UDC 615.322
DOI: 10.15587/1729-4061.2023.273709

CREATION OF A METHODOLOGY FOR DETERMINING THE INTENSITY OF MOISTURE EVAPORATION WITHIN VACUUM DRYING OF FRUITS

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The study objects were the Republic of Kazakhstan selection apple sorts: "Baiterek", "Sarkyt" and "Saya", also pear sorts: "Syilyk", "Zhazdyk" and "Nagima". Study of the process of moisture evaporation within vacuum drying of the fruits has essential value in the nutritional value saving. Basically, the product evaporative capacity is characterized by the evaporation resistance coefficient – μ. Also during moisture removal, thermodynamic state of moisture changes that is described by water activity indicator – aw. Experimental determination of these parameters allows for the analyzing moisture evaporation during vacuum drying process. Studies have established the following evaporation resistance coefficients: μ=2.03±0.07 for apple sorts and μ=2.3±0.05 for pear sorts. Either water activity decreases from 1.0 to 0.62±0.01 for apple sorts and from 1.0 to 0.65±0.04 for pear sorts. Two drying periods are discovered. The first drying period: 5.45–6.10 h for apple sorts; and 6.12–6.25 h. for pear sorts. The second drying period duration: 4.15–3.50 h for apple sorts; and 4.35–4.48 h for pear sorts. The critical humidity value: 27.1±2.1 % for apple sorts; and 30.1±2.5 % for pear sorts. Comparative analysis of calculated and experimental data shows maximum deviations 22.5 % for apple sorts and 23 % for pear sorts. The proposed equation for the calculating a moisture evaporation rate, considering the product properties and the hygroscopic parameters of air, can be used in practice to study the moisture evaporation dynamics from the product surface. The study results allow for the selecting an optimal mode for vacuum drying of apples and pears sorts in order to safe nutritional value and to produce biologically active additives for the food industry

Keywords: evaporation resistance coefficient, moisture evaporation, water activity, vacuum drying, ultrasound

Received date 14.12.2022
Accepted date 15.02.2023
Published date 28.02.2023

***How to Cite**: Shingisov, A., Alibekov, R., Evlash, V., Yerkebayeva, S., Mailybayeva, E., Tastemirova, U. (2023). Creation of a methodology for determining the intensity of moisture evaporation within vacuum drying of fruits. Eastern-European Journal of Enterprise Technologies, 1 (11 (121)), 6–14. doi: https://doi.org/10.15587/1729-4061.2023.273709*

1. Introduction

The range of orchards in Republic of Kazakhstan is quite diverse and it is represented by well-known ancient and new domestic selection with excellent quality that is very adaptable for the growing conditions [1].

Created domestic varieties of fruit and berry crops are used as biologically active substances in the form of food additives in food products to enrich the composition of new functional foods [2]. Dried fruits, as concentrated forms of fresh fruits, are mainly consumed as finger food snacks due to their delicate organoleptic properties and high-energy foodstuff [3].

Drying is one of the oldest methods for food preservation that removes the water from fruit and makes it available for consumption throughout the year. The most frequent uses of drying technology include osmotic dehydration, vacuum drying, freeze-drying and different combinations of other drying technologies [4]. Drying methods significantly influence the quality of products. It is important to choose a suitable drying method to obtain high quality of dried product [5].

Currently, different drying methods are used in the food industry [6]. There are various methods to dry fruits such as convective, freeze, spray, foam mat, microwave, and vacuum drying [7].

Among these drying methods, from the point of view of preserving the original quality of the product, and especially the composition of biologically active substances, drying in a frozen state in a vacuum is a promising approach [8]. However, this method requires a long time and high energy costs.

Authors have experience in the promising vacuum-sublimation drying of food products at a low temperature [9]. The advantage of this drying method over traditional convection drying is as follows: the tightness of the drying chamber guarantees that the final product is not contaminated by dust from the surrounding air and oxidized by atmospheric oxygen [10]. Additionally, when drying products in a vacuum at a low temperature, their biologically active substance composition is not so disturbed [7]. It is known that in the process of drying food products in a vacuum due to the action of a certain driving (thermodynamic) force, complex non-stationary heat and mass transfer processes occur [11].

In this regard, a creation of the calculating methodology for the intensity of moisture evaporation from the surface of the product, taking into account changes in the properties of the product during drying and the hygroscopic characteristics of the drying agent, it allows to choose the optimal drying mode with maximum preservation of the original quality of the product. Therefore, the research in the evaluation of the moisture evaporation process during vacuum drying of fruits is relevant.

2. Literature review and the problem statement

Presently, limited studies are devoted for the development a methodology for determining the intensity of moisture evaporation from the surface of a product within vacuum drying.

In [12], it is considered the methodological issues of organizing complex natural observations to determine the amount of evaporation from the surfaces of freshwater ice and snow in modern conditions of the high-latitude Arctic. The results of the experimental application of the developed complex methodology for determining the amount of evaporation from freshwater ice surfaces are presented. However, only the regularities of moisture evaporation from the surface of pure water and ice are discussed in this work.

