UDC 66.047.3.049.6+615.322
DOI: 10.15587/1729-4061.2023.282389

CREATION OF A METHODOLOGY FOR DETERMINING THE MOISTURE DIFFUSION COEFFICIENT WITHIN VACUUM DRYING OF FRUITS

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As the drying zone deepens, outer surface layer of the product does not have time to be moistened, due to a small amount of moisture coming from the inside. It becomes dry, its temperature rises. The intensity of moisture transfer from the inner layers of the product depends on many parameters, including a moisture diffusion coefficient. The study aim is to create a methodology for determining the moisture diffusion coefficient within vacuum drying of fruits, by taking into account cracks, channels and capillaries formed in the dry layer of the product through the resistance coefficient to evaporation. The work essence consists in the determining of the moisture diffusion coefficient as a driving force, a difference between water activity and air humidity, by considering the resistance coefficient to evaporation, characterizing the effect of hydrodynamic resistance of the dried dry layer of the product. This approach was used to determine the moisture diffusion coefficient during vacuum drying of the Baiterek apple sort and the Zhazdyk pear sort of Kazakhstani selection. It was established that in the first period of drying the moisture diffusion coefficient decreases on average from $24{,}4\cdot10^{-7}$ m^2/s to $13{,}2\cdot10^{-7}$ m^2/s. The critical humidity for pear is 37.4 %, and for apple 35.1 %. As result of the formation of dry layer on the surface and subsequent layers, the moisture diffusion coefficient gradually decreases. In the second drying period, the moisture diffusion coefficient decreases from 5,42·10-8 m^2/s to $2{,}12\cdot10^{-8}$ m^2/s. The work practical significance is related with the application of the obtained results in the determination of the optimal drying regime with maximum preservation of the product original quality. The proposed methodology can be used in the practice to study the moisture diffusion coefficient within vacuum drying of fruits, by considering the product properties and the hygroscopic parameters of the drying matter

Keywords: evaporation resistance coefficient, humidity, model with a moving boundary of the dry and wet state of the material, thermodynamic, water activity

Received date 12.04.2023
Accepted date 19.06.2023
Published date 30.06.2023

***How to Cite**: Shingisov, A., Alibekov, R., Evlash, V., Yerkebayeva, S., Mailybayeva, E., Tastemirova, U. (2023). Creation of a methodology for determining the moisture diffusion coefficient within vacuum drying of fruits. Eastern-European Journal of Enterprise Technologies, 3 (11 (123)), 24–32. doi: https://doi.org/10.15587/1729-4061.2023.282389*

1. Introduction

In recent years, as a result of the support of small and medium-sized businesses in the agro-industrial sector by the government of the Republic of Kazakhstan, the areas of fruit and berry crops are increasing annually. In the general structure of domestic pome and stone fruit plantations, apple and pear trees are prevail [1].

Mostly, grown domestic fruit and berry sorts are used as biologically active substances in the form of food additives in the food products to enrich the composition of new functional foods [2].

As known, fruits and berries are seasonal products. During the ripening period of fruits and berries, many peasant farms delivery the grown products by supply chain systems to the various consumers or markets. However, one of the important issues is the preservation of quality and nutritional value of the products that allows them to be stored within a long time [3].

One of the approaches for the saving nutritional values of raw materials is extraction. Currently, in the food industry, for the extraction of complex nutrients from the plant raw materials are various extraction methods apply that differ in the nature of the extractant (water, water-alcohol mixture, buttermilk) the method of physical [4].

In addition, many food producers for the enrichment purposes use dry powders or dried fruits and berries in the production of new products, including dietary and nutritional purposes [5].

Drying methods significantly influence the quality of products. It is important to choose a suitable drying method to obtain high quality of dried product [6].

The applied drying method is essential for the saving a qualitative composition of dry powders or dry fruits and berries [7, 8].

Authors have experience in the promising vacuum-sublimation drying of food products at a low temperature [1]. 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 [9]. Additionally, when drying products in a vacuum at a low temperature, their biologically active substance composition is not so disturbed. 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 [10].

In the physical sense, drying is a complex diffusion process, the rate of which is determined by the rate of moisture diffusion from the depth of the material being dried into the environment [10].

As the drying zone deepens, the outer layer of the surface of the product does not have time to be moistened, due to a small amount of moisture coming from the inside. It becomes dry, its temperature rises. The intensity of moisture transfer from the inner layers of the product depends on many parameters, including the moisture diffusion coefficient. The correct determination of the moisture diffusion coefficient depends not only on the qualitative composition of the dried product, but also has influence on the energy saving for the drying process or a product cost value decreasing. Therefore, improving the methodology for determining the moisture diffusion coefficient during vacuum drying of fruits is one of the actual tasks in the food processing industry.

