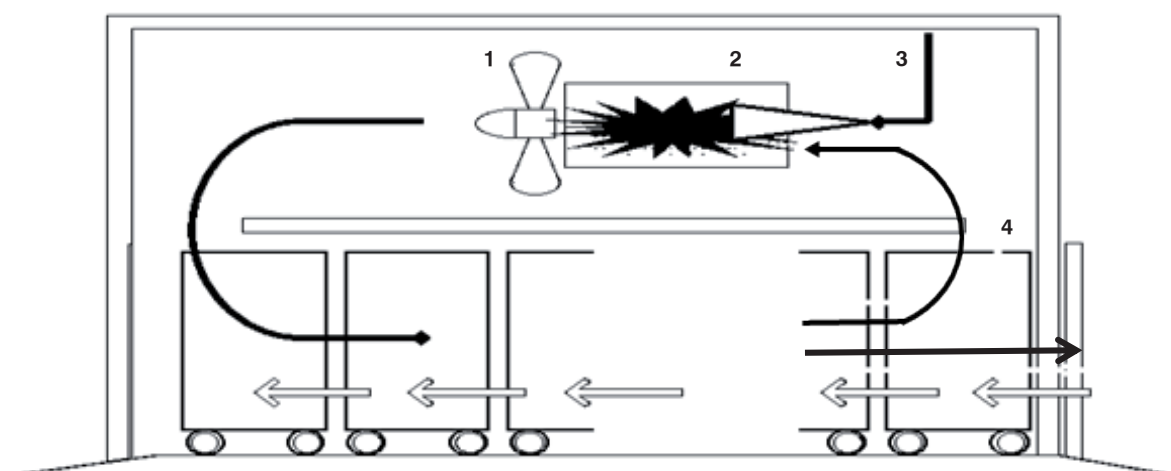


Fig. 1. Schematic diagram of the tunnel dryer.

1 – axial fan, 2 – heat generator, 3 – fuel pipe, 4 – drying cars loaded with product.

at pre-determined intervals, one car with dried product is unloaded at the outlet of the working chamber. Simultaneously, another car with the dried product is loaded at its inlet. The time intervals between loading of cars is determined by the estimated duration of the drying process for each type of the dried product. In this time interval, each car is stationary in the working chamber [1, 5].

In the tunnel dryer, with the appropriate drying technology, the product to be dried is placed in the drying cars that move in the drying cell in the flow of the drying agent, which is hot air. The drying cars move with periodic stops. After the given stop time τ_0 elapses, all the drying cars move simultaneously from the inlet to the outlet of the dryer so that one drying car with the dried product enters the cell while another car with the dry product leaves the cell. Therefore, quantity M of the drying cars is constantly in the drying chamber and the delay time (T) of the car in the chamber is equal to

$$T = M \cdot \tau_0 \quad (1)$$

Drying in tunnel-type dehydrators is carried out in batches in a nearly stationary regime. Before launch, the drying channel is heated to a temperature of 80 °C, when the burner works while the outdoor air intake window and the circulation sliding shutter are completely closed. After heating, the dryer is gradually loaded, a stationary mode is established in the dryer, after which the established loading-unloading mode of cars should be maintained.

Partial recirculation of the exhaust air can be used to increase the efficiency of tunnel dryers. Technological control of a tunnel dehydrator is carried out with the following parameters:

- temperature and relative humidity of the air supplied to the inlet and outlet of the working cell, as well as air pressure;
- the speed of air movement in the working cell.

At the wet end of the channel, that is on the side of the loading position of cars, a temperature of 60–65 °C and relative humidity of 70–85 % are usually maintained, while at the dry end of the channel (on the side of the unloading position of cars) temperature of 105–115 °C and relative humidity 7–12 % are usually maintained [1, 14]. The main mode parameters of tunnel dehydrators are as follows: loading (stopping) period of the drying cars; air circulation and the location of the intake sliding shutters; the location of the distribution valves ensuring even distribution of the drying agent flow in relation to the section of the drying channel; parameters of the drying agent at

the bottom of the drying channel (temperature and humidity). The main disturbing factors in the operation of tunnel dehydrators are as follows: change in the product temperature and initial moisture content; change in temperature and humidity of the incoming air; random change in the total amount of the product and non-uniformity of its distribution in the drying cars [14, 15]. Initial and final moisture control in industrial conditions is performed periodically by laboratory method.