In the next work [13], a method for calculating the drying rate of a food product depending on the water activity, and determined by an analogue of the tissue moisture of the product in the industrial temperature range of refrigeration technology is proposed. This proposed method is applicable for analyzing the evaporation process in the range of negative temperatures, i. e. during freezing and storage of foodstuffs.

Further experimental verification on the example of test semi-finished products with various fillings showed that the difference between the calculated and experimental data on evaporation during cooling and freezing of these products was 5...10 % [14]. It is noted that the proposed method for calculating evaporation allows to determine the amount of evaporation during refrigeration of multilayer food products. However, the proposed method does not take into account the quality indicators of test semi-finished products with various fillings.

In the following work [15], it is noted that one product dried at different initial concentrations and/or drying modes (soft, hard) forms different kinetic types of curves. Specifically, during the drying of liquid dispersed products in the first period, as a rule, a change in the layer thickness is observed, and in the second period, the evaporation zone deepening inside the formed solid frame is possible. Thus, the main difficulty is the description of the new surface that appears as a result of the motion of the interphase boundary, which previously belonged to another phase. In this regard, it is proposed a numerical method for calculating the evaporation of moisture from the product surface.

In [16] it is studied fruit and jackfruit, namely are slices by thermodynamic analysis of the static patterns of mass and mass transfer in the identification of the influence of the nature of moisture binding with the dry residue on the quality of the resulting dry product with a decrease in its moisture content. For wet thermolabile materials that include the jackfruit fruit, in static equilibrium between the product and the environment, the water content in it in the hygroscopic state depends on the type and energy, humidity and a number of parameters, in particular, temperature and partial pressure of its vapor above the surface of the object. However, this method does not take into account the hygroscopic characteristics of air.

In classical thermodynamics, for the calculation of the heat and moisture transfer process, the driving (thermodynamic) force is chosen as the difference in the temperatures, pressures, density, concentration (moisture content), and other parameters. For example, in Fourier's law, the temperature gradient causes a heat flux $j=-L\cdot\text{grad}t$, and in Fick's law, the concentration gradient causes diffusion $j=-D\cdot\text{grad}C$, etc. [17].

In the authors' opinion, the use of the above thermodynamic parameters as a driving force always fully reveals the features of the mechanism of the laws of heat and moisture transfer during vacuum drying, since they are not related to the parameters characterizing the properties of the product.

The equilibrium state of the thermodynamic system "product-environment" can be identified based on not only thermal equilibrium but also the condition that the chemical potentials of the liquid and solid (gaseous) phases are equal. The chemical potential depends on the concentration of the substance in the phase and on the water activity. Therefore, the use of water activity to determine the patterns of heat and moisture exchange processes is justified, since this indicator is an integral indicator of the product property [9].

It is known that the surface of the product is not always covered with a film of pure water, and when it is dried, only some of it participates in evaporation. Additionally, during the drying process of the product, the evaporation surface can move in depth, forming cracks, crevices, channels, and capillaries in the dried layer, through which the vapor molecules torn off from the evaporation surface make a difficult path, overcoming the resistance of the dry layer additional hydraulic resistance. These circumstances are currently considered using the coefficient of resistance to evaporation – μ [7].

The currently existing methods for determining the coefficient of resistance to evaporation are based on different ideas about the physics of the process of evaporation of moisture from the surface. For example, as a result of studying the freeze-drying of meat products [18] proposed a method for determining the coefficient of resistance to evaporation as the ratio of the duration of sublimation for ice to the duration of sublimation for the product.

Conversely, it is proposed a method for determining the coefficient of resistance to evaporation as the ratio of theoretical shrinkage to its experimental values [19].

However, in the above-mentioned methods for the determining a coefficient of resistance to evaporation, the parameters describing changes in the quality indicators of the product are not linked to the thermodynamic parameters of dried air.

The coefficient of resistance to evaporation is a characteristic of a specific product, its chemical composition, structure, drying conditions, etc. Therefore, in the authors' opinion, to study the dynamics of changes in this coefficient, it needs to determine the dynamics of moisture evaporation during the product drying process directly from the experimental data.

Recently, many researchers involved in the field of drying food products have proved that one of the main parameters describing the changes in the quality indicators is a water activity indicator, and high-precision modern devices for its determination have been created [17].

It can be concluded that presently, in the existing methods for determining the intensity of moisture evaporation from the surface of vacuum drying product, the parameters characterizing the properties of the product are not linked to the hygroscopic parameters of air, also the additional hydraulic resistance of the dry layer to evaporation is not considered.

The paper [20] presents the moisture evaporation rate of the of blanched apple slices within natural convection, where it is proposed following equation:

$$n_w = \frac{Q_{rev}}{r_w \cdot S},$$

where Q_{rev} – heat flux by evaporation, determined from the energy transfer balance equation, W;

r_w – heat of vaporization of water, kJ/kg;

S – area of the entire surface of the sample of the dried material, m^2.

The weakness of this equation, that it does not take into account the qualitative parameters of the dried product.

Thus, presently in the known approaches for determining the intensity of moisture evaporation, most researchers do not take into account the influence of the resistance of the dry layer formed during drying on the one hand and do not correlate the hygroscopic characteristics of air on the other hand. Therefore, the creation of a methodology that takes into account the above parameters is an urgent task.