2. Literature review and problem statement

In the previous work [1] the authors have considered the development a methodology for determining the intensity of moisture evaporation from the surface of a product within vacuum drying. Along with the difference in the physical parameters of the product (temperature, pressure, density, concentration, and other parameters) and the environment, moisture moves from the deep layers of the product into its environment. But there were unresolved issues related to the intensity of moisture transfer from the inner layers of the product depends on many parameters, including a moisture diffusion coefficient.

It is known that all types of diffusion satisfy the same laws. The diffusion rate is proportional to the cross-sectional area of the sample, the difference in concentration and temperature, as well as a parameter characterizing the properties of the specific product [10].

In the next work [11] it is noted the bases of the moisture transfer regularities in the product are related for the Fick's law, which is related to the distribution of concentration of matter in the space with its flows that in turn makes it possible to fully describe the dynamics of the transfer of matter in time and as a result of solving the so-called diffusion equation.

Shown, that in the classical thermodynamics, various analytical and numerical methods for the solving the moisture diffusion equation are available [12].

Meanwhile, each of the proposed analytical methods [9] for the calculating moisture diffusion is specifically related to the initial physical layout of the process, it is initial and boundary conditions, specified in a particular form. In addition, in analytical methods for the solving of the diffusion equations, they were obtained for the correct geometric shape: a plate, a cylinder and a ball, with the assumption of the constancy of a number of thermophysical parameters of the object under study.

A way to overcome these difficulties can be applicability of analytical methods in the determination of the diffusion equation concerned for the solving of this problem by using the numerical methods. Presently, a large number of the numerical methods and various computational capabilities are known that based on the replacement of temperature derivatives with respect to time and coordinates by finite differences. The numerical methods advantage is the absence of restrictions on the initial and boundary conditions of the problem and on their applicability to the objects of complex shape. However, the numerical methods application requires relatively powerful electronic computers [10, 13].

In [14] it is studied the moisture transfer process in raw gingerbread with fruit filling, by using various types of modified starch according to the diffusion factor. It is discovered that a moisture transfer rate is minimal for modified starch, which is confirmed by the lowest diffusion coefficient: 1097. The proposed solution for predicting the preservation of raw gingerbread with fruit filling is based on the study results of moisture transfer processes and the characteristics of moisture-retaining applications (modified starch) and it is applicable for analyzing a moisture diffusion coefficient via the packaging of materials for gingerbread by a fruit filling. But there are unresolved issues related to the influence of the dried product and the thermodynamic properties of the product on the moisture diffusion coefficient within the drying process.

In the following work [15], the identification of the moisture diffusion coefficient of medicinal plant materials is shown. The study object (medicinal plant material) was considered as a regular geometric figure (plate, cylinder and ball) and it was taken into account the influence of the initial and final moisture content, as well as the extraction duration on the moisture diffusion coefficient.

However, the proposed method does not solve the remaining issues related to the change in the technological parameters of the drying process, as well as the physicochemical properties of the product by the moisture diffusion coefficient in the process of product dehydration.

In the next work[16], the development of a methodology for the calculating effective diffusion of kinetic and dynamic parameters of the process, the surface temperature of the material and the behavior of diffusion in the process of drying fruits within a solar dryer is presented.

As a result of internal (heat and mass transfers inside fruits) and external (heat and mass transfers at the environment – solid border) values, by taking into account external the thermal and moisture exchange factors, the method for determining of the diffusion coefficients of the fruit drying process in the solar dryer was presented. The moisture diffusion coefficient for fruits it was in the range of $0.17...4.2 \cdot 10^{-10}$ m^2/s.

However, the proposed method [16] does not taken into account the influence of the dry layer of the product that is formed during its drying, and does not correlate changes in the thermodynamic parameters of the dried product during the drying process to the moisture diffusion coefficient that characterizes the state of water on the surface layer of the product.

If the above mentioned parameters are not taken into account, the values of the moisture diffusion coefficient lead to the significant discrepancies between the calculated and experimental data that essentially reduces a value of the proposed equation.

In the next work [17], it is proposed a method for accelerated experimental determination of the moisture diffusion coefficient in composite materials by introducing a new experimental parameter. In result a dependence of the variation in the mass of material over time is reached.

Following proposed method [18] for determining the moisture diffusion coefficient does not take into account the thermophysical properties of the dried product and the hygroscopic parameters of air. It is related with the complexity of the structure of the composite material that cannot simultaneously take into account all the thermophysical characteristics of the study object [19, 20].