If the stop time of the drying cars, the product entering the dryer, the fan output, and the fresh air entering the dryer are constant, a periodic, quasi-stationary drying regime is established. In this case, the main parameters represent the objects suitable for mathematical description, for the purpose of optimal control of the static mode of the drying technological process, estimation of unknown parameters and solution of kinetic problems. This stationary mode of tunnel dehydrators is characterized by the established distribution of the parameters of the material and the drying agent along the trajectory of their movement in the drying chamber. When a drying car loaded with fruits arrives at the inlet of the dryer, this mode will be disturbed, although this disturbance is relatively small due to the inertia of the system [1, 15].

Statistical analysis

To analyse the test parameters of the product, statistical analysis of the obtained data was conducted and the reliability of the obtained data was evaluated by T -test, using the Windows IBM SPSS Statistics version 20.0 program, (IBM, Armonk, New York, USA). To describe the ordered sample, we used statistical functions of the average arithmetic value and the average standard error. A reliability value of $p < 0.05$ was chosen.

RESULTS AND DISCUSSION

For the simulation, control and study of the drying process, it is important to use mathematical models, where mathematical equations describe the prediction of the behaviour of the drying process. Changes in air movement speed and temperature in the dehydrator have a significant effect on the drying rate and the rate of moisture evaporation can be slowed down by changes in the movement speed of the products. For product quality and storage safety, it is important to maintain low air temperature at the beginning and end of the process [8].

In previous works [7, 16], the authors con-

ducted a study of the drying process kinetics of sliced apples, persimmons and subtropical raw materials. The works presented a mathematical model of the drying process kinetics, which was obtained in laboratory conditions and took into account heat and moisture changes only at one point of the drying. Its solution required special computing techniques.

The previous studies [12, 17] analysed the drying process of fruits and vegetables. It was established that computational modelling can be an effective alternative to experimental approaches. Mathematical modelling is a useful tool for optimizing the dehydration process. Simple models are often effective in engineering activities, while complex models are closer to reality and useful for engineering and research purposes.

In the previous paper of ATYKHANOV et al. [18], the period of the drying process of fruits was determined experimentally and the rate of drying was described by a polynomial of the third degree, which allowed us to investigate only the second period of the drying process. The following papers [4, 19] mainly presented only experimental mathematical models of dehydration of fruits and vegetables obtained in laboratory conditions, which were not sufficient to study the heat-mass exchange process and optimizing the drying process. GOYAL et al. [15] investigated the drying process of processed apple and plum slices in a tunnel type dehydrator. The study was conducted only in a drying rate speed falling period and, therefore, a logarithmic mathematical model of the drying process was obtained for the second period. That could not fully describe the heat-mass exchange at dehydration.

Using the above-mentioned features of the tunnel drying process, the laws of physics and the heat-mass transfer control charts, the established distribution of heat-mass transfer of the drying product, temperature and moisture content of the drying agent along the longitudinal coordinate of the dryer, taking into account certain standard assumptions, can be described as a solution to the following system of ordinary differential equations Eq. 2–5 [14, 15, 20–22].

$$g \frac{dw}{dl} = -\varphi_1 N(w, T_M, y, T_a) \quad (2)$$

$$g_a \frac{dy}{dl} = \varphi_1 N(w, T_M, y, T_a) \quad (3)$$

$$g C_m \frac{dT}{dl} = K \varphi_2 (T_a - T_M) - \Delta H \varphi_1 N(w, T_M, y, T_a) \quad (4)$$

$$g_a C_a \frac{dT_a}{dl} = K \varphi_2 (T_M - T_a) \quad (5)$$

with initial conditions:

$$W(0) = W_0 \quad (6)$$

$$y(0) = y_0 \quad (7)$$

$$T_M(0) = T_{M0} \quad (8)$$

$$T_a(0) = T_{a0} \quad (9)$$

Eq. 2 describes the change in the moisture content of the product in the dryer along the longitudinal coordinate of the drying channel, Eq. 3 describes the change in the moisture content of the drying agent in the dryer along the longitudinal coordinate of the drying channel, Eq. 4 describes the temperature change of the heated air in the drying channel along the longitudinal coordinate of the drying channel and Eq. 5 describes the temperature change of the drying agent along the longitudinal coordinate of the drying channel.