3. The aim and objectives of the study

The aim of the study to create a methodology for determining the intensity of moisture evaporation within vacuum drying of fruits, taking into account the properties of the dried product and the effect of dry layer resistance, linked to the hygroscopic parameters of air.

To achieve this aim, the following objectives are accomplished:

– to study the dynamics of moisture evaporation during vacuum drying of fruits;

– to determine the water activity indicator during vacuum drying of fruits;

– to apply of the proposed method for the calculation an intensity of moisture evaporation from the surface of the product.

4. Materials and methods of research

4. 1. Objects and hypothesis of the study

The objects of the study were apple sorts, namely, "Baiterek" (No. 1), "Sarkyt" (No. 2), and "Saya" (No. 3), and pear sorts, namely, "Syilyk" (No. 1), "Zhazdyk" (No. 2), and "Nagima" (No. 3) freshly picked in the September-October, 2022.

For the measuring of water activity value, a water activity analyzer-AQUA LAB4TE-was applied (Germany).

The relative humidity of the air in the chamber was measured by using a TESTO 635-2 temperature and humidity-measuring device. For measuring the mass of the product during the drying process, a laboratory electronic balance of the CAS MWP-300H (Germany) brand was used.

Presently, various drying methods are used to obtain a dry product. Within drying, a complex heat and mass transfer processes occur that are characterized by simultaneous processes of evaporation of moisture from the surface and diffusion of moisture from the inner layers of the product, as a result of which the properties of the product change. The currently proposed methods for calculating the evaporation of moisture during drying of products, the parameters characterizing changes in the product properties are not linked to the hygroscopic characteristics of the drying agent. Therefore, a creation of such techniques allows for the choosing an optimal drying mode with maximum preservation of the product original quality.

4. 2. Description of the experimental setup

The unified experimental setup consists of two blocks that are assembled into a single frame (Fig. 1).

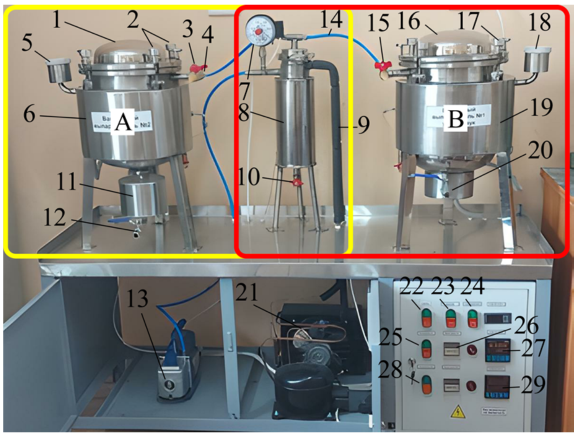


Fig. 1. The unified experimental setup: 1 – device cover; 2 – cover valves; 3 – valve for air intake; 4 – vacuum valve; 5 – expansion tank; 6 – vacuum chamber of the device; 7 – vacuum manometer; 8 – desublimator; 9 – cooling tube; 10 – drain cock; 11 – container for collecting liquid; 12 – valve for draining liquid; 13 – vacuum pump; 14 – air inlet valve; 15 – vacuum valve; 16 – device cover; 17 – valve cover; 18 – expansion barrel; 19 – vacuum chamber; 20 – ultrasonic installation; 21 – refrigeration unit; 22 – switch; 23 – remote control for turning on the vacuum pump; 24 – remote control for switching on the ultrasonic device; 25 – remote control for turning on the electric heating element; 26 – water temperature controller; 27 – electronic water temperature sensor; 28 – remote control for turning on the electric heating element; 29 – water temperature controller in a low-frequency vacuum ultrasonic device

The unified experimental setup consists of two blocks that are assembled into a single frame. Block A (1–13) is vacuum dryer and Block B (14–30) is low-frequency vacuum ultrasonic device. There are common for both blocks: desublimator, vacuum pump and chiller.

4. 3. The procedure for conducting an experiment with a vacuum evaporator

Before carrying out experiments with a vacuum evaporator, it is necessary to bring it to operating mode. To capture water vapor evaporating from the product being dried, the refrigeration machine is first turned on, cooling the desublimator of the vacuum evaporator. Then, having previously set the required temperature of the water jacket of the cylindrical body on the control panel, usually about T=+40 °C, the vacuum chamber heating system is turned on. Upon reaching the specified water temperature in the cylindrical body (T=+40 °C) and the temperature in the sublimator (from T=–20 °C and below), the vacuum evaporator is ready for operation. Afterward, the chamber of the vacuum evaporator is loaded with the product previously prepared for vacuum drying. Preparation of the product to be dried is carried out as follows. Before drying, the product is thoroughly washed in running cold water and subjected to mechanical cleaning, and the core of the product is removed from it, i. e., seeds. Furthermore, if the product is dried in pieces, then it is cut with a thickness of 2.7–3 mm in the form of a half ring and placed in a mesh cylindrical baking sheet, and if it is dried in the form of a paste-like mass. Then, it is first cut into slices and crushed in a mill until a state of a paste-like liquid mass and then poured into cylindrical baking sheets of the apparatus with a thickness of 2.5–3 mm. Then, the trays with the product are placed in a tiered pit in a vacuum chamber, and the vacuum pump is turned on by closing the chamber lids.

