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Equilibrium Humidity as One of Important Energy-Efficiency Indexes in Drying of Food Powder Materials of Biological Nature

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Abstract

Considering general trend of energy consumption, according to which the amount of consumed energy increases, its cost and scarcity continuously increase. The 10–12 % of all energy is spent on drying processes in the world. At the current stage of the development of dehydration processes in Ukraine and the world, an urgent problem has arisen in the creation and development of highly efficient thermal technologies that would ensure minimal energy consumption for the process and high quality of the material. When drying powdered food materials of a biological nature, equilibrium humidity is important, which allows you to determine the final moisture content. Energy costs for the dehydration process, term, storage conditions and quality characteristics of the product depend on this indicator. The tensometric (static) method of Van Bamelen was used to determine the equilibrium humidity of the studied samples depending on the relative humidity of the air. The article presents the results of research – the kinetic curves of water vapour adsorption of antioxidant functional powders and instant cooking products (dry borscht) based on them were obtained and the comparative characteristics of the studied samples were carried out.

Keywords: adsorption; energy efficiency; equilibrium humidity; dry borscht; instant products.

1. Definition of the problem to be solved

Modern nutrition needs new high-quality products [1]–[4]. The development of energy-efficient thermal technology for the production of innovative instant dry products at hot food for the population is an important task, since people's health depends on it.

The study of adsorption processes is preceded by a number of other important studies. Adsorption is one of the final stages of research in the development of thermal technology for obtaining food powders and products from them. Therefore, it is advisable to briefly describe the previous main stages of heat technology with energy-efficient modes of convective drying with the presentation of relative specific heat consumption depending on the drying mode.

New thermal technologies with energy-efficient modes of convective drying developed at the Institute of Technical Thermal Physics of the National Academy of Sciences of Ukraine make it possible to obtain high-quality dry materials for the production of new functional food products with increased biological activity. They include vitamins, micro- and macroelements, specially selected complexes of plant and animal components. The created compositions do not contain extraneous chemical ingredients and stabilizers, but contain natural antioxidants, folates, phytoestrogens and prebiotics [5]–[7]. Due to the high content of these components, products based on them acquire functionality when used. During the processing of such raw materials, the native properties of the raw materials are almost completely preserved and at the same time the environmental safety criteria are met. These products were obtained due to convective drying.

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Red beet betanine, which gives red beetroot its colour, is a water-soluble pigment that was previously classified as anthocyanins. Betanine degrades under the influence of light, temperature, oxygen, pH of the environment. Therefore, it is used in products with a short shelf life or dry products. The 20–80 % of betanine is lost during storage and heat treatment of red beetroot. The intensity of the colour depends on the content of organic acids and the pH value. Therefore, almost all methods of preserving and stabilizing the colour of red beetroot processing products are aimed at maintaining the required pH level, reducing the duration of heat treatment and limiting the time of interaction of the product with air.

The Institute of Engineering Thermophysics of the National Academy of Sciences of Ukraine has developed a method of preparing antioxidant vegetable raw materials for drying, namely, the blending method - combining red beetroot with vegetable raw materials with an increased content of organic acids (lemon, rhubarb, tomato) in the appropriate ratio [7]–[8]. As a result of experimental studies, the optimal ratio of the components of the composition was obtained with a pH value in the range of 3.8–4.2, in which betanine is preserved at the level of 95 %.

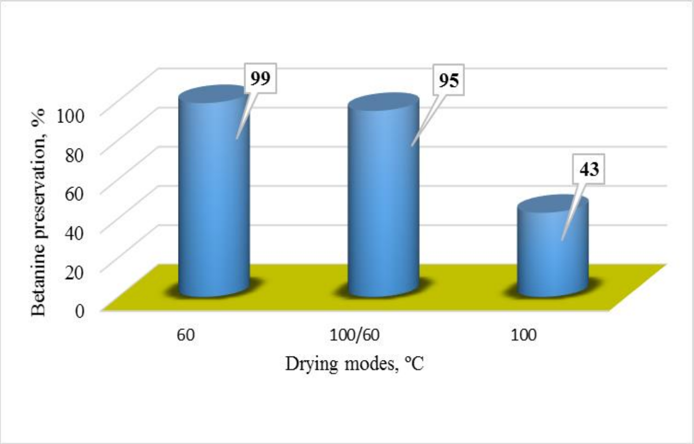


Fig.1. Preservation of betanine in the red beet-lemon mixture depending on the drying mode.