In equations:

- l is linear coordinate of the drying chamber (i. e. distance from the inlet of the drying chamber to the current point, in metres);
- w, y are average (by time) moisture content of the product and the drying agent, respectively, which are considered to be a function of the coordinate l (in percent);
- T_M, T_a are average temperature of the product and the drying agent, respectively, at the point with a coordinate l (in degrees Celsius);
- g is the amount of product dried in the drying chamber per unit of time, on dry weight basis (in kilograms per second);
- g_a is the amount of drying agent delivered to the cell per unit time, on an absolutely dry air basis (in kilograms per second);
- C_m is the heat capacity of the wet product,

$$C_m = C_1 + w C_{H_2O} \quad (10)$$

where C_1 and C_{H_2O} are the heat capacity of dry product and water, respectively (in kilojoules per kilogram multiplied by degrees Celsius);

- C_a is the heat capacity of the moist air,

$$C_a = C_{air} + w C'_{H_2O} \quad (11)$$

where C_{air} and C'_{H_2O} are the heat capacity of dry air and water vapour, respectively (in kilojoules per kilogram multiplied by degrees Celsius);

- φ_1 is the surface area of phase separation (per unit mass of dry matter moisture exchange) between the product and the drying agent (in square metres per kilogram);
- φ_2 is the heat transfer surface area per unit

mass of dry product between the product and the drying agent (in square metres per kilogram);

- K is the heat transfer coefficient between the product and the drying agent (in kilowatts per square meter per degrees Celsius);
- ΔH is specific heat of evaporation of water (in kilojoules per kilogram).

Assume that G is the average mass of the product arriving on one drying car (on dry matter basis), then

$$g = \frac{G}{\tau_0} \quad (12)$$

and

$$\varphi_{0,1} = \frac{F_{0,1}}{G} \quad (13)$$

where F_0 and F_1 are the values of area of the separating phase and heat exchange surface (in square metres), which are formed after loading them on one drying car.

The function $N(w, T_M, y, T_a)$ in the system of heat-mass exchange Eq. 2–5 describes the dependence of the convective drying rate on the coordinates of the process variable state, such as saturated vapour pressure, as well as the temperature and moisture content of the product being dried and the drying agent.

$$N(w, T_M, y, T_a) = K_1 [P_{aq}(T_M) - \varphi P_{aq}(T_a)] \quad (14)$$

for $w > w_{CR}$

$$N(w, T_M, y, T_a) = K_2 [w - w_{EQ}(\varphi)] \quad (15)$$

for $w < w_{CR}$

In equations P_{aq} is saturated vapour pressure (in pascals), K_1 , K_2 , w_{CR} are drying coefficients (in the first and second periods) and critical moisture content, respectively (in percent), w_{EQ} is the equilibrium moisture content of the product (in percent) and φ is relative humidity of the agent (in percent).

$$\varphi = \frac{y}{(0.621 + y)} \times \frac{P}{P_{aq}(T_a)} \quad (16)$$

The coefficient in the denominator of the latter formula is the ratio of the molecular weight of the moist vapour to the molecular weight of the drying agent (0.621 for wet air).

When constructing the system of heat-mass exchange equations Eq. 2–5, assumptions were made in such a way that the process of periodic loading of the drying cars with dry product is approximated with sufficient accuracy by the process of continuous movement of the drying cars in the drying channel.

The system of heat-mass exchange Eq. 2–5 with the initial conditions Eq. 6–8 must be solved together with the equations that determine the amount of fresh intake air during the operation of the unit for preparing the drying agent [1, 14]:

$$Q = k_{VN}(u_a)^{1/3} \quad (17)$$

$$X_0(t) = (1 - \beta)X_{Na}(t) + \beta X_{ENV} \quad (18)$$

$$i(T_{a0}, X_0) = (1 - \beta)[i(T_{Na}, X_N) + P_{HG}] + \beta i_{ENV} \quad (19)$$

where by Eq. 17, fan capacity (Q) is calculated (in cubic metres per second), Eq. 18 is used to calculate humidity of wet air X_0 (in percent) and Eq. 19 is used to calculate enthalpy (i) of wet air as a function of its temperature and humidity (in kilojoules per mole).