At the end of the experiment, the vacuum evaporator is switched off in reverse order. First, after turning off the vacuum pump, the refrigeration unit, and the power supply, the vacuum evaporator lid is opened by allowing air into the vacuum evaporator through an open valve. After unscrewing the lid valves, the baking sheets are removed in ascending order, one at a time. After separating the baking sheets from the dry product, the latter is subjected to milling to a fraction of the order between 0.7 and 1 mm.

4. 4. Moisture transfer from the surface of the products during drying

The transfer of moisture from the surface of the product during vacuum drying is a complex process and is still not well understood. When studying the phenomenon of moisture transfer, many authors expressed conflicting opinions, both in the interpretation of the physical essence of the process and in the choice of the method for calculating the main mass transfer characteristics.

The transfer of moisture from the surface of the product during drying in a vacuum is largely determined by the thermodynamic state of the water located on the surface layer of the product.

According to the principle of non-equilibrium thermodynamics during drying, dry air should diffuse toward the water vapor diffusing from the inner layers of the product to the phase transition surface, which is an insurmountable obstacle for it [15]. Consequently, the concentration of dry air near the surface increases, which, under certain conditions, leads to the appearance of the effect of a convective flow, called the Stefan flow. With this in mind, the intensity of moisture transfer from the body surface, considering both convective and diffusion vapor flow is determined by the Dalton equation:

$$j=\sigma_s\left(d''_s-\varphi\cdot d''_a\right), \tag{1}$$

where σ_s – the coefficient of moisture evaporation from the water surface, kg/(m^{2}s);

d''_s, d_a – the moisture content of saturated air on the water surface and away from it (air), respectively.

As known, the surface of the dried product is not always covered with a film of pure water. Additionally, during the drying, the moisture evaporation zone can move in depth, which creates additional hydraulic resistance, and evaporation does not occur from pure water but from a solution with a complex composition, which, according to Raoult's law, also affects the intensity of moisture exchange. All of the above circumstances are considered using the drag coefficient evaporation, i. e.

$$\mu=\frac{\sigma_s}{\sigma_n}. \tag{2}$$

Then, (1) by considering (2) takes the form

$$j=\left(\sigma_s/\mu\right)\left(d''_s-\varphi\cdot d''_a\right). \tag{3}$$

At a low partial pressure of water vapor and a small temperature difference between the dried product and its environment, the relationship between heat and mass transfer is established by the well-known Lewis relation [7]:

$$\frac{\alpha}{\sigma_s}=C_p, \tag{4}$$

where C_p – the isobaric heat capacity of air, J/(kg K).

Presenting the moisture content d''_w and d''_s through the partial pressures of water vapor P_w and P_s and barometric pressure In and considering the Lewis relation (4), equation (3) takes the form

$$j=0.622\cdot\frac{\alpha}{\mu C_p}\left[\frac{P_s^*-\varphi\cdot P_w^*}{\dot{B}}\right]\cdot f, \tag{5}$$

or

$$j=0.622\cdot\frac{\alpha}{\mu\cdot C_p}\cdot\frac{P_s^*}{\dot{B}}\left(a_w-\varphi\right)\cdot f, \tag{6}$$

where φ – the relative air humidity, %;

$\frac{P''_s}{B}$ – pressure criterion characterizing the effect of total pressure on the drying process;

a_w – water activity, %;

a – coefficient of heat transfer from the product surface to its environment, i. e., air, W/(m^{2}K);

f – area moisture exchange, m^2.

Along with the driving force behind the process of moisture transfer from the surface of the dried product is important the difference between the water activity index and the relative air humidity, i. e., expression (a_w–φ).

Since the relative humidity of the air and the water activity in the product change the drying of products in a vacuum, then an average value (a_w–φ) is usually used as the average logarithmic difference in the driving force.

$$(a_w-\varphi)=\frac{(a_i-\varphi_i)-(a_f-\varphi_f)}{\ln\dfrac{(a_i-\varphi_i)}{(a_f-\varphi_f)}}. \tag{7}$$

Denoting the expression before the bracket in equation (6) $\chi=0.622\dfrac{\alpha_T}{\mu\cdot C_s}\cdot\dfrac{P''_a}{B}$ by χ and substituting expression (7) into equation (6), the intensity of moisture transfer from the surface of the product is calculated:

$$j=\chi\cdot\frac{(a_i-\varphi_i)-(a_f-\varphi_f)}{\ln\dfrac{(a_i-\varphi_i)}{(a_f-\varphi_f)}}, \tag{8}$$

where a_t is the coefficient of thermal accommodation (a_t=1.0 W/(m^{2}K) and $ƛ$ is the coefficient characterizing the moisture transfer rate, kg/(m^{2}s).

Analysis of the operating mode of the installation for vacuum drying of food products shows that the value of the relative humidity of the air in the chamber fluctuates insignificantly during the entire drying period, i. e., during the drying process due to the constant removal of water vapor using a vacuum pump; the relative humidity of the air in the chamber can be considered as a constant value.