The results of studies of drying kinetics of antioxidant plant raw materials are described in previous works [6]–[8], from which it follows that an increase in the temperature of the coolant from 60 to 100 ºC reduces the drying time of the beetroot-lemon mixture, which is the basis of dry borscht, by 1.5 times, but at the same time biologically active substances are destroyed. The developed step-by-step mode allows you to reduce the duration of drying in comparison with the 60 ºC mode by 24 % while maintaining the chemical composition.

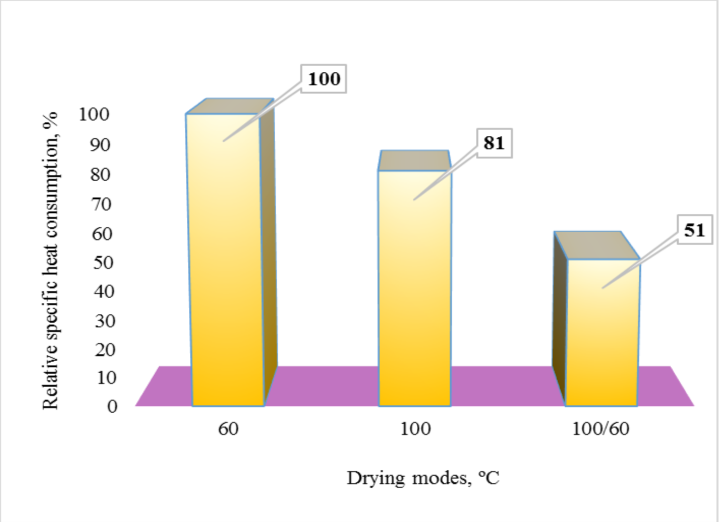


Fig.2. Relative specific heat consumption depending on the mode of drying the red beetroot-lemon mixture.

Figure 1 shows, the betanine preservation of the red beet-lemon mixture from the mode parameters of the coolant. The choice of the drying mode of red beetroot-lemon mixture was controlled by changing the content of betanine during the drying process. The best betanine preservation at the level of 99.1 % occurs at a coolant temperature of 60 ºC, the stepwise drying mode also has high results. At a temperature of 100 ºC, betanine is destroyed by almost half and is 43 %, while the colour of the beet-lemon mixture changes from red to brown, which indicates the destruction of the dye.

Figure 2 shows the relative energy costs for the drying process of the red beetroot-lemon mixture depending on the drying modes. In the step mode of 100/60 ºC, the relative specific heat consumption is 51 %, which is lower, than the drying mode at a heat carrier temperature of 60 ºC by 30 % and lower, than the 100 ºC mode by 49% (Fig. 2). The selected stepwise mode of 100/60 ºC allows you to reduce energy consumption by 49 % (Fig. 2) and save betanine by 95 % (Fig. 1).

Figure 3 shows the specific heat consumption during the drying of red beet-lemon raw materials in a stepwise mode 100/60 ºC. At the beginning of the stage mode process during the period of constant drying speed, the temperature of the heat carrier is maximum - intensive evaporation of moisture from the material occurs, while the specific energy consumption is minimal and amounts to 3450 kJ/kg of evaporate moisture. In the second drying period, the reduction of moisture removal is more intense, the temperature of the coolant is reduced because the temperature of the material rises, the average energy consumption is 4800 - 6500 kJ/kg of evaporate moisture (Fig. 3).