Thus, based on the above mentioned data, it can be concluded that at currently, in the created methods for determining the moisture diffusion coefficient within vacuum drying of fruits and berries, most researchers do not take into account the effect of the resistance of the dry layer formed during drying and thermodynamic parameters that describe changes in the property product, on the one hand, and are not linked to the hygroscopic characteristics of the air in the drying chamber, on the other hand. Therefore, the creation of a methodology for determining the moisture diffusion coefficient, by taking into account the described parameters, is an urgent task in the drying technology.

3. The aim and objectives of the study

The study aim is to create a methodology for determining the moisture diffusion coefficient within vacuum drying of fruits, by taking into account cracks, channels and capillaries formed in the dry layer of the product through the resistance coefficient to evaporation. The practical application will allow for the identification of vacuum drying acceptable conditions with maximum preservation of original quality of the dried fruits.

To achieve this aim, the following objectives are accomplished:

– to study the variations regularities of a water activity during vacuum drying of fruits;

– to determine the relation of a resistance coefficient to the evaporation during vacuum drying of fruits;

– to research the dynamics of moisture evaporation by product layers during drying of fruits;

– to calculate of the moisture diffusion coefficient within vacuum drying of apple and pear sorts by using the proposed method.

4. Materials and methods of research

4. 1. Objects of the study

The research objects were: the Baiterek apple sort and the Zhazdyk pear sort freshly have picked in the October, 2022 [1].

Water activity was determined by using a water activity analyzer – AQUALAB-4TE (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.

4. 2. Description of the experimental setup

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

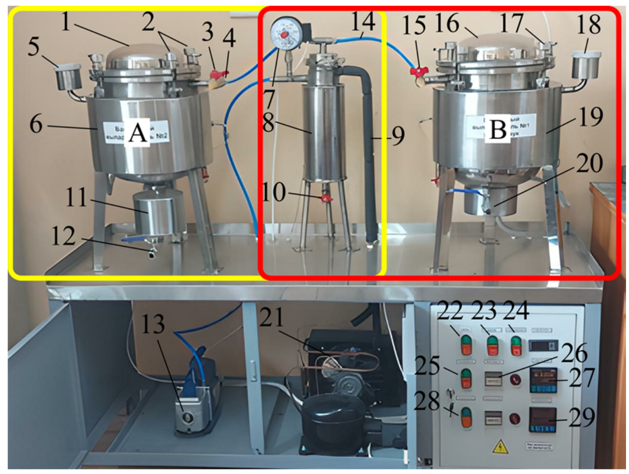


Fig. 1. The unified experimental setup [1]: 1 – device cover; 2 – cover valves; 3 – valve for air intake; 4 – vacuum valve; 5 – expansion tank; 6 – vacuum chamber of the device; 7 – vacuum manometer; 8 – desublimator; 9 – cooling tube; 10 – drain cock; 11 – container for collecting liquid; 12 – valve 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 (14–29) is low-frequency vacuum ultrasonic device. There are common for both blocks: desublimator, vacuum pump and chiller.

4. 3. The methodology for conducting an experiment on a vacuum evaporator

Before doing the experiments on a vacuum evaporator, it needs to bring to the operating mode. For that, in order 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 +40 °C, the vacuum chamber heating system is switched on. Upon reaching the specified water temperature in the cylindrical body (+40 °C) and the temperature in the sublimator (from –20 °C and below), the vacuum evaporator is ready for operation. After that, the chamber of the vacuum evaporator is loaded with the product previously prepared for vacuum drying. Preparation of the product to be dried for drying is carried out as follows. The product, after thorough washing in running cold water, is subjected to mechanical cleaning and the core is removed from it, i.e. bones. Next, the fruit is cut 2.1...2.5 mm in the form of a ring and placed in a mesh cylindrical baking sheet (Fig. 2).

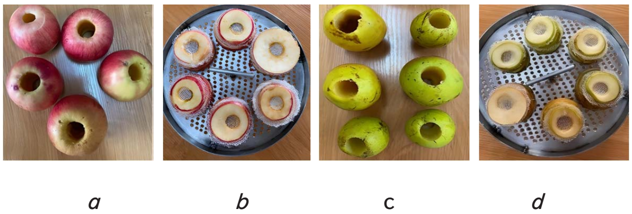


Fig. 2. Apple and pear samples: *a* – apples; *b* — apples on the tray; *c* – pears; *d* — pear on the tray

Then the trays are placed in tiered order in the vacuum chamber, and by closing the chamber lids, the vacuum pump is turned on. After a certain drying time has elapsed, stopping the apparatus, the product is taken out piece by piece and its moisture content is determined by the standard method of drying.

