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REVEALING THE INFLUENCE OF ULTRASONIC PROCESSING ON THE KINETIC PARAMETERS OF CONVECTIVE AND COMBINED DRYING OF RAW APPLE MATERIALS

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The object of research is the process of convective and combined drying of apple raw materials treated before dehydration in an ultrasonic bath. The use of pretreatment solves the issue of intensifying the dehydration process and maintaining the quality of the product.

Sonication for 5 min reduces the dehydration process by 13.7 %, and at 10 min processing – by 27.8 % compared to traditional convective drying. With increasing processing time to 20 minutes, the dehydration rate deteriorates.

Sonication of raw materials for 5 minutes under combined heating does not intensify the dehydration process, and within 10 and 20 minutes it reduces the efficiency of moisture removal. When processed for 10 minutes, the time to reach the final moisture content is increased by 17.2 %, and at 20 min – by 23.4 % compared to control samples.

Regardless of the processing time, there is a decrease in the maximum temperature of the samples in the combined drying process. When processed for 5 minutes, the maximum temperature of the samples decreased by 4.3 %, and with 10 and 20-minute processing – by 8.6 % and 12 % compared to the temperature of samples without sonication.

The results are explained by the "sponge effect" caused by ultrasonic vibrations and the phenomenon of cavitation that occurs in the liquid during the action of the ultrasonic field.

The peculiarity of the pre-sonication before drying is the possibility to intensify the convective dehydration process without increasing the heat carrier's temperature. The use of this type of processing in a combined energy supply will solve the problem of preserving the quality of the finished product by reducing the maximum temperature of the raw material.

The research reported here could be a prerequisite for practial design of an energy-efficient electrical system for drying fruit and vegetable raw materials

Keywords: apple raw materials, sonication, convective drying, combined drying, direct electric heating

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1. Introduction

Vegetables and fruits are an indispensable source of nutrients and vitamins that are necessary for the normal functioning of the human body. Most of them are seasonal products and need to be processed for long-term storage. The reason for the rapid deterioration of such products is the high moisture content, the level of which can sometimes reach up to 90 %. It is moisture that is the main source of microorganisms and enzymes that accelerate the rotting processes of freshly harvested fruits and vegetables. The most common way to solve this issue is to remove moisture by drying raw materials.

Unlike other methods of processing, in particular, canning and freezing, dried raw materials do not require special packaging or containers for storage. In addition, during the drying process, the mass and volume of finished products are significantly reduced, which leads to a reduction in transport costs and a decrease in warehouse space.

The most common dehydration technique is convective drying, by passing heated air through a layer of dried raw materials [1, 2]. This method of moisture removal is simple and does not require complex and expensive equipment for its implementation. The main disadvantages of convective drying are low intensity of moisture removal, high energy costs, and low nutritional value of the products obtained as a result of exposure to high temperatures.

From the point of view of preserving the nutritional value of raw materials, the best dehydration technique is freeze-drying in a vacuum environment [3, 4]. This technology minimizes the loss of vitamins, deterioration of taste, color, texture, and other organoleptic qualities of the finished product. However, due to the significant energy intensity, cost, and complexity of technological equipment, freeze-drying is not widely used.

Existing electrophysical methods of moisture removal (drying by using ultrahigh frequencies, infrared, ultrasonic, combined, etc.) make it possible to maximize the drying process while maintaining the established requirements for the quality of the finished product [5–8]. However, each of the methods has a number of disadvantages, in particular, high temperatures and increased energy costs for the process.

Despite the large number of existing methods of dehydration, drying remains the most energy-intensive stage of processing raw materials. The quality and speed of implementation of the drying process largely determine the quality and cost of the resulting product.

The cost of energy resources in the market is quite significant, in addition, there is a tendency to further increase it in the near future. Therefore, research aimed at solving the issues of reducing energy consumption for drying fruit and vegetable raw materials and improving the quality of the finished product is relevant.

2. Literature review and problem statement

Practical experience shows that one of the simplest methods to intensify the process of dehydration and reduce energy consumption is the pretreatment of raw materials immediately before drying. Pre-processing can be carried out by chemical and physical methods.