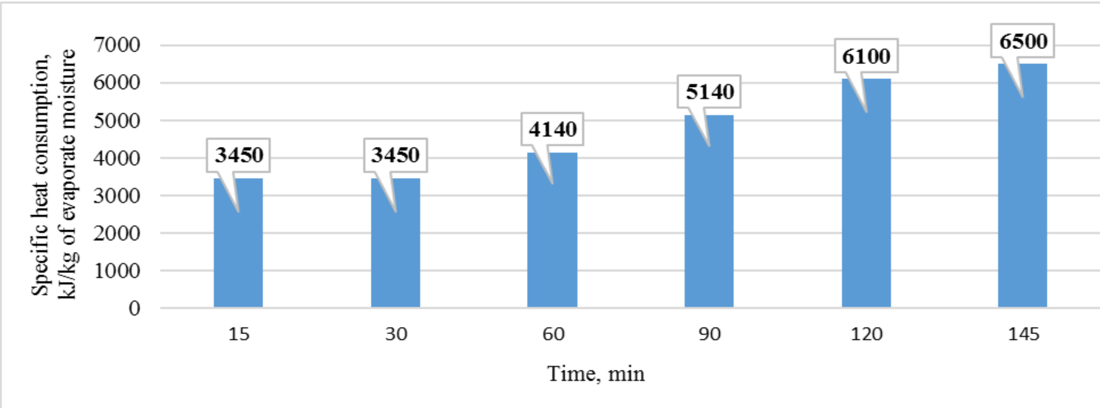


Fig.3. Specific heat consumption during drying of red beetroot-lemon raw materials in stepwise mode 100/60 ºC.

The specific heat consumption in the stage drying mode of 100/60 ºC depending on the time of the process showed that an increase in the drying time leads to an increase in the specific heat consumption.

At the same time, due to the use of a stepwise drying mode, it became possible not only to preserve red beetroot betanine by 95 %, but also to reduce energy carriers and develop heat technology for obtaining antioxidant powder.

Dry instant borscht (Fig.4) is one of those functional products developed at the Institute of Engineering Thermophysics of the National Academy of Sciences of Ukraine [9]. The dish is a mixture of natural dried vegetables in the form of pieces and food powders from them.

Dry borscht is the basis for the hot meals field ration of military personnel and the population in extreme conditions [10].

The main advantages of such dry instant products are: preservation of functional ingredients on 93–95 %; cooking time is 3–5 minutes, which is especially important in extreme situations; during recovery (adding dill to the dry mixture), the volume increases 7–8 times; do not contain chemical impurities (preservatives, stabilizers, emulsifiers, citric acid, starch); have high organoleptic indicators.

When developing thermal technology for obtaining such products, an important stage is the determination of storage conditions. Since equilibrium humidity is important during transportation and storage in warehouses, which determines not only the conditions of their storage, but also the final moisture content during drying. This is important, first of all, from the point of view of economical consumption of energy resources during drying and the use of production facilities [10]–[11].

Fig.4. Dry instant borscht for the preparation of hot meal, developed by
the Institute of Engineering Thermophysics of the NAS of Ukraine.

2. Analysis of the recent publications and research works on the problem

According to literary sources, this direction has a limited amount of information and therefore requires in-depth study and is an actual direction of research. Previously, experimental studies of the adsorption processes of food mono powders, antioxidant plant powders based on red beetroot were carried out [12].

3. Formulation of the goal of the paper

The main goal of this work was to determine the equilibrium moisture content of the studied samples and to conduct a comparative characterization of the adsorption properties of functional combined powders and instant product for hot food based on them. Since it is possible to obtain a real assessment of the shelf life and storage conditions of the developed new food products only as a result of research on adsorption properties.

4. Presentation and discussion of the research results

The tensometric (static) method of Van Bamelen was used, to determine the equilibrium humidity of the studied samples depending on the relative humidity of the air. The essence of the method is that material samples with predetermined moisture content are kept in desiccators over aqueous solutions of sulfuric acid. At a given temperature, the known concentration of solutions corresponds to a certain partial vapour pressure, that is, the corresponding value of the relative pressure [10], [12]–[14].