4. 4. Moisture transfer within food products

From the course of thermodynamics [10], it is known that any process of heat and moisture transfer is caused by a certain driving (thermodynamic) force *X*, usually expressed as a potential gradient. This force causes a thermodynamic irreversible flow of substance (heat, mass, etc.), the intensity (density) *j* of which, according to Onsager's theory, linearly depends on the thermodynamic force *X*:

$$J=\sum\nolimits_{k=1}^{n} L_{jk}\cdot X_k, \tag{1}$$

where L_{jK} is the coefficient of proportionality, which generally determines the ability of the medium to conduct the flow (kinetic coefficients).

Thus, according to the Fourier's law of heat conduction, the temperature gradient causes a heat flux $j=-\chi\,\mathrm{grad}T$, $L=\chi$; according to Fick's law, the concentration gradient causes diffusion $j=-D\,\mathrm{grad}C$, $L=D$, etc.

In the classical thermodynamics, to calculate the process of heat and moisture transfer, the driving (thermodynamic) force is the difference in temperature, concentration (moisture content), pressure and other parameters [5].

Currently, many methods were proposed for determining the moisture diffusion coefficient [18]. They can be divided into the following groups.

In the first group of methods, the moisture diffusion coefficient is calculated from the basic equation of moisture flow q_m based on experimental data on the flux density and values of local concentrations [10].

In the second group of methods, the diffusion coefficient is determined from the solution of the differential mass transfer equation using experimental data on concentration fields or process kinetics [10].

From the point of view of thermodynamics, the movement of moisture in products is due to the presence of a gradient of the transfer potential in them, and the transfer of moisture occurs from a higher potential to a lower one.

At low ambient pressures, typical for vacuum drying of a product, the dependence of the moisture transfer potential inside the product on its moisture content is non-linear, the value of the moisture transfer flux varies with moisture content.

Taking in to account that moisture content of the material (u) is a single-valued function of temperature for isothermal conditions, the moisture transfer flux is equal to:

$$J_1=-D_m\cdot\rho_0\cdot\nabla u, \tag{2}$$

where D_m – the moisture diffusion coefficient.

The moisture diffusion coefficient D_m depends on the humidity and temperature of the product. The nature of the dependence of D_m on humidity is determined by the form of the bond between moisture and the material. This dependence is very complex, since at the same time moisture is removed from different layers of the product, which is differently associated with the solid skeleton, and the total moisture flow is made up of separate flows that overcome various resistances.

According to the mass conservation law, the amount of flow diffused from the inner layers of the product that marked as J_1, should be equal to the amount of evaporated moisture flows from the surface of the product which shown as J_2 to its environment, as can be seen from Fig. 3.

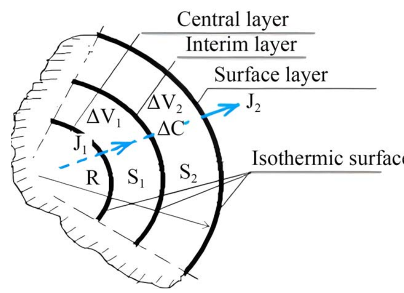


Fig. 3. For the derivation of the diffusion coefficient equation

The intensity of moisture transfer from the product surface to its environment is determined by the expression [10]:

$$J_2=0.622\frac{\alpha_T}{\mu\cdot C_p}\cdot\frac{P_b^{**}}{B}\cdot\nabla(a_w-\varphi)\cdot S. \tag{3}$$

Equating equations (2), (3) and solving with respect to D_m, it can be find an expression for determining the diffusion coefficient of moisture in the product during vacuum drying of fruits:

$$D_m=\frac{\chi}{\rho_0}\cdot\frac{\nabla(a_w-\varphi)}{\nabla u}, \tag{4}$$

where the kinematic coefficient characterizing the moisture transfer rate:

$$\left(\chi=0.622\cdot\frac{\alpha_T}{\mu\cdot C_p}\cdot\frac{P_b^{**}}{B}\cdot S\right),\ \text{kg/s}.$$

Based on the foregoing, it can be concluded that the use of moisture transfer potential in the product a difference between water activity and relative humidity makes it possible to link the thermodynamic characteristics of the dried product with the parameters of its environment and allows calculating the moisture diffusion coefficient in the fruits [10].

At the calculating of a moisture diffusion coefficient according to the method proposed by the authors, due to the lack of an analytical relationship between water activity and relative humidity, their values in this work are determined empirically, and the moisture gradient inside the product is found by the equation:

$$\nabla u = \left(W_f(\tau) - W_p(\tau)\right), \tag{5}$$

where difference is the average moisture content in the central and surface layers, %.