Given the above, the equation for calculating the intensity of moisture transfer from the surface of the product (8) will take the following form:

$$j=\chi\cdot\frac{(a_i-a_f)}{\ln\dfrac{(a_i-\varphi)}{(a_f-\varphi)}}. \tag{9}$$

Representing the intensity of moisture transfer as the difference between water activity and relative air humidity, in the authors' opinion, most objectively reveals the physical meaning of the moisture transfer mechanism and, most importantly, explains the direction of the process.

To determine the intensity of moisture transfer from the surface of the product during the drying of fruit and berry crops in a vacuum, it needs to locate the patterns of change in the coefficient μ and a_w of the water activity indicator, and the remaining parameters do not change significantly during the drying process, and therefore in calculations can be taken as a constant value.

Unfortunately, presently, an analytical dependence on the nature of the relationship between the coefficient of resistance to evaporation μ and the water activity of the product a_w has not been established. Therefore, in this work, based on experimental data on the drying of domestic sorts of apples and pears, the nature of the relationship between the coefficient of resistance to evaporation μ and water activity a_w are analyzed.

4. 5. Method for determining the coefficient of resistance to evaporation, μ, and water activity, a_w

Before drying, each product sample should be weighed and the reading of the electronic weight is logged; then, some part is taken from this product to determine the water activity indicator. To study the regularity of the dynamics of moisture evaporation from the surface of the product during the drying process, from time to time, stopping the installation, the trays with the product are taken out and weighed. The obtained data on the change in the mass of the product are recorded in the log. Furthermore, some parts are taken from this product to determine the water activity corresponding to this drying time. Experiments on weighing the tray with the product and determining the water activity indicator are continued until the difference in the mass of the tray with the product between the previous weighing reaches a constant mass or the difference should not be more than a hundredth of a fraction.

Furthermore, knowing the experimental data on the dynamics of moisture evaporation from the surface of the product and the patterns of change in the water activity index, from (9), the numerical values of the evaporation resistance coefficient are determined.

The moisture content of the product at the current time is calculated (10):

$$W_p=\frac{G_i\cdot(G_i-G_p)}{G_i}\cdot 100\,\%, \tag{10}$$

where W_p – the humidity at the time of measurement, %;

G_i – the initial weight of the dried product, g;

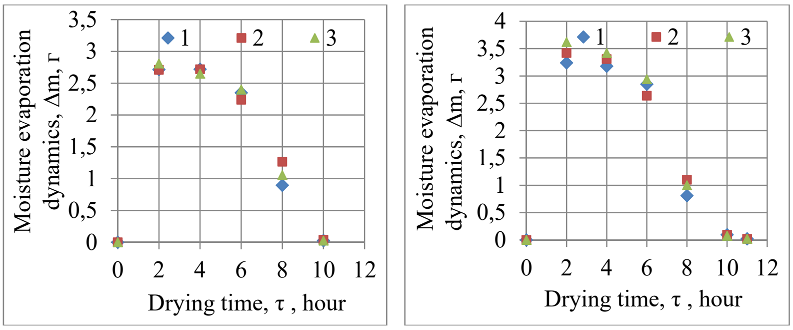
G_p – the mass of the dried product at the time of measurement, g.

5. Results of moisture evaporation within vacuum drying of fruits

5. 1. Experimentally study the dynamics of moisture evaporation within vacuum drying of fruits

The study results of the dynamics of moisture evaporation from the surface of the products are shown in Fig. 2.

Specifically, Fig. 2 shows that during the drying period of the product, the dynamics of moisture evaporation from the surface of the product are not the same: at the initial stage it has a maximum value, and then, in the time interval between 2.0 h...6.0 h, the same amount evaporates on average with slight difference moisture. Furthermore, in the time interval between 6.0 h...11.0 h, the rate of evaporation decreases monotonically.

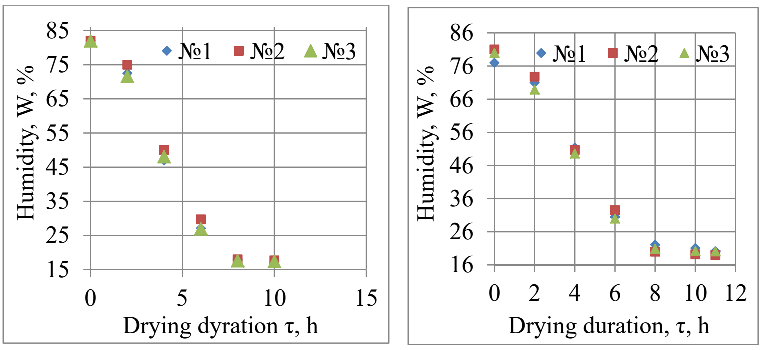


a *b*

Fig. 2. Dynamics of moisture evaporation from the surface: *a* – apple sorts; *b* – pear sorts

Analysis of Fig. 2 shows that in a dry product, the dynamics of moisture evaporation with a surface product is not the same: in the initial period of drying, it is of great importance, and in the interval between 2.0 h...6.0 h it evaporates on average with a slight difference in general amount of moisture. Further, in the time interval between 6.0 h...11.0 h, the rate of evaporation monotonously dissipates.

