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**ENERGY-SAVING
HEAT
TECHNOLOGIES
FOR
OBTAINING SOY
BASED
PLANT
POWDERS**

NATIONAL ACADEMY OF SCIENCES OF UKRAINE
INSTITUTE OF ENGINEERING THERMOPHYSICS

НАЦІОНАЛЬНА АКАДЕМІЯ НАУК УКРАЇНИ
ІНСТИТУТ ТЕХНІЧНОЇ ТЕПЛОФІЗИКИ НАН УКРАЇНИ

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ТЕПЛОТЕХНОЛОГІЇ
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PLANT POWDERS**

*PROJECT
«UKRAINIAN SCIENTIFIC BOOK
IN A FOREIGN LANGUAGE»*

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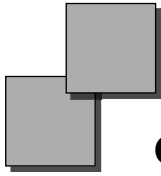
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The monograph is devoted to solving the problem of energy-saving and development of resource-saving heat technology for processing soybeans and their mixtures with carotene-containing raw materials on functional phytoestrogenic food powders. The paper considers modern research and methods of processing phytoestrogenic raw materials. The study of heat and mass transfer processes during convective drying and the study of thermophysical and physicochemical properties of phytoestrogenic raw materials and its protein-carotene mixtures are presented. Innovative heat technology for the production of phytoestrogenic powders based on soybeans, recommended for use in the pharmaceutical, dairy and food industries, has been developed.

The monograph is intended for employees of the food industry, students of higher educational institutions, masters and graduate students of engineering and technical specialties.

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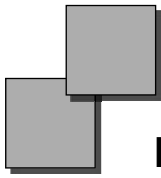
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INTRODUCTION

Outdated technologies used in the drying process lead to irrational use and high energy consumption and cause an increase in energy consumption. This brings the issue of energy saving and energy efficiency to one of the most important tasks to be solved. In current conditions, these issues are an integral part of the problem of ecology. Ukraine, having a unique environment for Europe, being fully supplied with natural resources, is also one of the countries in the region where energy resources are used least efficiently.

One of the most relevant areas of research is the issue of energy efficiency of drying methods. Drying of plant materials is a thermal process during which the technological and biochemical properties of the material change. The application of process parameters that do not correspond to the properties of plant material leads not only to unnecessary energy costs, but also to deterioration of the quality characteristics of the final product.

A polluted environment directly affects the physical condition of the population. Poor nutrition, constant stress and a problematic ecology compose a complex that interacts daily with human immunity. The Ministry of Health of Ukraine reports: «The highest mortality rate in the world is caused by malnutrition. This figure is higher than due to smoking, high blood pressure and other risk factors. Therefore, food must have functional properties, and its processing should ensure maximum preservation of biologically active substances contained in it.

One of the processing methods is drying of vegetable raw materials. The problem of energy saving occupies a leading place in the drying process. In the food industry, drying is one of the ways to preserve plant raw materials, which allows one to extend the shelf life of products and preserve their quality characteristics and nutrients as long as possible. This is extremely positive in the case of canning (drying) of PPRMs with a high content of protein and fat, in particular soybeans. As recently predicted, the growth of protein deficit in Ukraine is becoming more common. It is noted that soy products are able to compensate the lack of protein in the diet of people around the world.

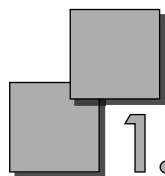
It is known that soybeans contain antifoed components that interfere with the digestion of soy proteins. Therefore, there is a problem of their neutralization, which involves hydrothermal treatment of PPRMs. Existing techniques involve the use of high temperature and multi-hour treatments, which leads to high energy consumption. Consequently, there is a need to improve them.

At present, the most effective equipment for drying vegetable raw materials in the industry, are convective drying units, the advantages of which are in operational and structural simplicity.

In processing PPRMs, it is very important to properly perform their preliminary preparation for drying, during which there is a risk of abrupt changes in technological and biochemical properties of the material.

It is proved that appropriate vegetable raw materials require appropriate technological modes of previous preparing and drying. PPRMs especially need most accurate adherence to the technological mode of processing, because an improper mode can lead to oxidation of their lipids, which chain reaction can start the process of destruction of all biologically active substances contained in them.

Drying of PPRMs is a long process. Together with the stage of the previous preparing, the drying process has a high total energy consumption. Therefore, there is a need to intensify the process with the maximum reduction of drying time and the development and improvement of heat technologies for drying vegetable raw materials, which will allow processing products with minimal energy consumption, long shelf life and preservation of biologically active substances.



1. CURRENT STATE OF EQUIPMENT AND TECHNOLOGIES FOR DRYING OF PLANT RAW MATERIALS

1.1. Phytoestrogenic raw materials of plant origin as an object for drying

Nowadays, the international status of Ukraine depends on the effective realization of its advantages of resource potential in the world labor market and in competitiveness. In the agricultural sector of Ukraine, the strategy of its development should be aimed at creating an environmentally safe, efficient, socially oriented and resource-saving scientific sector of the state economy, capable of securing the position of world food market leader in agriculture and domestic needs [1].