Samples of powders adsorb water from the surrounding air on the outer and inner strongly developed surface, since their surface has free energy. Adsorption on the surface of a solid dispersed body proceeds spontaneously until the dynamic equilibrium state of this thermodynamic system is established. Due to the variety of forms of moisture connection with dispersed materials, the analytical structure of sorption isotherms of dispersed materials is complicated. While the equation of the sorption isotherm is derived analytically, only for the Langmuir isotherms of capillary-porous bodies. Therefore, we, like most researchers, chose the empirical way of determining the equilibrium humidity [10].

The transfer potential in the adsorption process is the partial vapour pressure. Equilibrium in the system occurs when the partial pressure of air vapour $p_{air\ vapor}$ and steam in a thin layer over the material $p_{Mat.vapor}$ are aligned, namely at equality of temperatures of air and material $p_{air\ vapor} = p_{Mat.vapor}$. Under these conditions, the material receives a constant humidity $W_{equilib}$, which is called equilibrium, and the equilibrium in the system is understood only as dynamic. If the material absorbs moisture $p_{air\ vapor} > p_{Mat.vapor}$ – there is a sorption, if it gives off moisture $p_{air\ vapor} > p_{Mat.vapor}$, – there is a desorption [10], [12], [14]. At equilibrium, the humidity of the material $W_{equilib}$ is the same at any point.

The content of water vapour in the air is determined by the relative humidity φ, equal to the ratio of the partial pressure of air vapour $p_{air\ vapor}$ to saturation pressure p_{satur} at the same temperature over water.

Since the reference literature shows the dependence of water vapour pressure on sulfuric acid solutions in mm Hg from concentration H_2SO_4 in weight %, the recalculation of this pressure on relative humidity is carried out φ according to the following formula:

$$\varphi = \frac{p}{p_S}, \qquad (1)$$

where p and p_s are partial pressure and water vapour saturation pressure at pressure 760 mm Hg and temperatures covering the possible range of their change in the experiment.

The results of recalculation are presented in [10], [15]. The reference books show in tabular form the dependence of the water vapour pressure above the solutions on the weight % of H_2SO_4 in the solution (that is, on its concentration), as well as the dependence of the H_2SO_4 content in grams per 100 g of solution and on 1 litre of solution on the density of the solution in g/cm^3 at 20 °C for an acid with a density of 1.8305 [10], [15].

Since the determination of the equilibrium humidity of the combined powders had to be carried out in the range of relative air humidity φ from 0.4 to 0.9, which is typical for production conditions, the necessary characteristics of sulfuric acid were determined from the conversion table and reference data [11]. The experiments were carried out at ambient air temperature, which fluctuated within the limits 20 ± 0.5 °C.

It is advisable to calculate the equilibrium moisture in relation to the absolutely dry mass of the material, because this value remains unchanged in the processes of sorption-desorption and drying-wetting, so when processing all experimental data, the moisture absorbed by the material was attributed to the mass of the absolutely dry material [10], [15]–[17].