The most common chemical method of processing raw materials before drying is osmotic dehydration [9, 10]. This method makes it possible to improve the quality of the finished food product and reduce energy consumption for the drying process. The technique involves immersing the raw material in hypertonic solutions (sugar or salt) for some time. In the process of osmotic treatment, the cellular structures of the processed raw material become semipermeable membranes, as a result of which mass is transferred: solution to the product, and moisture is transferred from the middle of the cells to the osmotic solution. And due to osmotic dehydration, moisture removal can be achieved up to 10–70 % at ambient temperature [11]. However, this method of processing adversely affects the final quality of the product, in particular, the content of minerals, vitamins, and other useful substances decreases. This is due to the transfer of the mass of the content of the processed raw materials to the osmotic solution. In addition, the processing of raw materials in sugar syrups leads to sticking of pieces of the finished product and sticking them to the drying surface [12].

Sulphitation or sulfonation is often used in the processing industry to reduce darkening during drying and prevent loss of quality during food handling and storage. Studies [13, 14] show an improvement in the quality of dried products as a result of sulphitation, in particular, color, rehydration coefficient, content of nutrients, etc. Also, in [15] it was shown that the processing of samples in ascorbic acid and potassium meta-bisulfite made it possible to reduce the duration of their drying. However, pretreatment with sulfite contributes to the loss of some water-soluble compounds, can create an undesirable taste and soft texture of the product [15].

Another chemical method that ensures the preservation of the color of the product and the intensification of the dehydration process is pretreatment in citric acid. The authors of [16, 17] found that in addition to improving the organoleptic characteristics of products, soaking the raw material in citric acid before drying can reduce the drying time to 20–30 %. However, the use of this method, as in previous cases, entails a decrease in the product of beneficial water-soluble vitamins and minerals.

The most common of the physical methods of pre-processing raw materials before drying is thermal blanching. It is usually carried out by immersing the raw material for some time in hot water at a constant temperature of 60 to 100 °C.

The authors of works [18, 19] found that conventional blanching in hot water can reduce the duration of drying products, as a result of an increase in the permeability of cells of the material. Also, such blanching prevents the deterioration of product quality by inactivating enzymes and microorganisms [20]. However, blanching with water at high temperature can lead to a noticeable deterioration in the quality of the finished product, discoloration, loss of water-soluble and heat-sensitive elements. Also, blanching in hot water leads to the formation of large amounts of wastewater and an increase in the amount of environmental pollutants.

In order to solve the issue of loss of water-soluble elements and reduce the amount of wastewater, thermal blanching with superheated steam is used. In works [12, 21] it was found that blanching of products with superheated steam leads to softening of the surface of samples and damage to cell membranes, which makes it possible to reduce energy consumption for drying up to 30 %. However, processing is carried out with superheated steam with a high temperature (up to 200 °C). At the same time, the temperature of the test samples during processing reached almost 100 °C, which negatively affects the content of nutrients of heat-sensitive substances in the finished product. Also, at an early stage of processing, as a result of a significant temperature difference between the product and steam, the latter smears to condense on the surface of the samples, resulting in a heterogeneous blanching effect.

An effective technique of thermal blanching is the preheating of raw materials by passing electric alternating current through it. Studies [18, 22] show that ohmic heating of raw materials before drying can reduce the duration of dehydration by 25–30 %. Compared to thermal blanching with hot water or steam, ohmic heating provides faster and uniform heating of the product. However, this method also has some limitations to use. With increasing processing stress, intensive heating of the material occurs. The temperature of the product increases rapidly, reaching the boiling point of water. At the same time, moisture does not have time to completely come out in the form of steam and boils inside the product. This leads to the destruction of the cellular structure of the material and changes in the color of the finished product [22].

Due to undesirable negative changes in the quality of finished products during heat treatment, non-thermal methods of processing raw materials have recently become common.

A fairly effective non-thermal pretreatment method is freezing-defrosting the product before drying. The authors of work [23] found that freezing (at –30 °C for 5 days) followed by defrosting (at 25 °C for 30 minutes) made it possible to reduce the drying time of samples by 14.6–20.3 %. At the same time, blanching in hot water reduced drying time by 2 %, and acid treatment – only by 6 %. However, as a result of freezing and defrosting, the dried samples were of the worst quality compared to other types of pretreatment. Also, the disadvantages of this method include a significant pretreatment time and high energy intensity of the freezing process.