Protein deficit of the Ukrainian population is more than 20% [2]. It is predicted that in the near future the most important factor in the nutrition of people around the world may be soy [3]. Soy-based protein products are an ideal source of essential amino acids that supplement grain proteins and can completely replace animal protein. There are more than 50 variations of soybean products [3]. The most popular are: soy flour, soy protein concentrate, soy isolates, textured protein, soy milk, meat and milk substitutes, soy cheese (tofu).

The same product can be both alternative and concomitant for soybean products, which is facilitated by the variety of applications of soybean products, whether for feed or for food purposes. In view of the law of demand, rising meat prices lead to low meat consumption, which in turn reduces the demand in the livestock industry for feed, where soybean meal is one of the components of feed. At the same time, the reduction in demand for meat increases the consumption of soybean products such as textures, concentrates, isolates; in this example soybeans and meat products are alternative products [4].

Over the years 2005-2018 soybean cultivation increased by 16 times, and according to the State Statistics Service of Ukraine from 1990 to 2018 soybean yield doubled (Fig. 1.1).

Ukraine is a leading supplier of soybeans to the European Union. In particular, out of 2.76 million tons of exported beans harvested in 2017, almost 30% was sent to the EU (according to the European Danube Soybean Association) [5].

1. CURRENT STATE OF EQUIPMENT AND TECHNOLOGIES FOR DRYING OF PLANT RAW MATERIALS

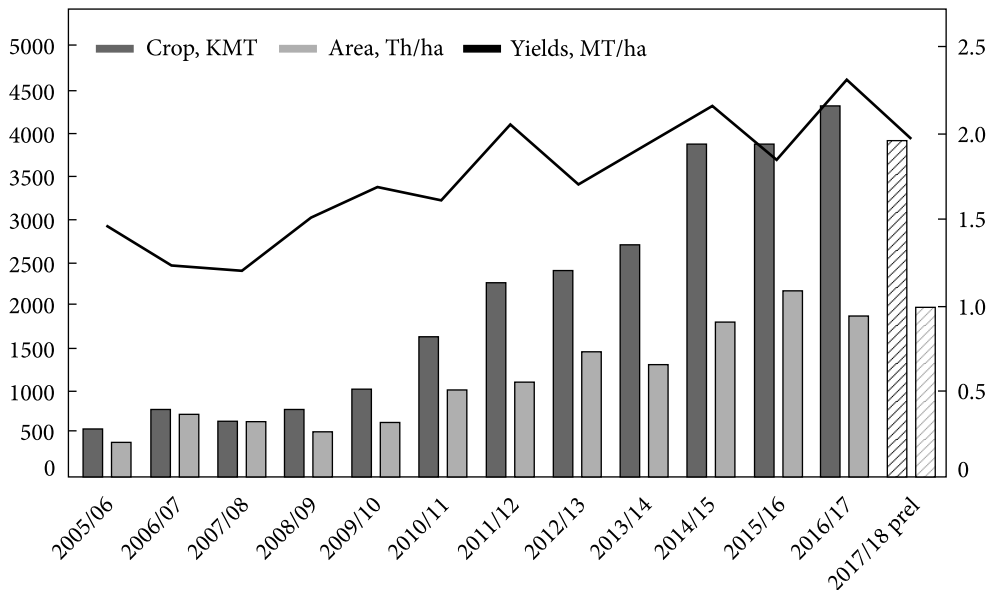


Fig. 1.1. Soybean crop over the period 2005-2018 (UkrAgroConsult)