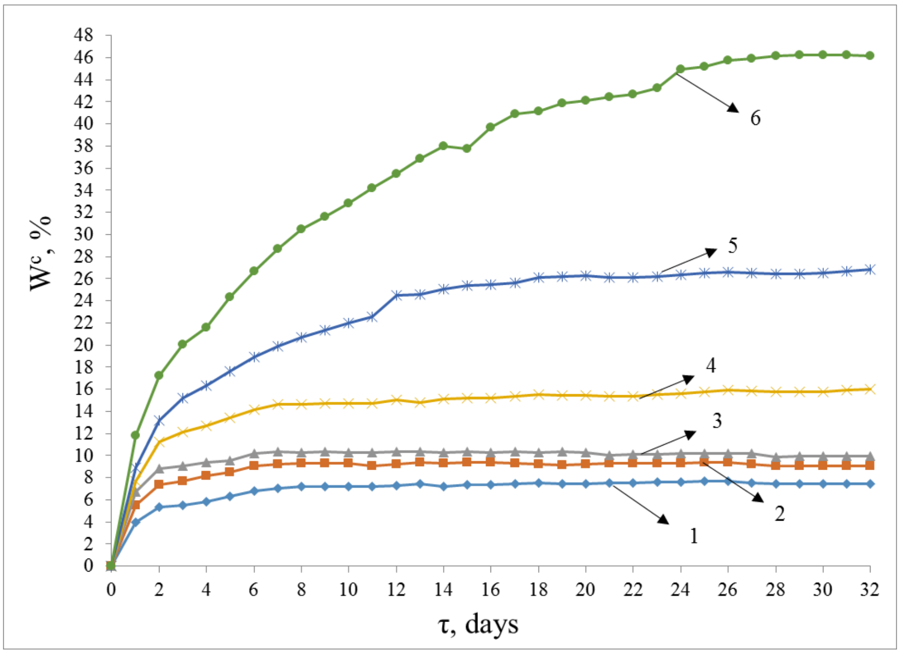


Fig.5. Kinetic curves of water vapour adsorption of antioxidant powder red beetroot – rhubarb: 1) φ = 0.4; 2) φ = 0.5; 3) φ = 0.6; 4) φ = 0.7; 5) φ = 0.8; 6) φ = 0.9.

Thus, sorption isotherms were obtained $W^s_e = f(\varphi)$ in the studied interval of relative humidity of air and the curve of sorption kinetics $W^s = f(\tau)$, since the experiment scheme also provides for the possibility of recording the change in moisture content of the samples over time.

The kinetic curves of water vapour adsorption by samples of combined powders with a particle size of d<0.5 mm obtained as a result of the experiments at the ratio of the components specified for each powder are shown in Fig.5, Fig.6 [12].

Analysis of experimental data shows that the curves have the same character. Within the limits of the studied air humidity, they are returned to the convexity W, which indicates the polymolecular nature of adsorption.

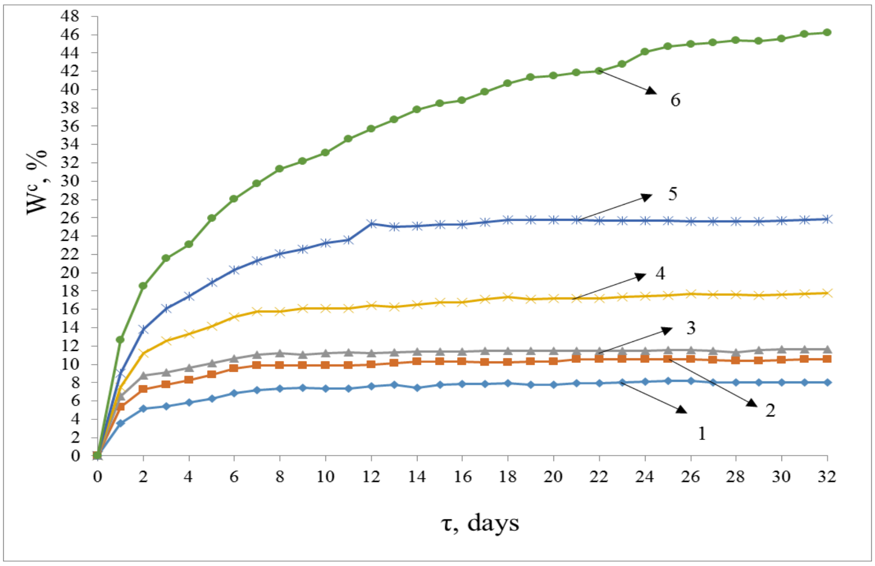


Fig.6. Kinetic curves of water vapour adsorption of antioxidant powder red beetroot – lemon:
1) φ = 0.4; 2) φ = 0.5; 3) φ = 0.6; 4) φ = 0.7; 5) φ = 0.8; 6) φ = 0.9.