The average moisture content in the central and surface layers of dried samples at different time intervals are determined from the experimental graph of the drying rate.

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

Before drying, sliced, half-ring or ring-shaped pieces of fruit are sent to determine the water activity by using an analyzer – AQUALAB4TE. Further, from time to time, stopping the vacuum evaporator, the product is taken out, a part of the dried fruit is sent to determine the humidity, and the remaining parts determine the water activity indicator. Experiments are continued until the difference in the weight of the tray with the product between the previous weighing reaches a constant weight or the difference should not be more than a hundredth of a fraction.

Further, 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 equation (3) the numerical values of the evaporation resistance coefficient are determined.

The moisture content of the product at the current time is calculated by the formula:

$$W_n = \frac{G_i \cdot (G_i - G_n)}{G_i} \cdot 100\,\%, \tag{6}$$

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

G_i – initial mass of the dried product, g;

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

5. Results of determining a moisture diffusion coefficient in vacuum drying of fruits

5. 1. Study the variations regularities of a water activity during vacuum drying of fruits

The results of the study of water activity during the drying of apple and pear sorts are shown in Fig. 4.

Analysis of Fig. 4 shows that in the time interval from the beginning of the drying process to 11.00 hours, the variation in the water activity indicator for the both apples and pears has a smoothly decreasing character, and the subsequent drying time drops sharply. For example, if at the time interval between from the beginning of the process to 10.35...11.00 hours of drying time, water activity for pears, depending on the variety, decreases on average by 11.45–13.6 %, then for an apple this indicator has values from 8.42–9.36 %. Analysis of the dynamics of changes in activity in the time interval from 10.35...11.00 hours to the completion of the drying process, this indicator for a pear, depending on the variety, decreases on average 28.04...32.90 %, and for an apple, decrease averages 33.33...34.48 %.

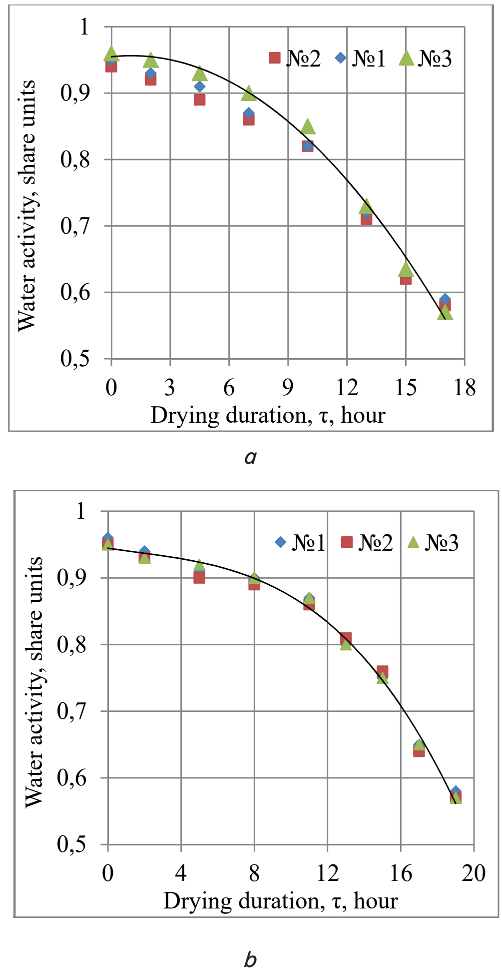


Fig. 4. Dependence of water activity on the duration of drying: *a* – for pear sorts; *b* – for apple sorts

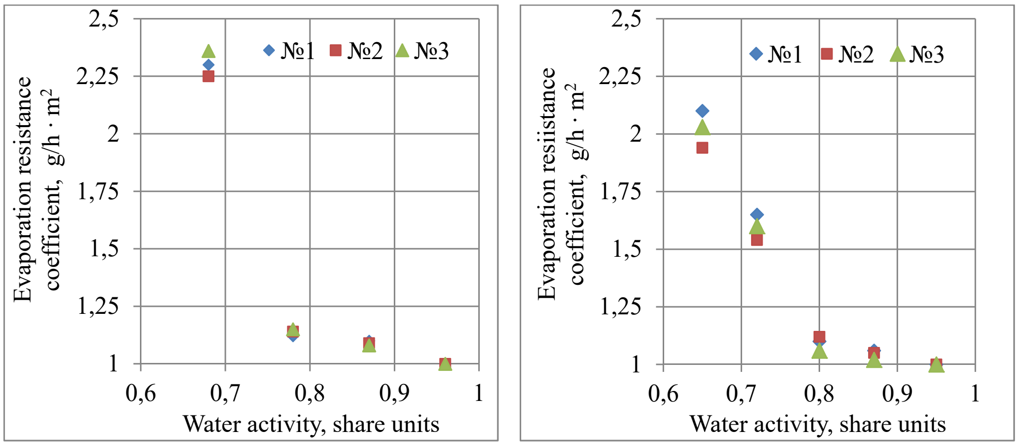
Thus, on the basis of the foregoing, it can be concluded that when the water-bound moisture is removed from the product, the changes in water activity are monotonically decreasing. After reaching the critical humidity W_{cr}, and before the end of the period of falling drying, the activity of water has a non-linear broken character.