In equations u_a is fan motor power (in kilowatts), k_{VN} is coefficient of proportionality, t is the supplied drying air temperature (in degrees Celsius), β is clean air share in the flow of exhaust gases entering the dehydrator, X_{Na} is the moisture content of the drying agent (in percent), X_{ENV} is humidity of the surrounding air (in percent), X_N is the moisture content of the drying agent (mixture) sucked into the dryer (in percent), T_{a0} is the temperature of the air mixture sucked into the dryer (in degrees Celsius), T_{Na} is the temperature of the drying agent (in degrees Celsius), P_{HG} is thermal capacity of the heat generator (in kilojoules per mole) and i_{ENV} is enthalpy of the surrounding air (in kilojoules per mole).

The system of equations describing heat-mass exchange Eq. 2–8, together with algebraic Eq. 17–19 that determine the amount of fresh air sucked into the dryer, uniquely determines the relationship between the input and output variables of the drying channel, namely, temperature and moisture content of the product and of the drying agent. Therefore, in order to solve the problem of static optimization, it was sufficient to determine the relationship between the vectors of input and output variables.

To control the drying process of the established (static) mode in the tunnel dehydrator, the following technological parameters can be influenced:

- the air flow and temperature of the heat generator and fan,
- the stopping time of the drying cars τ_0 or their average speed in the drying chamber,
- the proportion of clean air β in the flow of exhaust gas supplied to the drying chamber.

The undetermined coefficients of the system of equations Eq. 2–5, which must be assessed as a result of identification, are as follows:

- ϕ_1 , the surface area of phase separation (per unit mass of dry matter moisture exchange) between the product and the drying agent (in square metres per kilogram),
- ϕ_2 , the heat transfer surface area per unit mass of dry product between the product and the drying agent (in square metres per kilogram),
- K_1, K_2 , coefficients of the convective drying speed,
- w_{CR} , critical humidity of Eq. 14 and Eq. 15 (in percent),
- K , coefficient of heat transfer between the product and the drying agent (in kilowatts per squared meter per degrees Celsius).

The other coefficients of the system were determined through calculation or by reference data.

For example, g (the amount of product dried in the drying chamber per unit of time) is calculated using Eq. 12.

The listed coefficients are included in the system of equations Eq. 2–5 as a product of $K_1\phi_1$, $K_2\phi_1$ and $K\phi_2$.

In accordance with Eq. 14 and Eq. 15, speed of the convective drying process is

$$w_{CR} = w_{EQ}(\varphi) + \frac{K_1}{K_2} [P_{aQ}(T_M) - \varphi P_{aQ}(T_a)] \quad (20)$$

Critical moisture content in many cases depends only on the ratio of K_1/K_2 . Therefore, it is appropriate to determine only three unknown parameters, specifically, $K_1\phi_1$, $K_2\phi_1$ and $K\phi_2$.

The experimental data processing algorithm, the solution of the problem of determining the undefined parameters of the system of Eq. 2–5, is reduced to the solution of minimization problem of the assessment criterion of the degree of error. In this case, the minimization equation is Eq. 21 (Tab. 1).

We solved the minimization problem of the criterion for evaluating the degree of the mean square deviation between the experimental results and the data of the solutions of the given

system of equations Eq. 2–5 by the Nelder-Mead direct search method after processing the experimental data using MS Excel (Microsoft, Redmond, Washington, USA), dynamic systems modelling by Matlab/Simulink program (MathWorks, Natick, Massachusetts, USA) and Optimization Toolbox package [22, 23]. When drying apricots in a tunnel-type dehydrator, we managed to obtain the following values of unknown parameters: drying coefficient in the first period $K_1\phi_1 = 0.8553 \times 10^{-4} \text{ kg}\cdot\text{m}^{-2}\text{s}^{-1}\text{°C}^{-1}$, drying coefficient in the second period $K_2\phi_1 = 0.3023 \times 10^{-4} \text{ kg}\cdot\text{m}^{-2}\text{s}^{-1}\text{°C}^{-1}$ and heat exchange coefficient $K\phi_2 = 0.0451 \text{ kW}\cdot\text{m}^{-2}\text{°C}^{-1}$.

Adequacy of the proposed mathematical model of the tunnel-type dehydration in the case of apricots drying could be judged based on 95–98 % compliance with experimental values, which can be clearly seen in Fig. 2 and on the curves presented in Fig. 3.

Fig. 2 illustrates that when drying apricots, the dependence of its equilibrium moisture content on relative humidity of the drying agent had “S” shape. In the first period of drying, as the relative humidity of the drying agent increased, the equilibrium moisture content of apricots increased rapidly, while the rate of change in the equilibrium moisture content of apricots within the range between 38 % and 76 % relative humidity of the drying agent decreased slightly. However, in the second period of drying, the rate of change in the equilibrium moisture content of apricots increased again and finally reached 28 %. This indicates that dehydration occurred more intensively under conditions of low relative humidity of the drying agent.