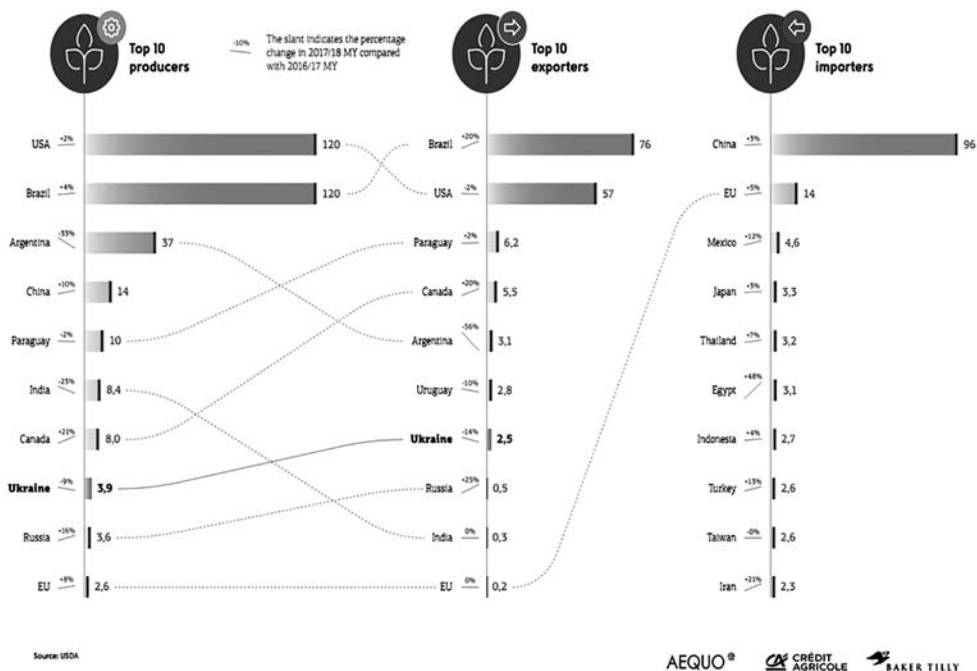


Fig. 1.2. The largest producers and exporters/importers of soybeans in the world according to the Danube Soybean Association

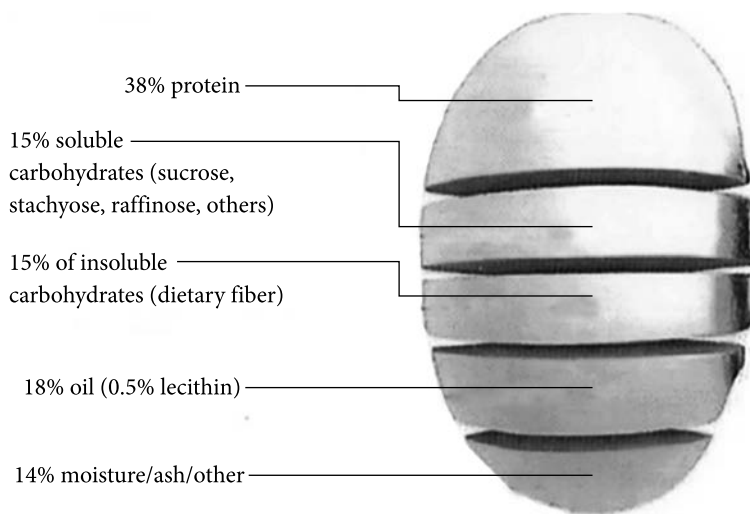


Fig. 1.3. The composition of soybeans

Ukraine is the largest producer of soybeans in Europe and ranks the 8th in production and the 7th in export in the world (Fig. 1.2).

According to the agrarian news agency «Agravery», in 2018 Ukraine increased exports of soybeans to Turkey, Belarus, Azerbaijan, etc. Belarus imports soybeans for further processing of protein-containing raw materials.

An expert of agrarian markets of the association Ukrainian Club of Agrarian Business has informed Landlord that Ukrainian soybean producers have been leading for the last 5 years, annually increasing their rating in the Chinese market [6].

The main factors that affect and form the supply of soybeans and their processing product are as follows [4]:

- change in resource prices: rising mineral fertilizer prices reduce supply of soybean;
- technology change: integration of new technology in soybean processing increases supply;
- change in taxes and subsidies: annual compensation to agricultural producers for soybeans sown and compensation from the state budget for high-quality soybean seeds cause an increase in production and, adequately, in supply of soybeans;
- change in prices for other goods: a decrease in purchase prices for feed protein ingredients causes an increase in the supply of soybean meal;
- change in the number of suppliers: an increase in the number of enterprises engaged in soybean processing is related to an increase in the supply of processing products.

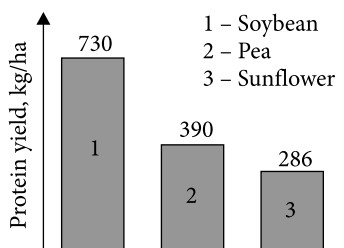


Fig. 1.4. Protein yield, kg/ha

Soy protein has a fairly balanced amino acid composition, which is almost identical to the balance of an ideal protein. Soybeans contain: 35-45% of complete protein, 18-25% of fats, biologically active substances (BAS) and 8 essential amino acids [7]. The composition of soybeans is shown in Fig. 1.3.

The World Health Organization recommends soy as an important protein-containing product that helps to overcome protein starvation [2]. Soybean proteins include all essential amino acids necessary for human and animal life: leucine, isoleucine, lysine, methionine, cysteine, phenylalanine, tyrosine, threonine, tryptophan, valine and histidine, although they are limited by two amino acids — methionine and tryptophan [2].

Physicochemical properties of soybeans depend on the natural features of the structure and properties of plant tissues and cells [9].

Alternatively, a deficiency of vegetable protein in foods can be eliminated by increasing production of legumes and perennial legumes. Protein yield from soybean seeds per 1 ha of field with the same yield (20 c/ha) is 2.5 times higher than from sunflower seeds and twice higher than from pea seeds (Fig. 1.4) [10].

Soy contains plant phytoestrogens, that is, substances contained in scanty amount in almost every plant food but in different quantities and, most importantly, are not synthesized in the human body.