Researchers are increasingly interested in non-thermal ultrasonic (US) processing of raw materials. Studies conducted in [24, 25] have shown that the use of raw material processing in an ultrasonic bath can reduce the drying time by 25–40 % and reduce energy consumption by up to 35–70 %. The sonicated raw material showed 6–20 % lower density and 9–14 % higher porosity compared to control samples. It has been established that the processing intensity depends on its duration and ultrasonic power. At the same time, this type of treatment can lead to a decrease in the nutrient content of products as a result of changes in the microstructure of samples, destruction of cell surfaces, and leakage of their contents into the environment [26].

The analyzed methods of processing fruit and vegetable raw materials before drying can intensify the process of dehydration but, very often, can lead to a deterioration in the quality of the finished product. Despite the possible negative effects of sonication, this method is the most promising technique in terms of efficiency and preservation of all useful components in the finished product, including heat-sensitive elements. This type of processing is carried out only under laboratory conditions and is practically absent in industrial production. This is due to the small number of studies conducted to establish a relationship between changes in the microstructure and physicochemical properties of food products during pretreatment and subsequent drying.

This suggests that it is advisable to conduct a study aimed at determining the effect of pre-sonication on the kinetic parameters of the convective and combined drying of apple raw materials.

3. The aim and objectives of the study

The aim of this work is to identify the influence of pre-sonication on the kinetics of moisture content and temperature of apple raw materials in the convective and combined drying process. This will make it possible to substantiate the most rational modes of processing raw materials in order to intensify the dehydration process and improve the quality of the finished product.

To accomplish the aim, the following tasks have been set:

– to determine the influence of preliminary ultrasound processing on the kinetic parameters of the apple drying process with convective heat supply;

– to determine the influence of preliminary ultrasound processing on the kinetic parameters of the process of combined drying of apple raw materials using direct electroheating.

4. The study materials and methods

4. 1. Materials, equipment, and devices used in experimental studies

Apples of the early summer and summer ripening varieties “Red Mac”, “Mantet”, and “Helios”, grown under the conditions of the Sumy region (Ukraine), were chosen as research objects.

The pre-treatment of apples before drying was carried out in an ultrasonic bath DSA 50-JY2 (China) with the following parameters: generator output power, 50 W; ultrasonic intensity of oscillations, 0.4 W/cm^2; ultrasonic frequency, 44 kHz. Bath capacity is 1.9 liters.

The determination of the mass of samples before and after processing was carried out with electronic scales of type MN-200 (China) with a measurement accuracy of up to 0.01 g.

Further drying of apple samples was carried out in an experimental installation, the structure and description of which is given in [8].

4. 2. Research methodology

Pre-prepared apples were cut into discs 0.005 m high and 0.028 m in diameter. After that, the sliced apples after weighing were immersed in a container of the ultrasound bath, which was filled with water to the set level. In order to prevent ascent and increase the area of contact with ultrasound, the test samples were pressed down with a metal mesh. Subsequently, they were sonicated for 5, 10, and 20 minutes.

After sonication, the samples were removed from the ultrasound bath and placed on a mesh tray for draining water. Next, the samples were re-weighed and dried in various ways according to the procedure given in [8].

Convective and combined drying of apple raw materials using direct electroheating was carried out under the following technological parameters:

– air temperature in the drying chamber – 40 °C;

– voltage gradient across the thickness of the material – 30 V/cm;

– speed of heated air – 0.2 m/s.

These parameters were determined as optimal for the combined drying of apples using direct electric heating in the course of previous studies [8].

The current moisture content of the samples (humidity calculated in relation to the mass of absolutely dry matter of the material) during the experiments was determined by the expression from [8]:

$$X_i = \frac{M_i - M_{abs}}{M_{abs}}, \qquad (1)$$

where X_i is the current moisture content of material, kg/kg;

M_i – current mass of the sample, kg;

M_{abs} – mass of absolutely dry insoluble and soluble minerals in the sample, kg.