5. 2. Determination of the relation of a resistance coefficient to the evaporation during vacuum drying of fruits

Using the experimental data of water activity and the dynamics of moisture evaporation from the surface of the product, a graphical relationship was built between the coefficient of evaporation resistance and water activity. The results obtained are shown in Fig. 5.

Analysis of Fig. 5 shows that in the range of water activity values from 0.95...0.97 to 0.78...0.80 both in an apple and in a pear as a result of the movement of the moisture evaporation zone into the thickness of the product, the value of the coefficient of resistance to evaporation monotonously increases.

Upon reaching the critical humidity W_{cr}, character of the curves for the coefficient of resistance to evaporation changes. For example, if in the range of changes in water activity from 0.95 to 0.80, the coefficient of resistance to evaporation in apples monotonously increases on average 4.8 %–6 %, and then in pears it is 13.7–15 %.



a *b*

Fig. 5. Dependences of the evaporation resistance coefficient on water activity: *a* – for pear sorts; *b* – for apple sorts

In the range of water activity change from 0.78 to 0.63, the evaporation resistance coefficient sharply increases, and its values at the end of the drying process increase by two or more times.

Based on the foregoing, it can be concluded that a sharp increase in the values of the coefficient of resistance to evaporation occurs after the critical humidity W_{cr}, 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 evaporation resistance coefficient.

5. 3. Research the dynamics of moisture evaporation by product layers during drying of fruits

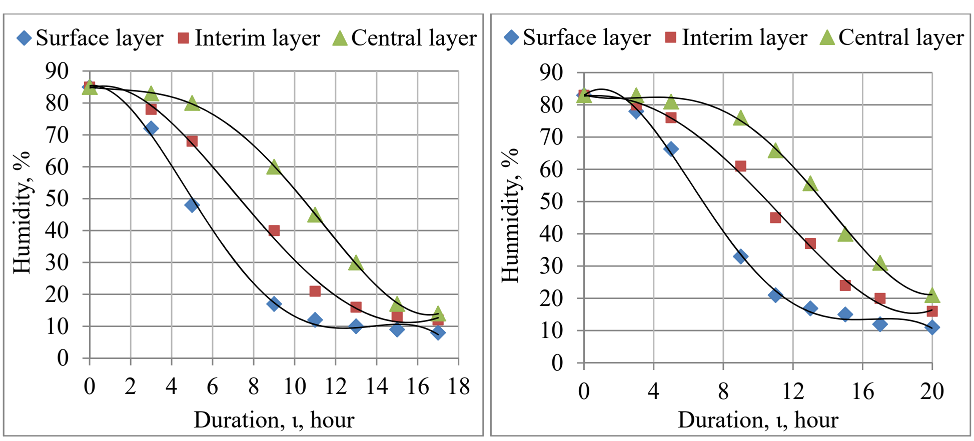
Numerous of the authors studies on the drying of fruits, including varieties of apples and pears, show that the nature of the curve of the dynamics of moisture evaporation over the layers of the product also obeys the general pattern known in the theory of drying. Therefore, in this article, the dynamics of moisture evaporation over the layers of only one variety of apple and pear was considered.

For the study the patterns of moisture changes in the layers of apple and pear, the technique proposed in [13] was used. The study results are shown in Fig. 6.

Analysis of Fig. 6 shows that, according to the curves variations, it can be noted that in all the studied samples of apples and pears, there are available periods of constant and decreasing drying rates.

In the first drying period, moisture is redistributed inside the dried product. Depending on the value of $W=f(\tau)$, after a certain period of time after the start of drying, there comes a moment (for pear and apple varieties, it is 8.30 h and 10.0 h, respectively), when the moisture on the surface of the product becomes equal to hygroscopic. This point is marked on the drying rate curve by the critical point W_{cr}. The critical point W_{cr} divides the entire drying process of the studied varieties of apples and pears into two periods that differ from each other in the drying speed.