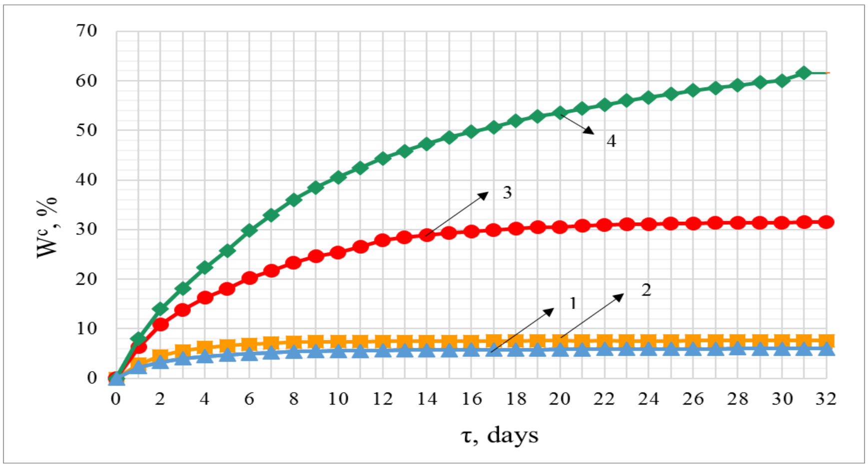


Fig.7. Kinetic curves of water vapour adsorption of dry instant borscht:
1) φ = 0.4; 2) φ = 0.6; 3) φ = 0.8; 4) φ = 0.9.

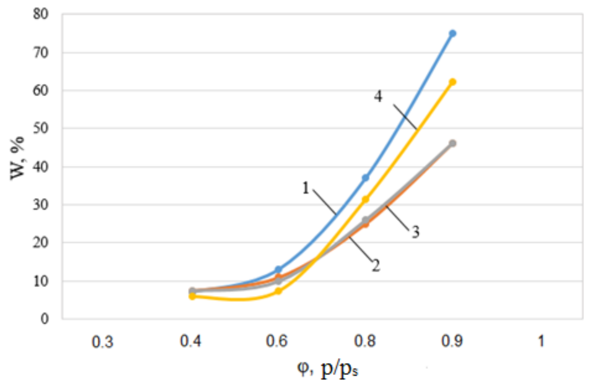
For red beetroot – rhubarb powder at φ = 0.4 – 0.6 equilibrium is set on 10 – 14 days, at φ = 0.7 – 0.8 on 16 – 19 days (Fig.5). For red beetroot – lemon powder at φ = 0.4 – 0.6 equilibrium is set on 8 – 10 days, at φ = 0.7 – 0.8 on 18 – 19 days (Fig. 6) [12].

To determine the equilibrium moisture content of dry instant products (in this case dry borscht) desiccators with relative humidity values were used φ = 0.4; 0.6; 0.8; 0.9 (Fig. 7). For borscht at φ = 0.4; 0.6 the equilibrium state is established on 7 days, at φ = 0.8 on 20 days, and at φ = 0.9 on 32 days. Table 1 presents the equation of experimental water vapour adsorption isotherms for beetroot–rhubarb, beetroot–lemon functional powders and the instant product dry borscht.

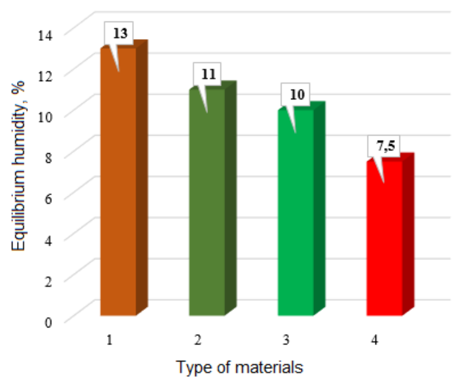
Table 1. Equation of the experimental water vapour adsorption isotherms of the studied samples

Food powder	Equation of experimental isotherms	Equations of linearized isotherms
Red beetroot–lemon	$W = 670.83\varphi^3 – 1076.2\varphi^2 + 583.92\varphi – 96.8$	$W = 1.5531e^{3.5923\varphi}$
Red beetroot–rhubarb	$W = 462.5\varphi^3 – 663.75\varphi^2 + 324.75\varphi – 45.8$	$W = 1.4493e^{3.674\varphi}$
Dry borscht	$W = 684.17\varphi^3 – 950.25\varphi^2 + 437.78\varphi – 60.86$	$W = 0.6484e^{4.8592\varphi}$