The rate of moisture removal from the material was determined by the expression:

$$u = \frac{\Delta m_i}{\Delta \tau_i}, \qquad (2)$$

where Δm_i is the amount of moisture removed over the period of time, kg;

$\Delta\tau_i$ – drying time on the site, min.

To calculate the kinetic parameters of drying and visualization of the obtained data, the standard software package Microsoft Excel 2013 (USA) was used.

5. Results of studying the effect of sonication on the drying process of apple raw materials

5. 1. Results of the influence of sonication on the kinetic parameters of convective drying of apple raw materials

Repeated measurements of the initial mass and electrical resistance of the samples after ultrasound bath showed that the above parameters before and after processing practically do not change. It should be noted that after ultrasonic treatment for 20 minutes, there was a slight increase in the mass of samples and their softening.

Fig. 1–3 show the results of determining the kinetic parameters of convective drying of apple raw materials at a drying agent temperature of 40 °C after pretreatment in an ultrasonic bath for 5–20 minutes.

Fig. 1 shows the dependence of the moisture content of apples in the process of convective drying at an air temperature of 40 °C after pretreatment in an ultrasonic bath.

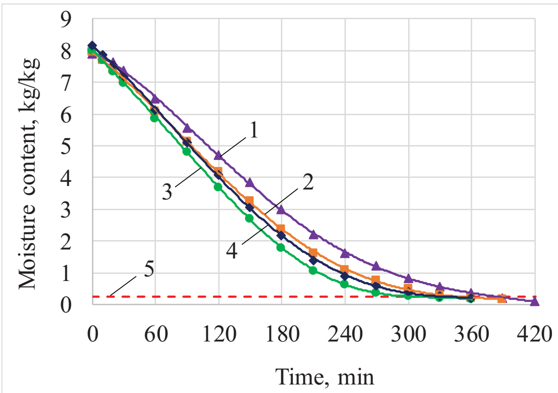

Fig. 1. Dependence of the moisture content of apples in the process of convective drying at an air temperature of 40 °C after pretreatment in an ultrasonic bath during: 1 – without processing; 2 – 5 min; 3 – 10 min; 4 – 20 min; 5 – final commodity moisture content of finished products

The resulting drying curves show that the duration of traditional convective drying (Fig. 1, curve 1) to an equilibrium humidity of 0.25 kg/kg (horizontal curve 5 in Fig. 1) is 395 minutes. After pre-treatment of samples in the ultrasonic bath for 5 (Fig. 1, curve 2) and 10 minutes (Fig. 1, curve 3), the drying time decreased by 13.7 and 27.8 %, and amounted to 340 and 285 minutes, respectively. Pre-treatment of ultrasound for 20 minutes (Fig. 1, curve 4) slightly speeds up the process of convective drying but compared to processing for 10 minutes, has a worse effect. The duration of dehydration after treatment for 20 minutes was 317 minutes, which is 32 minutes longer than the results obtained after treatment for 10 minutes.

The moisture removal rate curves (Fig. 2) take a classic form for convective drying. The maximum moisture removal rate increases with increasing duration of ultrasonic processing of raw materials up to 10 min.

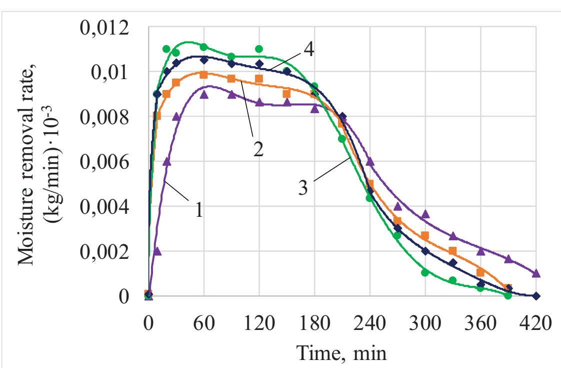

Fig. 2. Dependence of the moisture removal rate during convective drying at air temperature of 40 °C after pretreatment in an ultrasonic bath during: 1 – without treatment; 2 – 5 min; 3 – 10 min; 4 – 20 min

At the same time, there is a decrease in the period of increasing rate of moisture removal from the test samples. The duration of this period for raw materials processed in the ultrasonic bath for 10 minutes (Fig. 2, curve 3) is about 20 minutes, and for raw samples – almost 60 minutes (Fig. 2, curve 1).