Phytoestrogens have the ability to keep the hormonal balance of the human body [11]. They are chemically similar to human estrogens. Fig. 1.5 presents the classification of phytoestrogens.

It is proved that natural phytoestrogens, especially isoflavones (genistin, daidzein), when consumed by children and adults in food, do not cause hormonal imbalances in the body. Soy contains more than 100 phytoestrogens and is almost their main source of human intake, especially in Asia [12]. They include several classes of chemical compounds: isoflavones, coumestans and lignans.

Isoflavones are present in various edible plants, but are most common in soybeans [13-15]. They are similar in structure to the human hormone estradiol, which is the most active form of estrogen [16, 11]. The greatest attention of researchers is directed to studying the influence of isoflavones as the main representatives of a phytoestrogenic soy origin on the human body [12]. People whose diet includes soy have higher levels of isoflavones in the blood plasma. Soy is common in the diet of the Asians, so the consumption of isoflavones reaches 50 mg/kg.day. Consumers of the Western diet have 1-3 mg/kg.day. The average level of plasma genistein for an Asian woman is about 25 ng/ml. Among vegetarians who follow the Western-type diet, this figure is lower. Among US women, it is 2 ng/ml. Vegetarianism or consumption of supplements can not

only increase the use of phytoestrogens to the level of the Eastern diet, but also exceed it [17-19].

Soybeans contain vitamin E, which together with isoflavones forms a complex that can reduce the risk of dangerous diseases such as breast cancer, osteoporosis, coronary heart disease, kidney stones and relieves women of postmenopausal symptoms. Researchers from India emphasize the healing properties of soybeans and other peculiarities of this legume, 92-100% protein of which is digested by the human body [20].

Brazilian scientists found that it is important to process whole soybeans due to the high amount of saponins that are lost during processing in the soybean shell [21]. Saponins have the ability to protect the human body from radiation exposure, namely radionuclides that weaken the immune system [22].

Since 2000 in Ukraine, soybeans have turned from an outsider into one of the main oilseeds due to their high fat content [23]. Polyunsaturated fatty acids, which are part of its cell membranes, as well as other structural elements of plant tissues, perform in the body a number of important functions, such as ensuring normal growth and metabolism, vascular elasticity, etc. [7].

The human life-time depends on various factors, and the main one is a balanced diet. If a person has a protein deficiency in the diet, then various diseases can occur, as well as reduced life expectancy. Research over the past 20 years has shown that soy-based products have the ability to promote good health [10] (Fig. 1.6).

Soy is associated with a reduced risk of certain diseases, such as heart disease, hypertension, cholesterol and breast cancer [24]. The use of soy ingredients in foodstuff is receiving considerable attention from the food industry and consumers due to their role as functional food. The functionality of food can be solved in terms of food components.

Low-salt soy foods are recommended for a healthy diet and longevity in Japan, as well as worldwide, where non-communicable disease mortality rates are over 60% [25]. Soybeans and other protein-containing legumes are considered to be an environmentally friendly source of protein that is stably available and able

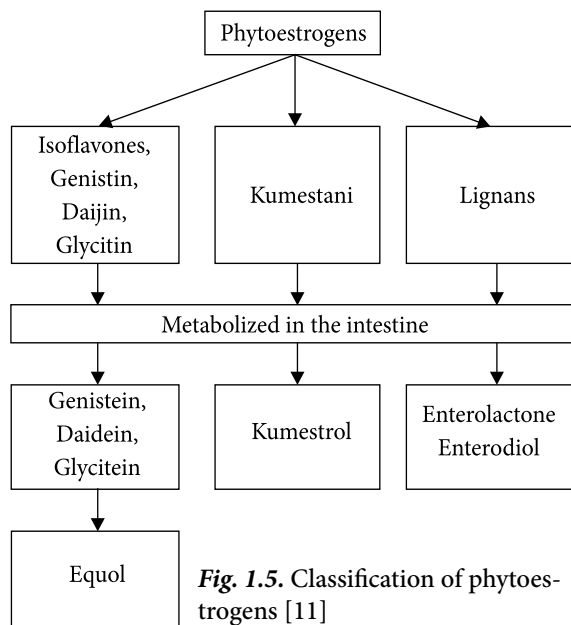


Fig. 1.5. Classification of phytoestrogens [11]