Based on the foregoing, it can be concluded that the nature of the distribution of moisture over the thickness of the product during the drying process is not the same, and the dynamics of moisture changes in the layers of the product are described by polynomial power equations.



a *b*

Fig. 6. Dependences in humidity by fruit layers: *a* – for pear sorts; *b* – for apple sorts

5. 4. Calculation of the moisture diffusion coefficient within vacuum drying of apple and pear sorts by using the proposed method

By taking into account the experimental data of the humidity changes regularities in the layers of pear and apple sorts, water activity and evaporation resistance coefficient, and choosing the difference between water activity and relative air humidity as the moisture transfer potential in the product, also using the proposed method, a value of the moisture diffusion coefficient during drying of apple and pear sorts were calculated.

As an example, it could be considered the methods for determining the moisture diffusion coefficient at the pear drying in the period between 2 and 4 hours of drying time. At the beginning the values of the coefficients included in equation should be determined (4):

$$\chi = 0.622 \cdot \frac{\alpha_T}{\mu \cdot C_p} \cdot \frac{P_b^{**}}{B} \cdot f.$$

In the calculation, the values of the coefficient are taken equal to α_T=1.0 W/(м^2·K).

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.

Barometric air pressure is equal to B=101 325 Pa.

Apples surface area (considered as a hemisphere: Ø=0.060 m).

The calculation results of moisture diffusion coefficient within product drying, by time duration are shown in Table 1.

Table 1

Values of moisture diffusion coefficient of pear and apple

Product name	Values of moisture diffusion coefficient within product drying, by time duration, $D \cdot 10^{-8}$m^2/s					
	2–4 (h)	4–6 (h)	6–8 (h)	8–10 (h)	10–12 (h)	12–14 (h)
pear	13.52	12.91	9.42	5.42	3.46	2.86
apple	24.80	10.92	5.38	2.40	2.39	2.42

The calculation results according to the proposed method for calculating the moisture diffusion coefficient during vacuum drying of pears and apples are shown in Fig. 7.

As can be seen from Fig. 7, over the entire range of humidity changes, the moisture diffusion coefficient changes ambiguously: at the beginning of drying, it decreases and after the transition to critical humidity, it decreases monotonically.

The fall area relates to the removal of loosely bound moisture from the product or a period of constant drying rate. The reason for the drop in the moisture diffusion coefficient is the rapid decrease in product moisture from initial to critical moisture.

With a further decrease in humidity below the critical one, a significant role in changing the value of the diffusion coefficient is exerted by the structure of the dry layer of the product and the increase in the temperature of the product at the end of the drying process.

In the presented work, the research problems of the impact of hydrodynamic resistance to evaporation of the dried dry layer, expressed by the moisture diffusion coefficient of evaporation resistance and variations in the quality of the dried product within drying, through the thermodynamic indicator of water activity on the moisture diffusion coefficient, were considered and solved.

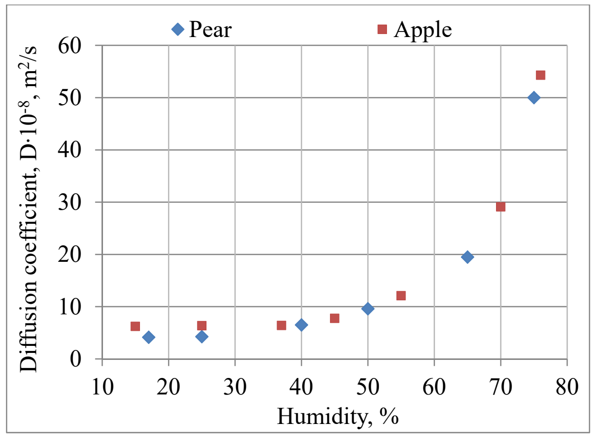


Fig. 7. Moisture diffusion coefficient in pear and apple sorts

6. Discussion of the results of determining a moisture diffusion coefficient in vacuum drying of fruits

Analysis of the data of the dependences of water activity on the duration of drying shows (Fig. 4) that in the time interval from the beginning of the drying process to 10.35...11.00 h, and the subsequent drying time drops sharply. The decrease in water activity during the period of removal of total-bound moisture, if for pears in average is 11.45–13.6 %, then for apples varieties this figure is 8.42–9.36 %. During the period of removal of weakly bound moisture, water activity decreases, for example, for pears by an average of 28.04...32.90 %, and for apples, the decrease is an average of 33.33...34.48 %.