On the basis of experimental data on the equilibrium moisture content, water vapour adsorption isotherms of functional powders and instant products based on them were constructed (Fig. *8.a*). The main ingredients of dry borscht are carrot and red beetroot powders. At the value of $\varphi = 0.4$, the equilibrium moisture content of all the tested samples is within the limits 6 – 7 %. At $\varphi = 0.8$, the equilibrium moisture content of red beetroot-rhubarb and red beetroot-lemon powders is the lowest, almost the same and amounts to 24 – 25 %, carrot powder 38 %, and dry borscht about 31.5 %.



a)



b)

Fig.8. Water vapour adsorption isotherms *(a)* and equilibrium humidity *(b)* of mono- and combined powders and instant products based on them: 1 – carrot; 2 – red beetroot-lemon; 3 – red beetroot-rhubarb; 4 - dry borscht.

At $\varphi = 0.9$, the moisture value for carrot powder is 76 %, for red beetroot–containing powders 48 %, and for dry borscht 62 %. The comparative characteristics of the equilibrium humidity at $\varphi = 0.6$ of carrot, red beetroot–lemon, red beetroot–rhubarb powders and dry borscht based on them are presented in Fig.8.*b*. As can be seen from the figure, the equilibrium moisture content of carrot powder is the highest and is equal to 13 %, red beetroot–lemon and red beetroot–rhubarb powders are 11 % and 10 %, respectively, and dry borscht is only 7.5 %.

5. Conclusion

The experimental data presented in the article show that the studied materials are capillary-porous colloidal bodies in powder form, obtained with the help of developed energy-efficient modes of convective drying. They have the same forms of moisture binding (adsorptive, capillary and osmotic), yet they differ from each other in equilibrium moisture. Water vapour adsorption isotherms demonstrate that monopowders have the highest equilibrium humidity. When combining them and creating functional powders, this ability is reduced, which leads to improved storage conditions, and the equilibrium moisture content of instant products is in most cases lower, even than that of combined functional powders. This is probably due to the interaction of the components of the composition. When storing composite powders and dry instant products based on them, in order to preserve their technological properties, it is recommended to maintain the following conditions in the room: air humidity 60–70 % at a temperature of 20–25 ºC and pack them hermetically.

Dry borscht, developed at the Institute of Engineering Thermophysics of the NAS of Ukraine, is used to compose hot food field ration of the country's Armed Forces under the extreme conditions. Development of new and improvement of existing energy-saving heat technologies solves the problem of rational use of raw materials, fuel and energy resources. This has not only a scientific, but also a social aspect, because at the same time the scientific foundations of rational nutrition are formed and, accordingly, the quality of life increases.

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Рівноважна вологість як один із важливих показників енергоефективності при сушінні харчових порошкоподібних матеріалів біологічної природи

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Анотація

Із урахуванням загальної тенденції енергоспоживання, згідно з якою кількість спожитої енергії збільшується, її вартість та дефіцит безперервно зростають. На процеси сушіння в світі витрачається 10–12 % всієї енергії. На сучасному етапі розвитку процесів зневоднення в Україні та світі постала нагальна проблема в створенні та розробці високоефективних теплотехнологій, які б забезпечували мінімальні витрати енергії на процес та високу якість матеріалу. При сушінні харчових порошкоподібних матеріалів біологічної природи важливою є рівноважна вологість, що дозволяє визначити кінцевий вологовміст. Від цього показника залежать енергетичні витрати на процес зневоднення, термін, умови зберігання та якісні характеристики продукту. Для визначення рівноважної вологості досліджуваних зразків залежно від відносної вологості повітря застосовувався тензометричний (статичний) метод Ван Бамелена. В статті представлено результати досліджень – отримано кінетичні криві адсорбції водяної пари антиоксидантних функціональних порошків та продуктів швидкого приготування (сухий борщ) на їх основі та проведена порівняльна характеристика досліджуваних зразків. В результаті досліджень виявлено, що рівноважна вологість функціональних (буряково–лимонного та буряково–ревеневого) порошків становить 11 % та 10 %, а сухого борщу лише 7,5 %.

Ключові слова: адсорбція; енергоефективність; рівноважна вологість; сухий борщ; продукти швидкого приготування.