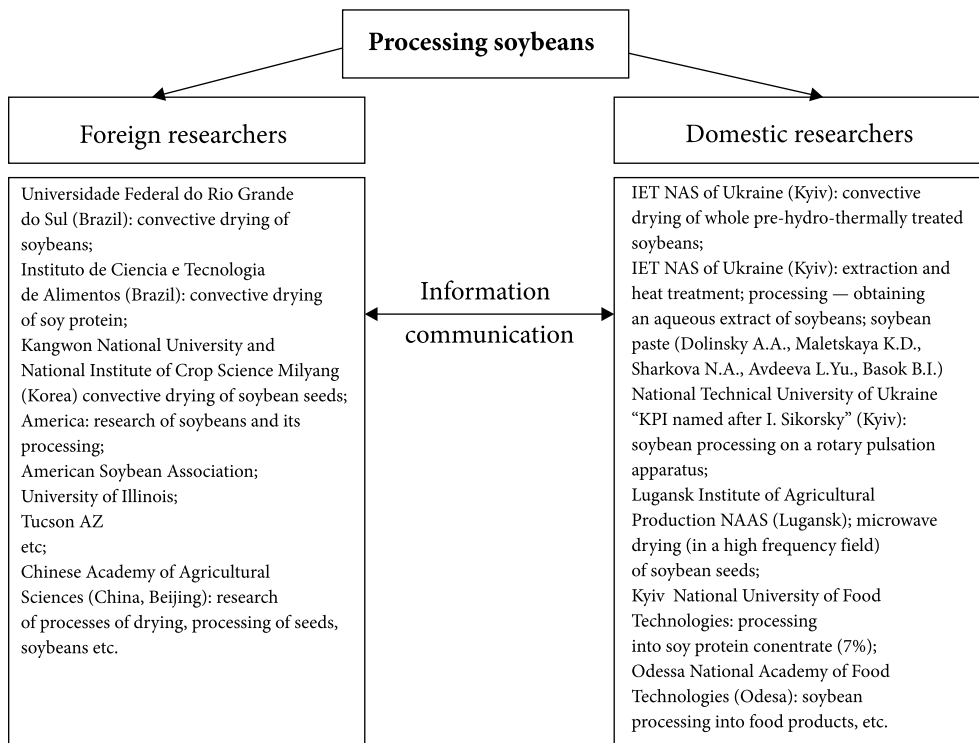


Fig. 1.6. Current foreign and domestic researchers of soybean processing

to support about 10 times more people than the number of people in Japan who typically receive protein mainly from beef and pork [26].

Japanese scientists recommend adding soy to the diet to achieve healthy longevity by preventing cardiovascular diseases worldwide [27].

Despite the great health benefits of soy ingredients, the availability and rich amino acids composition, the variety of processing products, the issue of soybean processing and energy efficient production require detailed study [28].

Due to the high content of lipids, which during storage have the ability to oxidize, soybeans need processing [29, 2]. The main purpose of processing vegetable raw materials is to obtain products with a long shelf life. One of the most effective methods of preserving agricultural raw materials is drying [30].

The technology for drying protein-containing raw materials (soybeans) and the quality of the obtained product largely depend on their properties and chemical composition. Soybeans as an object of drying are characterized by a number of features due to its biological nature, which must be taken into account when choosing the type of drying equipment and conditions of the dehydration process, namely:

- high initial moisture content;

- thermolability (color, aroma, taste, structure, nutritional value of the product deteriorates, proteins are denatured when using high heat carrier temperatures);
- the content of anti-food components (trypsin inhibitor) that require additional energy consumption for inactivation;
- high amount of lipids (fats), which reduces the shelf life of finished products.

1.2. Review of existing methods for processing and drying of phytoestrogenic plant raw materials (PPRM)

Drying is one of the most energy-intensive operations. Several authors report that it uses up to 25 % of all industrial energy [31, 32].

Great contribution to the development of energy-efficient processes of drying vegetable raw materials was made by such well-known scientists as A.V. Lykov, P.A. Rebinder, A.A. Dolinsky, Yu.F. Sniezhkin, Zh.O. Petrova, K.D. Maletska, N.A. Sharikova., L.Yu. Avdeeva, A.V. Dumanskyi, B.V. Deriagin, Yu.A. Mykhailov, P.D. Lebedev, B.M. Smolskyi, O.A. Kremnev, Yu.L. Kavkazov, A.A. Guhman, B.B. Krasnikov, A.S. Ginzburg, M.F. Kazanskyi, N.V. Churayev, N.N. Gamaiunov.

Problems in the environmental and energy sectors, including greenhouse gas emissions, fossil fuel depletion, etc., make it extremely important to reduce energy consumption in all industries [33].

One of the most pressing issues today is the issue of energy efficiency of drying methods [34]. Dehydration of wet plant materials is both a heat-engineering and technological process, which changes the technological and biochemical properties of the material [35, 36]. The drying process is a complex set of interconnected processes of heat transfer to the material through the boundary layer, the stage of heat transfer; phase transformation, evaporation stage; transfer of moisture and heat inside the material, stage of heat transfer; transfer of moisture and heat from the surface of the material to the environment through the boundary layer, stage of heat and mass transfer, which is realized by diffusion or molecular transfer, characteristic for the transfer of vapor mass and inert gas; filtration or molar transfer under convection; thermodiffusion, ie the transfer of moisture under the influence of the temperature gradient, while the direction of thermal diffusion of the mass flow density of the substance corresponds to the direction of heat flux density [37].