The study results of the dependences of the evaporation resistance coefficient on water activity (Fig. 5) show that water activity value in the range from 1.0 to 0.78 is monotonically increasing, and subsequent drying times increase sharply. A sharp increase in the values of the coefficient of resistance to evaporation is explained by an increase in the thickness of the dry layer (as a result of the deepening of the moisture evaporation zone into the depth of the product) that resists the release of water vapor molecules detached from the evaporation surface.

Analysis of the curves (Fig. 6) shows that variations in humidity curves for pear and apple layers differ sharply not only in product layers, but also by fruit types. For example, if at 6 hours of drying time the moisture content of the surface layer of pears is 40 %, then the moisture content of the intermediate and central layers is 60 % and 77 %, respectively. In the apples, during this time, the moisture content on the surface layer decreases from 83 % to 60 %, while the intermediate and central layers decrease by 72 % and 80 %, respectively.

The obtained experimental data assume that according with the proposed method, to calculate the diffusion coefficient of moisture during vacuum drying of pears and apples. The calculation results show that the average value of the moisture diffusion coefficient at the first drying period is 24.2·10^{-8} m^2/s, and on the second drying period

$1.29 \cdot 10^{-8}$ m^2/s. However, the authors did not discover any related available reference in this field to compare the obtained values of the diffusion coefficient for pears and apples.

The obtained scientific results can be used in the food industry to analyze the drying process of fruits in order to determine the optimal mode of their drying. The positive effect in the using of the study results is the obtaining the dry powders with the maximum preservation of the product original quality. The presented methodology is the logical continuation of the authors' previous published work [1].

The proposed method for determining the moisture diffusion coefficient within vacuum drying of fruits has limited practical application, due to the absence of an analytical dependence of the resistance coefficient on water activity and also for other types of fruits. Therefore, in the future studies, the authors will determine the analytical relationship between the resistance coefficient and the thermodynamic indicator of water activity, as well as the physical parameters that are taken into account to determine the moisture diffusion coefficient during vacuum drying of various fruits. For that, the authors will use the laws applied in the theory of non-equilibrium thermodynamics.

7. Conclusions

1. By studies were established that the water activity in the process of vacuum drying of pears and apples changes ambiguously: until the critical moisture content W_{cr} is reached, it monotonically decreases (for pears, for 10.35...11.00 h of drying time, water activity decreases on average 11.45–13.6 % compared to the original value, and for apple this figure decreases 8.42–9.36 %). After passing the critical humidity W_{cr} in all the studied fruits, the water activity decreases sharply (for pears, the average decrease is 28.04...32.90 %, and for apples 33.33...34.48 % compared to the value of water activity at critical humidity).

2. The results of the study showed that in the range of water activity from 1.0 to 0.78, the coefficient of resistance to evaporation gradually increases from 1.0 to 1.13. After critical humidity and until the end of the drying process, its value grows more than doubles.

3. Comparative analysis of the experimental data on the change in moisture in the layers of pears and apples showed the ambiguous nature of the change in the moisture curve in the layers of the product. For example, the humidity on the surface layer after 3 hours of drying time, if in pears decreases by 15.29 %, and in apples by 6.02 %, then in the central layer in pears during this time the humidity changes slightly only 2.35 %, and in apples no change. In the case of comparing the moisture changes in the layers of the product after 9 hours of drying time, then it can be observed the following: if the moisture on the surface layer decreases in pears by 80.1 %, and in apples by 63.86 %, then in the central layer in pears it decreases by 29.41 %, and in apples 8.43 %. Such case of moisture changes in the layers of the product is explained by thermophysical properties, structure, and also the form of moisture bonding.

4. The calculation results according to the proposed method show that in the period of constant drying rate, the moisture diffusion coefficient in the studied products decreases (in average from $2.42 \cdot 10^{-8}$ m^2/s to $1.29 \cdot 10^{-7}$ m^2/s. In this period, the value of the moisture diffusion coefficient is mainly determined by the diffusion of vapor from the surface layer of the material. As a result of the formation of a dry layer on the surface layer, it leads to an increase in the resistance to internal diffusion, i.e. the moisture diffusion coefficient gradually decreases. When the critical humidity W_{cr} is reached, the main driving force of the entire process becomes the difference between the moisture content of the central and surface difference between the average moisture content in the central and surface layers. As can be seen from Fig. 7, a border between the first and second drying periods for pears is 37.4 %, and for apples is 35.1 %. On the second drying period, the value of the moisture diffusion coefficient decreases from $5.42 \cdot 10^{-8}$ m^2/s to $2.12 \cdot 10^{-8}$ m^2/s.

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.

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