Fig. 2 also shows that for an apple (*a*) in the first 4 h of drying, the dynamics of moisture evaporation from the surface of the product average 2.71 g, and for the next 2 h, it decreases monotonically to 2.31 g. The same picture of moisture evaporation dynamics is observed for pears. For example, in the first 4 h of drying, the dynamics of moisture evaporation average 3.41 g, and in the next 2 h of drying time, the evaporation dynamics decrease to 2.78 g. Such a difference in the dynamics of moisture evaporation in products is explained by the structural structure and its form of moisture bonding in the product. After reaching the time of 6 h of drying, the dynamics of moisture evaporation in both studied products have a monotonically decreasing character.



a *b*

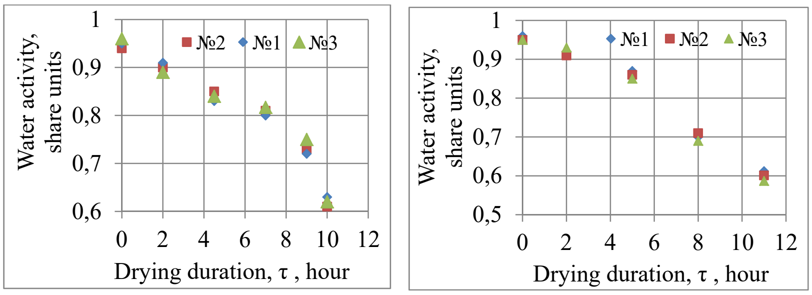
Fig. 3. Drying curves: *a* – apple sorts; *b* – pear sorts

Based on experimental data, the dynamics of moisture evaporation have constructed the relationship between the average moisture content of the material and the drying duration. The study results of the drying process changing are shown in Fig. 3.

Analysis of Fig. 3 shows that during vacuum drying of both apples and pears, the well-known regularity in the theory of food drying is observed: i. e. drying consists of two periods. In the first period: drying for equal periods of time, the same amount of moisture evaporates, i. e. period of constant drying rate (humidity at the end of the period 27.1±2.1 % for apple sorts, and 30.1±2.5 % for pear sorts). After reaching the hygroscopic moisture W_{cr} (27.1 % for apple sorts, and 30.0 % for pear sorts) of the product, the nature of moisture evaporation is changed. The duration of the first drying period 5.45 h...6.10 h for apple sorts, and 6.12 h...6.25 h for a pear sorts. The duration of the second drying period 4.15 h...3.50 h for an apple sorts, and 4.35 h...4.48 h for pear sorts.

5. 2. Experimentally determination a water activity index within vacuum drying of fruits

Fig. 4 shows the results of the study of water activity in the drying process of apple sorts and pear sorts.



a *b*

Fig. 4. Dependence of water activity on drying duration: *a* – apple sorts; *b* – pear sorts

Analysis of Fig. 4 shows that during the drying process of both apple sorts and pear sorts, the water activity index changes ambiguously: in the first four hours of the drying time, it monotonically decreases, and the subsequent drying time drops sharply. For example, if for apple sorts the decrease in water activity in the first four hours of drying is on average 1.14–2.27 %, then for pear sorts this indicator is 1.30–3.04 %. The dynamics of changes in activity in the time interval from four hours to the end of the drying process shows that a sharp decrease in water activity. For example, for apple sorts in the period 6 h...8 h of drying time, the water activity indicator decreases by 5.36–7.59 %, and at the end of the drying period its value reaches 22.38–25.01 %, and for a pear in the period 6 h...8 h of drying time, the water activity decreases by 6.57–9.86 %, and subsequent periods of time decrease by 14.75–20.44 %.

Thus, based on the above data, it can be concluded that when the water bound moisture is removed from the product, the changes in water activity become monotonically decreasing. After reaching the critical humidity W_{cr}, and before the end of the period of falling drying, the activity of water has a non-linear broken character. The obtained data prove the reliability of the methodology for conducting the experiment and determining the activity of water in experiments.

The results of the mathematical processing of experimental data using the "Microsoft Excel" software (Microsoft Corporation, USA) made it possible to describe the dependence of the coefficient of resistance to evaporation on the activity of water by an equation of the following form:

$$\mu = \frac{0.924}{a_w}. \tag{11}$$

Based on the above-mentioned data, it can be concluded that a noticeable increase in the values of the evaporation resistance coefficient occurs after the first drying period, i. e., after removing the free bound in the product. This conclusion proves the existence of cracks, crevices, channels, and capillaries in the dried layer, which prevent the free movement of the vapor molecule detached from the evaporation surface, causing an increase in the value of the coefficient of resistance to evaporation.

To verify the reliability of the experimental data obtained, the evaporation resistance coefficient was compared with the literature data of other researchers.

5. 3. Application of the proposed method to calculate the intensity of moisture evaporation from the product surface

Application the experimental data of the coefficient of resistance to evaporation and water activity, according to (9), the dynamics of moisture evaporation from the surface of apple sorts and pear sorts is calculated. The obtained calculated data are compared with experimental data. As an example, Table 1 presents the results of comparing the calculated data on the dynamics of moisture evaporation from the surface of apple sorts and pear sorts.