Most of the substances obtained in industrial conditions are wet bodies that contain large amounts of water. Wet material consists of three phases: solid skeleton (dry matter), liquid (water) and gas (air, water vapor). Raw materials of plant origin are a colloidal capillary-porous body, in the pores of which there is air or water vapor.

Drying of colloidal capillary-porous bodies is a process of removing water, accompanied by disruption of the bonds of water molecules among themselves and with the other components [38].

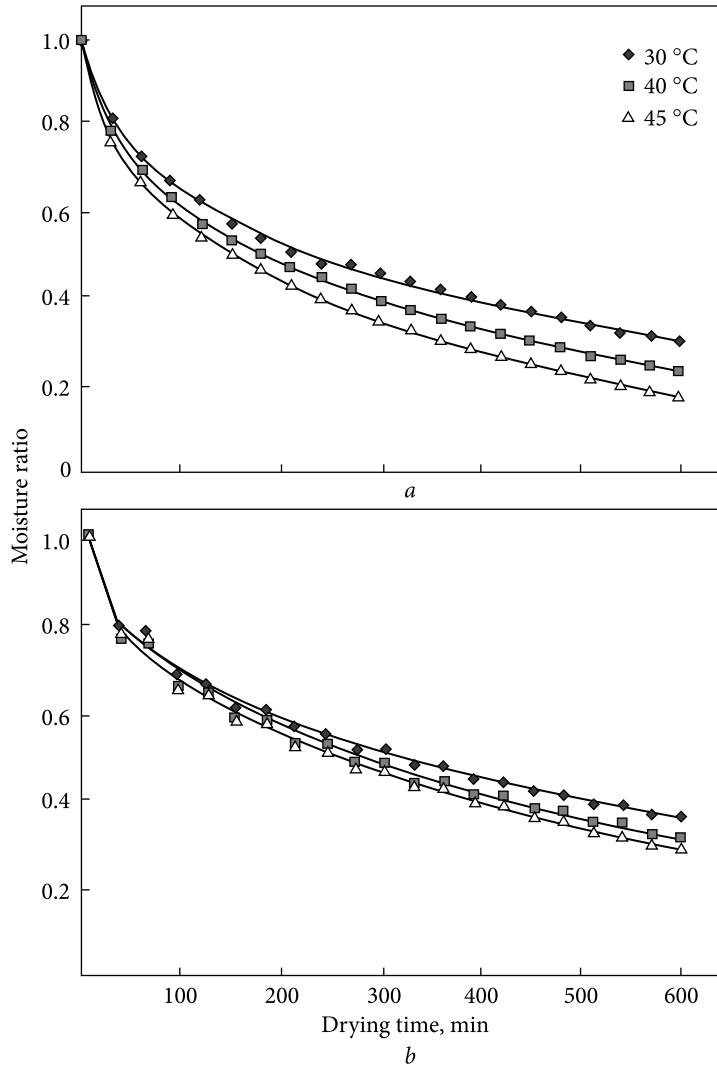


Fig. 1.7. Change in the moisture content in soybeans at the drying temperature under (a) continuous and (b) periodic drying

The classification of moisture bonding forms in such bodies is based on the principle of changing the energy of its bonding [35, 39, 40]. As the binding energy decreases, the forms of moisture bonding are arranged in the row: chemically-, adsorption-, osmotically- and capillary-bound water. Bound water in materials of plant origin is divided into osmotically-, colloidal- and capillary-bound [41-43].

Chemically bound water has the highest binding energy to the material and is not removed during drying [44]. The energy of a chemical bond is identical by magnitude to the heat of chemical reactions (tens of kJ per mol) [38].

Adsorption-bound water is held by molecular forces on the outer and inner surfaces of micelles (colloidal particles). Adsorption of water by micelles of the body is accompanied by the release of heat and compression of the system. Absorption-bound water differs in its properties (heat capacity, density, etc.) from free moisture [44].

Osmotically-bound water is a structural water that is absorbed by complex bodies. Osmosis through the plant membrane occurs due to the difference in chemical potentials on different sides of the membrane [45]. Osmotically-bound water is considered entropically bound because osmotic binding reduces free energy due to an increase in entropy. In the absence of stronger bonds of water, the energy of the osmotic bond becomes noticeable.

Capillary-bound water: the liquid fills the capillaries not only upon contact, but also by sorption from moist air. The radii of the capillaries should be so small that the free surface of the liquid could take the shape due to the surface tension forces and interaction with capillary walls. The capillary bond energy is about 102 J/mol [41-43].

The process of removing moisture from plant material is accompanied by the consumption of energy to break the bond between moisture and material. Drying modes depend on the nature of this connection and provide the most efficient removal of moisture, as a result of which microorganisms do not develop in dried fish, dairy products, milk, fruits, mushrooms and vegetables [46]. During drying, the products significantly lose weight, which facilitates their storage and transportation, increases the energy of the product compared to the raw material [47]. Dried products have an extended shelf life. However, in the process of drying there are undesirable changes: oxidation of lipids and vitamins, deterioration of taste and aromatic properties, etc. [7].