Fig. 3 shows that in the first period of drying (at 65–90 °C), equilibrium moisture content of apricots decreased rapidly with increasing the temperature. With further temperature increase (92 °C and more), the rate of decrease in equilibrium moisture content of apricots decreased (second period of drying). This indicated that

Tab. 1. The equation for minimizing the criterion for evaluating the degree of the mean square deviation between the experimental results and the data of the solutions of the given system of equations.

Function	Equation	Eq.
Minimizing the criterion	$\phi(a) = \sum_j \{p_j[w_j(1) - w'_j]^2 + q_j[y_j(1) - y'_j]^2 + r_j[T_{aj}(1) - T'_{aj}]^2\} \rightarrow \min$	21

where $a = (K_1\phi_1, K_2\phi_1 \text{ and } K\phi_2)$ is a vector of undefined parameters; j is the number of the experiment; $w_j(1)$, $y_j(1)$ and $T_{aj}(1)$ are the calculated values of humidity and temperature of the product and drying agent at the outlet of the drying chamber, obtained as a result of solving the system of heat-mass exchange equations Eq. 2–5; w'_j , y'_j and T'_{aj} are experimental data of humidity and temperature of the product and drying agent at the outlet of the drying chamber; p_j , q_j , r_j are given non-negative weight coefficients.

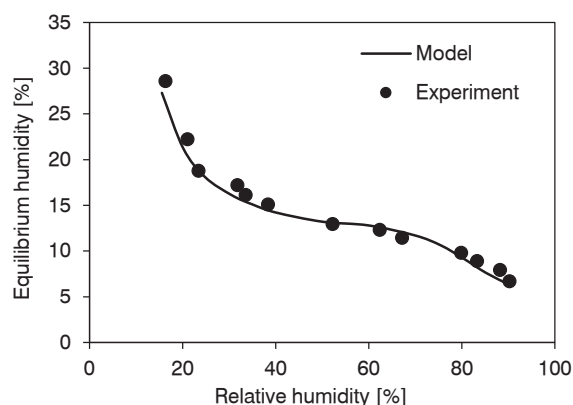


Fig. 2. The relationship between equilibrium humidity and relative moisture content of the drying agent during drying of apricots.

The chart shows a section of the curve.

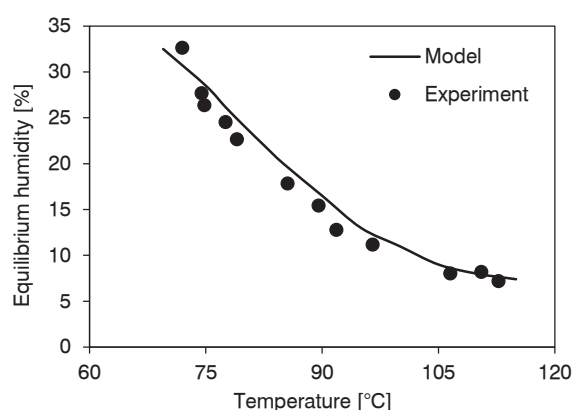


Fig. 3. The relationship between equilibrium moisture content and temperature of the drying agent during drying of apricots.

The chart shows a section of the curve.

evaporation of moisture from the deep layers of apricots was difficult and required an increased energy supply.

CONCLUSION

The mathematical model of the tunnel dehydration developed on the basis of the heat and mass exchange between the drying agent and the product can provide a reliable prediction of the drying speed and temperature distribution in the product, as well as the temperature and moisture content of the drying agent along the longitudinal coordinate of the tunnel dehydrator. The model represents the equilibrium moisture content ratio between air and the product. The developed mathematical model of the apricots drying process

with distributed parameters can be used to: determine the unknown parameters of the technological process of drying and solve the problems of optimal management of the static mode. Also, it can be used to determine the drying and heat exchange coefficients of various high-moisture fruits in the first and second periods of drying, as well as for developing the optimal management algorithm of the static mode of the tunnel drying process. The presented curves can also be used to determine the energy consumed in the drying process. The developed mathematical model will provide practical help to the designers of the industrial technology of fruit canning and the automated management system, as well as to the managers employed in this field in the decision-making process.

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