The rate of moisture removal in the first drying period for raw materials was $0.008–0.009 \cdot 10^{-3}$ kg/min (Fig. 2, curve 1). At the same time, after pretreatment for 5 (Fig. 2, curve 2) and 10 minutes (Fig. 2, curve 3), the removal rate for this period increased and amounted to $0.01 \cdot 10^{-3}$ and $0.011 \cdot 10^{-3}$ kg/min, respectively. For samples processed in the bath for 20 min (Fig. 2, curve 4), the drying rate in the first period was $0.0104–0.0105 \cdot 10^{-3}$ kg/min.

Analysis of temperature curves (Fig. 3) shows that the temperature of processed and untreated samples during the drying process is almost the same. That is, it can be concluded that sonication pretreatment makes it possible to intensify the process of convective drying of raw materials without increasing the temperature in the drying chamber.

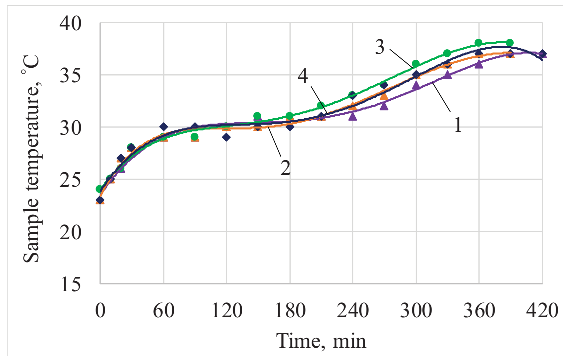

Fig. 3. Dependence of sample temperature in the convective drying process at an air temperature of 40°C after pretreatment in an ultrasonic bath during: 1 – without treatment; 2 – 5 min; 3 – 10 min; 4 – 20 min

The temperature of the samples during the dehydration process gradually increases and, when the equilibrium humidity is reached, is almost equal to the air temperature in the drying chamber.

5. 2. Results of the influence of sonication on the kinetic parameters of the combined drying of apple raw materials

Fig. 4–7 show the results of determining the kinetic parameters of combined drying of apple raw materials after pretreatment in an ultrasonic bath for 5, 10, and 20 minutes. The field strength of direct electric heating during the drying process was 30 V/cm, and the temperature in the drying chamber was 40 °C.

The resulting drying curves show (Fig. 4) that the duration of combined drying using direct electric heating with an intensity of 30 V/cm (Fig. 4, curve 1) to equilibrium humidity is 145 minutes. The obtained values are 2.7 times less than with convective drying of raw materials. After preprocessing the samples in the ultrasound bath for 5 minutes (Fig. 4, curve 2), the dehydration time decreased slightly and amounted to 130 minutes.

Increasing the duration of pre-sonication of samples to 10 and 20 min under combined heating adversely affected the drying time. The dehydration time for samples treated for 10 min (Fig. 4, curve 3) was 165 min. The drying time of apples after processing for 20 minutes (Fig. 4, curve 4) was almost 180 minutes. Thus, when processing samples in an ultrasonic bath for 10 minutes, the time to achieve the final moisture content increases by 17.2 %, and at 20 minutes – by 23.4 % compared to the processing mode for 5 minutes.

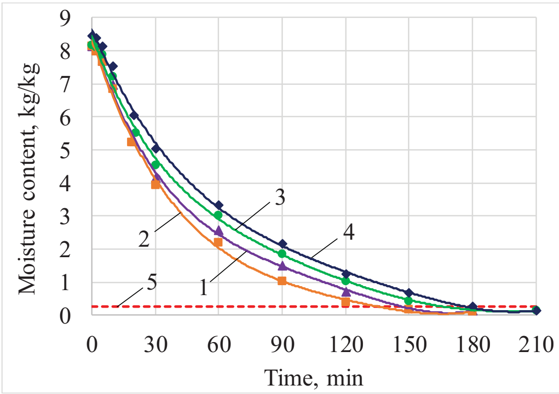

Fig. 4. Dependence of the moisture content of apples in the process of combined drying at a field strength of direct electroheating of 30 V/cm and an air temperature in a chamber of 40 °C after pretreatment in an ultrasonic bath during: 1 — without processing; 2 — 5 min; 3 — 10 min; 4 — 20 min; 5 — final commodity moisture content of finished products