Scientists from Korea (College of Agricultural Sciences and the National Institute of Plant Sciences) study the processes of drying soybeans using an interval drying [48]. The study consisted in the fact that 25 g of raw soybeans were convectively dried at 35, 40 and 45 °C, the velocity of the coolant (dry air) was 3 m/s. The total drying time was 600 min. Every 30 min, a change in the mass of the material was recorded. The initial moisture was 22%, drying lasted until the residual moisture content 7.7%.

As a result, such studies have shown that periodic drying provides a higher rate of decrease in moisture content mainly due to the diffusion of moisture from the center to the surface during the rest period. Thus, an interval drying can help reduce the energy consumption required for drying soybeans (Fig. 1.7) [48].

Scientists from the Central Institute of Agricultural Engineering (India) studied the effect of drying on protein, trypsin inhibitor, nitrogen solubility, water absorption, color and electrophoretic structures of flour prepared from sprouted soybean varieties «JS 9305» and «MAUS 47» [49]. The whole drying process con-

sisted of: drying in the sun (35-40 °C), steaming with hot air drying at 60 °C, drying in a hot air oven at 100 °C, and microwave heating at 400 W and 630 W. Scientists have found that the required 80% and steaming followed by drying and microwave heating affect the color; herein the solubility of nitrogen is negative. Drying at 100 °C reduced the trypsin inhibitor to safe limits and did not adversely affect the solubility, color and electrophoretic structure of nitrogen and can be recommended for drying germinated soybeans on an industrial scale to prepare good quality soybean flour for product development. Drying at 35-40 °C has minimal effect on color, nitrogen solubility, and electrophoretic structure and can be used to prepare soy flour for baking purposes. The disadvantage of this drying is the long high-temperature drying, which leads to the denaturation of proteins contained in soybeans [49].

The influence of 30, 60, 90 and 120 °C on the drying of composite films of soy protein isolates/carboxymethylcellulose/stearic acid was studied at the Beijing Academy of Agrarian and Forestry Sciences. Scientists were able to establish that when dried at 90 °C, the tensile strength of composite films was 2.63 times higher than the control, and the vapor permeability of composite films was 77.6% of the control. Hence, the temperature of 90 °C was the balance point of the composite films [50].

Brazilian scientists of São Paulo University studied the effect of drying conditions (air temperature and relative moisture) on the mechanical properties, solubility in water and color of two types of soy protein isolate film: commercial (CSPI) and others obtained in the laboratory (LSPI), which were evaluated using the surface response methodology. Soy protein films were prepared by casting using glycerin as a plasticizer, then dried in a chamber with air circulation at a controlled parameter of relative moisture (24, 30, 45, 60, 66%) and air temperature (34, 40, 55, 70, 76 °C). It was confirmed that the mechanical properties of films made of LSPI and CSPI are affected differently by the drying conditions due to the different initial structure of protein in both types of materials. The researchers found that the solubility of LSPI films was affected by temperature and relative moisture, which is the lowest (~50%) for commercial films obtained at high relative moisture and from 45 to 76 °C. For CSPI films, on the contrary, the solubility is not dependent on the drying process and remains relatively constant (40%). The optimal drying conditions determined by the surface response methodology were: 70 °C and 30% for CSPI films and 60 °C and 60% for LSPI films. CSPI films dried under these conditions were characterized by higher tensile strength, less elongation at break, less solubility and better water permeability and oxygen permeability than LSPI films [51]. Therefore, the higher the moisture content in soybeans, the higher the temperature threshold of denaturation of proteins depending on the exposure time.

Heat treatment is the main method for destroying anti-food components found in raw soybeans. There are various technologies that are based on the fol-

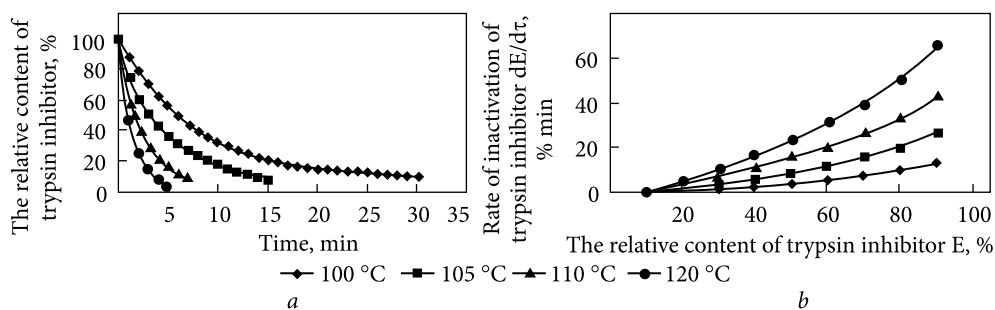


Fig. 1.8. Dependence of (a) inactivation of trypsin inhibitor and (b) its rate on the heat treatment temperature of soy suspension

lowing sequence: the beans are heated for some time, sometimes using the principle of additional moisture, usually in the form of steam. The values of temperature, time and moisture change not only during processing, but also at individual stages. After heat treatment, the nutritional value of the product sharply improves and the contamination of seeds with microflora decreases [7].