Table 1

Comparison of calculated data with experimental data

Product	Type of data	Mass of evaporated moisture during drying, g/(h·m^2)							Amount, g/(h·m^2)
		0	2	4	6	8	10	11	
Apple									
No. 2 (Sarkyt)	experimental	0	2.71	2.72	2.24	1.26	0.40	0.25	9.58
	calculated	0	2.69	2.57	2.11	1.41	0.31	0.20	9.29
Deviations, %		0	1.0	5.51	5.80	11.89	22.5	20.0	3.03
Pear									
No. 1 (Syilyk)	experimental	0	3.24	3.18	2.85	0.81	0.10	0.020	10.20
	calculated	0	2.52	2.45	2.52	0.94	0.12	0.023	8.573
Deviations, %		0	22.0	23.0	11.5	15.6	16.7	16.8	15.06

The analysis of tabular data shows, the maximum deviation of the calculated and experimental data on the dynamics of moisture evaporation from the surface are for apples is 22.5 %, and for pears, 23 %. Comparative analysis of the amount of evaporated moisture from the surface of the product during the drying process shows that the deviations between these data are within the experimental error. Some deviations from the calculated and experimental data are explained by the accepted assumption that some physical quantities included in (9) are constant.

As an example, it can be considered methods for determining the mass of evaporated moisture from the surface of an apple in two hours between 4 h...6 h of drying.

First, it is determined the values of the coefficients included in the equation:

$$\chi = 0.622\cdot\frac{\alpha}{\mu\cdot c_p}\cdot\frac{P_s^*}{B}\cdot f. \qquad (12)$$

In calculating the values of the coefficient, it was taken equal to α_T=1 W/(m^2·K).

The heat capacity of air at constant pressure is C_p=1.0048 kJ/(kg·K).

According to the reference table, the value of the partial pressure of saturated water vapor at a temperature of 40 °C is P_s''=12350.7 Pa. The barometric air pressure is B=101 325 Pa. The area of the Petri dish (D=0.12 m) is f=0.0113 m^2.

Based on the numerical values of the parameters, the value of the coefficient characterizing the rate of moisture transfer was calculated, i. e.,

$$\begin{gathered}\chi=0.622(1/(1.10\cdot1010))\cdot(12350.7/101325)\text{x}\\ \text{x}0.0113\cdot3600\cdot10^3=2.778\text{ g/h.}\end{gathered}$$

Furthermore, knowing the values of χ and a_w and ϕ using (9), the masses of the evaporated during the drying process for 2 h between 4 h...6 h can be determined:

$$\begin{gathered}j=2.778\cdot((0.95-0.80)/(\ln(0.95-0.11)/(0.80-0.11))=\\ =2.11\text{ g/h.}\end{gathered}$$

An example of determining the mass of evaporated moisture for two hours between 6 h...8 h of the drying time of apple sorts is shown.

At the beginning, the value of the coefficient characterizing the rate of moisture transfer is calculated, i. e.,

$$\begin{gathered}\chi=0.622(1/(1.57\cdot1010))(12350.7/101325)\text{x}\\ \text{x}0.0113\cdot3600\cdot10^3=1.95\text{ g/h.}\end{gathered}$$

Then, the mass evaporated during the drying process for two hours between 6 h...8 h

$$\begin{gathered}j=1.95\ ((0.95-0.75)/(\ln(0.95-0.11)/(0.75-0.11))=\\ =1.43\text{ g/h.}\end{gathered}$$

Now, the calculation masses that have evaporated moisture from the surface of the pear in two hours between 2 h...4 h of drying time are considered.

The value of the coefficient characterizing the rate of moisture transfer is determined, i. e.,

$$\begin{gathered}\chi=0.622(1/(1.10\cdot1010))\cdot(12350.7/101325)\text{x}\\ \text{x}0.0113\cdot3600\cdot10^3=3.056\text{ g/h.}\end{gathered}$$

Considering the values of χ mass of moisture evaporated during the drying process for two hours between 2 h...4 h of drying time

$$\begin{gathered}j=3.056\ ((0.96-0.91)/(\ln(0.96-0.11)/(0.91-0.11))=\\ =2.52\text{ g/h.}\end{gathered}$$

As an example, the calculation of the mass of evaporated moisture during the drying process for two hours between 6 h...8 h of drying time is considered.

The value of the coefficient characterizing the rate of moisture transfer is calculated, i. e.,

$$\begin{gathered}\chi=0.622(1/(1.2\cdot1010))\cdot(12350.7/101325)\text{x}\\ \text{x}0.0113\cdot3600\cdot10^3=2.55\text{ g/h.}\end{gathered}$$

Then, the mass of evaporated moisture during the drying process for two hours between 6 h...8 h of drying time:

$$\begin{gathered}j=2.55\cdot((0.96-0.82)/(\ln(0.96-0.11)/(0.82-0.11))=\\ =2.52\text{ g/h.}\end{gathered}$$

Thus, the above stated shows that (9) can be used in practice to study the general dynamics of moisture evaporation from the product surface during the vacuum drying of products.