The curves of moisture removal rate, temperature, and current strength passing through the sample under combined heating before and after sonication are peak in nature. At the same time, the maximum values of moisture removal rate (Fig. 5) and sample temperature (Fig. 6) account for the maximum current values (Fig. 7). The results of the nature of the drying process flow confirm the studies conducted in [8].

The maximum rate of moisture removal during combined drying without pre-treatment of raw materials (Fig. 5, curve 1) was $0.053{\cdot}10^{-3}$ kg/min. As a result of pre-processing of samples in the ultrasonic bath for 5 minutes, the removal rate increased by 5.7 % and amounted to $0.056\ 10^{-3}$ kg/min (Fig. 5, curve 2).

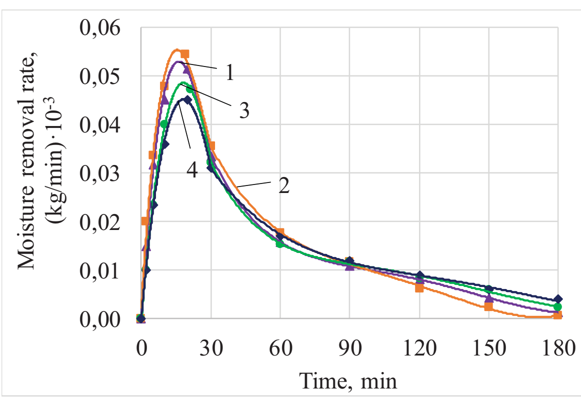

Fig. 5. Dependence of the moisture removal rate in the combined drying process at a field strength of direct electroheating of 30 V/cm and an air temperature in the chamber of 40 °C after pretreatment in an ultrasonic bath during: 1 — without processing; 2 — 5 min; 3 — 10 min; 4 — 20 min

For samples treated for 10 (Fig. 5, curve 3) and 20 min (Fig. 5, curve 4), the maximum value of moisture removal rate was 0.048 and $0.045{\cdot}10^{-3}$ kg/min, respectively. With increasing pretreatment time, the maximum moisture removal rate decreases, which leads to an increase in the drying time of apples.

At the same time, regardless of the duration of ultrasonic treatment, a decrease in the value of the maximum temperature of samples in the combined drying process is observed (Fig. 6).

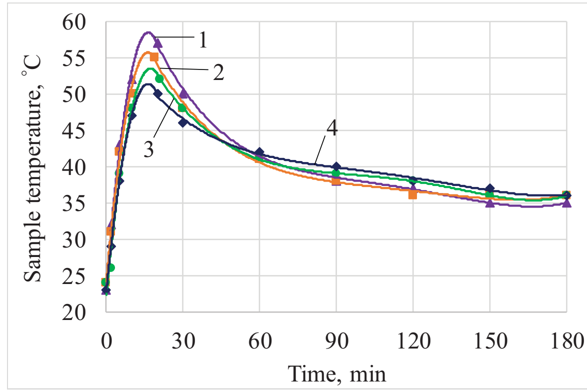

Fig. 6. Dependence of the sample temperature in the combined drying process at a field strength of direct electroheating of 30 V/cm and an air temperature in the chamber of 40 °C after pretreatment in an ultrasonic bath during: 1 — without processing; 2 — 5 min; 3 — 10 min; 4 — 20 min

The maximum temperature of samples without pretreatment during the drying process was 58 °C (Fig. 6, curve 1). After ultrasonic treatment for 5 minutes, the temperature of the samples decreased by 4.3 % and amounted to 55.5 °C. Increasing the duration of pretreatment to 10 and 20 minutes allowed reducing the maximum temperature to 53 (Fig. 6, curve 3) and 51 °C (Fig. 6, curve 4), respectively. The obtained values are 8.6 and 12 % less compared to control samples.