6. Discussion of the results of the study of moisture evaporation within the vacuum drying of the fruits

The obtained data (Fig. 2) indicate that the largest amount of moisture is released from the product during the first six hours of drying time. Further, the dynamics of evaporation monotonically decreases. For apple sorts, in the interval from 1.5...6 h, an average of 2.47 g evaporates, while for pear sorts such value is 3.01 g.

The analysis of the drying curves (Fig. 3) shows that fruit drying consists of two periods. At the border of periods, the critical humidity for apple sorts is 27.1±2.1 %, and for pear sorts 30.1±2.5 %.

The results of the study presented in Fig. 4 show that the dependence of the coefficient of resistance to evaporation on water activity is non-linear.

The obtained experimental data allow for the calculating the evaporation intensity during fruit drying that can be seen from Table 2. The discrepancy between the calculated and experimental data is 22.5 % for apple sorts and 23.0 % for pear sorts. The deviations of the calculated and experimental data are explained by the accepted assumption that some physical quantities are constant.

The results of comparing the calculated data with the experimental data indicate that the proposed equation qualitatively describes the dynamics of moisture evaporation from the surface of the product during the vacuum drying of products.

Some discrepancies between the calculated data and the experimental data are explained according to the accepted assumptions about the constancy of some physical quantities included in the equation for calculations. Further for the application of the study results in the industrial production, the differences in devices should be considered, and the experimental verification is required. Also, the cost of different drying equipment was not discussed in this work. Therefore, the actual realization of the study results is related for the available technological conditions.

The distinctive feature of the proposed method for calculating the moisture evaporation within vacuum drying of the products in comparison with existing ones [16] that in the proposed method, the difference between the water activity and the relative humidity of the air is chosen as the driving force of heat and mass transfer processes. In addition, in the proposed method, changes in the properties of the product during the drying process are taken into account by the thermodynamic indicator of water activity.

In the proposed method for the calculating moisture evaporation during vacuum drying of the product, the boundaries, conditions and reproducibility of the results are determined with degree of accuracy the regression equations that describing the coefficients included in the obtained equation.

The proposed method for calculating moisture during vacuum drying of a product has limited practical application due to the lack of the resistance coefficient dependence on water activity for other types of fruit products.

The disadvantage of the proposed method for calculating the evaporation of moisture during vacuum drying of the product is the use of the coefficients of experimental data included in the equation.

Thus, it can be concluded following: taking into account the properties of the product and the hygroscopic parameters of air, the proposed equation for calculating the moisture evaporation from the surface of the product can be used in practice for study the dynamics of moisture evaporation from the surface of the product during its vacuum drying of products. The proposed equation for calculating the evaporation rate of moisture from the surface of the product, considering the properties of the product and the hygroscopic parameters of air, it can be used in practice to study the dynamics of moisture evaporation from the surface of the product, during the vacuum drying.

In the further studies, the authors will be engaged in the establishment of the analytical relationship between the coefficient of resistance to evaporation and the thermodynamic indicator of water activity included in the equation for calculating the evaporation of moisture during vacuum drying of the product. Because the vacuum drying process of the product, the regularities of changes in the above parameters depend by many factors. Therefore, in order to establish an analytical relationship between the coefficient of resistance to evaporation and the thermodynamic indicator of water activity, it will be used the laws used in the theory of non-equilibrium thermodynamics.

7. Conclusions

1. By experimental studies are established that at the initial stage of fruit drying, the evaporation rate has a maximum value, and then, in the time interval between 2 h ... 6 h, the same amount of moisture evaporates on average with a slight difference. Further, in the time interval between 6 h ... 11 h, the rate of evaporation decreases monotonically.
2. Results indicated that in the process of fruit drying, the water activity a_w, which characterizes the properties of the product, decreases: for apple sorts from 1.0 to 0.62±0.01, for pear sorts this indicator decreases from 1.0 to 0.65±0.04.
3. Comparative analysis showed that the maximum deviation of the calculated data calculated according to the proposed method for calculating the dynamics of moisture evaporation from the surface during the drying process compared with the experimental data for apple sorts is 22.5 %, and for pear sorts is 23 %.

Investigations established that the theoretical dependence of evaporation resistance coefficient on the water activity is non-linear, i.e. the graph of the functional dependence is hyperbolic with convex upwards. The dependence has inversely proportional specificity, i.e. with a decrease in water activity, the evaporation resistance coefficient increases, and vice versa, with an increase in water activity, the evaporation resistance coefficient decreases.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

Financing

The study was performed by the financial support of the “Ministry of Agriculture of the Republic of Kazakhstan” for the research project “Development of technology for processing promising varieties of fruit, berry crops and grapes of domestic selection in order to obtain biologically active substances and fruit and berry powders for use in the food industry” within the framework of Programme Targeted Funding No. BR10764977.

Data accessibility

Data will be provided upon founded request.

Acknowledgment

The authors gratefully acknowledge the "Ministry of Agriculture of the Republic of Kazakhstan" for the financial support of the research project "Development of technology for processing promising varieties of fruit, berry crops and grapes of domestic selection in order to obtain biologically active substances and fruit and berry powders for use in the food industry" within the framework of Programme Targeted Funding No. BR10764977.

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