The decrease in the maximum temperature is due to a decrease in the magnitude of the electric current passing through the sample (Fig. 7).

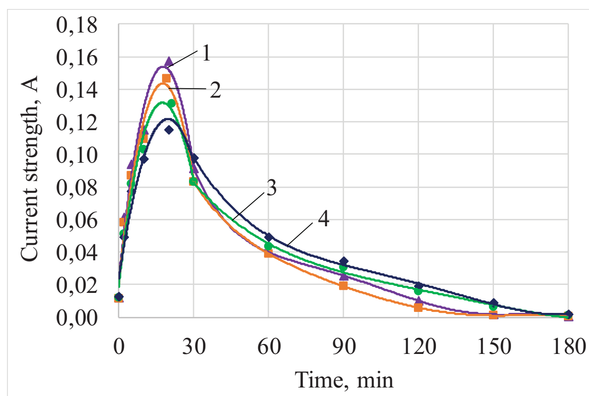

Fig. 7. Dependence of the current passing through the sample in the combined drying process at a field strength of direct electroheating of 30 V/cm and an air temperature in the chamber of 40 °C after pretreatment in an ultrasonic bath during: 1 — without processing; 2 — 5 min; 3 — 10 min; 4 — 20 min

The maximum value of the electric current passing through the raw samples under combined heating was 0.159 A (Fig. 7, curve 1). After sonication for 5 min, the maximum current strength during the drying process reached a value of 0.142 A. A further increase in the processing time to 10 and 20 min reduced the maximum current values during dehydration to 0.131 and 0.116 A. Thereby, increasing the sonication duration to 20 min reduced the maximum current strength through the sample by 27 %.

6. Discussion of results of investigating the influence of sonication on the kinetic parameters of drying of apple raw materials

Our results of studying the influence of sonication on the kinetic parameters of drying are a continuation of a series of experiments on the combined technique of supplying energy to dried fruit raw materials, reported in [8, 22, 27–31].

The use of direct electric heating in the process of convective drying of raw materials is a very promising direction to reduce the energy intensity of dehydration. This method of additional heating makes it possible to reduce the dehydration time compared to traditional convective drying by 3–5 times [8].

However, the use of direct electric heating can lead to overheating of raw materials above the established values. Therefore, there is a need to find ways to reduce the temperature of the product in the process of combined heating. In the course of the research, it was found that one of such methods is the use of pretreatment of raw materials in an ultrasonic field.

Immersion in water and ultrasonic processing of raw materials lasting up to 10 minutes practically does not affect the mass of samples. However, with an increase in the processing time to 20 minutes, a slight increase in the mass of the samples and their softening was observed. This phenomenon is explained by the "sponge effect" caused by ultrasonic vibrations. That is, changes in the volume of material, leading to the formation of microscopic channels that help tissue fluids (juice) penetrate into the environment or vice versa – water inside the material [32, 33].

Fig. 1 demonstrates that the processing of raw materials in the ultrasonic bath allows for the intensification of the convective drying process without increasing the temperature of the heat carrier in the drying chamber. It was found that sonication for 5 min reduces the dehydration process by 13.7 %, and at 10 min processing – by 27.8 % compared to the traditional drying method. This is due to the aforementioned "sponge effect", as well as the phenomenon of cavitation, characterized by the appearance of small air bubbles in the liquid under the action of ultrasound. The rupture of bubbles causes high and rapid local pressure and temperature drops, which leads to damage to the cells of the raw materials under study. As a result, the surface roughness of the sample and its porosity increase, which facilitate the movement of moisture from the inner layers to the surface [25, 32–34].

However, ultrasonic processing has an ambiguous effect on the flow of the drying process. With increasing processing time to 20 min, the rate of dehydration of samples deteriorates (Fig. 1, curve 4). Obviously, this is due to the swelling of raw materials in the process of pre-ultrasonic processing, which leads to an increase in drying time. Furthermore, it is known that long-term exposure to ultrasound on the material can cause pores to close [35]. Therefore, the movement of cell components (juice) into the environment is slower. Also, prolonged exposure to ultrasound fluctuations reduces the content of polyphenols and the antioxidant ability of dried apples, which negatively affects the nutritional value of the finished product [35].

Based on the foregoing, it can be concluded that the raw material pre-treatment time in the ultrasonic bath before convective drying should not exceed 10 min. The use of ultrasonic treatment lasting up to 10 minutes (Fig. 2, curve 3) reduces the duration of the first drying period by 11 % and increases the rate of moisture removal at this stage by 1.4 times compared to traditional convective dehydration.

The influence of sonication on the kinetic parameters of drying with a combined power supply is somewhat different. Processing of raw materials in the ultrasonic bath before drying with a combined heating technique for 5 minutes (Fig. 4, curve 2) practically does not intensify the dehydration process, and within 10 and 20 minutes (Fig. 4, curves 3 and 4) – on the contrary, somewhat reduces the efficiency of moisture removal. When processing samples in an ultrasonic bath for 10 minutes, the time to reach the final moisture content increases by 17.2 %, and at 20 minutes – by 23.4 %. Obviously, this is due to the aforementioned phenomenon of closing micropores in samples, which impairs their juicy yield.

At the same time, regardless of the duration of ultrasonic treatment, a decrease in the value of the maximum temperature of samples in the combined drying process is observed (Fig. 6). The maximum temperature of samples during ultrasonic sound before drying for 5 minutes decreased by 4.3 %, and during 10- and 20-minute processing – by 8.6 and 12 % compared to the temperature of unvoiced samples.

The decrease in the maximum temperature is due to a decrease in the magnitude of the electric current passing through the sample (Fig. 7). Increasing the ultrasound processing time to 20 minutes reduces the maximum current value by 27 %. This is due to increased values of the electrical resistivity of raw materials as a result of the deterioration of its juice output due to the closure of pores in the material.

It should be noted that the decrease in the strength of the electric current as a result of ultrasonic processing practically does not affect the time of electroplasmolysis of raw materials. The duration of reaching peak current values for all processing modes is 15–20 minutes. This is due to damage to the membranes of ultrasound cells by oscillations, which reduces their current and heat resistance.

The studies reported in this paper prove the feasibility of using ultrasonic treatment before the implementation of the technological process of drying. In case of convective dehydration, the use of ultrasound will significantly speed up the drying process, and its use in a combined energy supply will solve the issue of preserving the quality of the finished product by reducing the maximum temperature of raw materials.

One of the main parameters that can determine the ultrasonic processing efficiency of raw materials is the frequency and intensity of ultrasonic vibrations. In this work, these parameters were limited to one value – 44 kHz and 0.4 W/cm^2, respectively. Therefore, of practical interest is the study of the influence of sonication on the kinetics of the drying process at other values of ultrasound frequency and intensity. The disadvantages include the fact that the studies were carried out only for one type of fruit – apples.

The further stage of our study is to design, on the basis of the obtained data, an industrial prototype of a technical means for ultrasonic processing of fruit and vegetable raw materials before drying.

7. Conclusions

1. The pretreatment of apple raw materials in an ultrasonic bath makes it possible to intensify the convective drying process without increasing the temperature of the heat

carrier in the drying chamber. It was found that sonication for 5 v reduces the dehydration process by 13.7 %, and at 10 min processing – by 27.8 % compared to the traditional drying method. With increasing processing time to 20 min, the sample dehydration rate deteriorates, which increases the duration of dehydration by 32 minutes compared to 10-minute treatment.

2. Processing of raw materials in the ultrasonic bath before drying with a combined heating technique for 5 minutes practically does not intensify the dehydration process, and within 10 and 20 minutes, on the contrary, reduces the efficiency of moisture removal. When processing samples in an ultrasound bath for 10 minutes, the time to reach the final moisture content is increased by 17.2 %, and at 20 min – by 23.4 % compared to control samples. At the same time, regardless of the duration of ultrasonic treatment, a decrease in the value of the maximum temperature of samples in the combined drying process is observed. The maximum temperature of samples during sonication before drying for 5 minutes decreased by 4.3 %, and during 10 and 20-minute processing – by 8.6 and 12 % compared to the temperature of non-sonicated samples.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

The manuscript has associated data in the data warehouse.

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