At the Institute of Engineering Thermophysics (IET) of NAS of Ukraine, N.A. Sharkova and other scientists have studied the solubility of soy proteins and the kinetics of inactivation of inhibitor trypsin in obtaining an aqueous extract of soy in order to create a technology for production of soy drinks [52]. The scientific idea was as follows: in order to obtain a soy suspension pre-soaked in a soy/water ratio of 1:1, soybeans were loaded into the installation with the addition of water to create a hydraulic module 1:9. The product was ground, heated in hermetically sealed volume by direct contact and mixed with coolant-water vapor at a rate of 18-20 °C/min. After reaching operating temperature, samples were taken to determine the content of trypsin inhibitor by standard methods. Built-in sensors (chromel-copel thermocouple) allowed control and regulation of the processing temperature.

Figs. 1.8 and 1.9 show the results of studies on inactivation of trypsin inhibitor after treatment of soy suspension in the apparatus at temperatures of 100, 105, 110 and 120 °C. The researchers found that as the processing temperature of the soy suspension increased, the process of inactivation of the trypsin inhibitor accelerated. That is, at 100 °C inactivation of trypsin inhibitor lasted 30 min, while at 110 °C did 7 min [52].

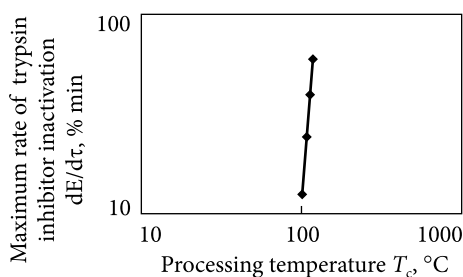


Fig. 1.9. Dependence of the maximum rate of inactivation of trypsin inhibitor on temperature

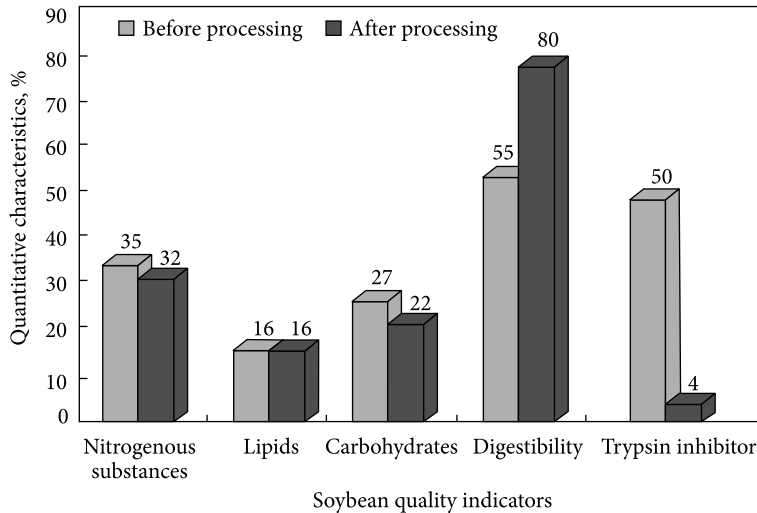


Fig. 1.10. Diagram of quality indicators of soybeans

At the IET NAS of Ukraine Zh.O. Petrova in the frame of her candidate dissertation «Development of processes of obtaining carotene-containing food products» studied the influence of hygrothermal treatment on the quality of soybeans (Fig. 1.10) [29, 7].

Hydrothermal treatment is a thermal effect on raw materials which dramatically changes its properties. It has the following sequence: soaking soybeans in water for an hour ($t_{\text{water}} = 50\text{ }^{\circ}\text{C}$) and changing it after 30 min, cooking for 20 min at $t = 100\text{ }^{\circ}\text{C}$. Compared to soybeans without hydrothermal treatment, the treated ones lose only up to 5% of soluble protein, which is converted into water, and fats remain unchanged.

During hydrothermal treatment there are observed: insignificant loss of 10% of soluble carbohydrates due to loss of oligosaccharides that are not absorbed by the human body (a positive factor); completely inactivated trypsin inhibitor (anti-food protein), and therefore improvement of the digestibility of proteins, which is positive [29, 7].

At the National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute» (KPI) scientists analyzed the kinetic patterns of grinding soybean seeds in water, obtained using a three-stage rotary pulsation apparatus [53].

Fig. 1.11 shows the kinetic curves for large and small fractions. It was established that small fractions of soy are extremely tiny particles, and so move together with water, are difficult for mechanical processing and weakly destroy under the hydrodynamic effects.

Moreover, at IET NAS of Ukraine, Zh.O. Petrova has studied drying of protein carotene-containing mixtures, in particular, soybeans with carrots, in the coolant temperature range from 70 to 120 °C (Fig. 1.12).

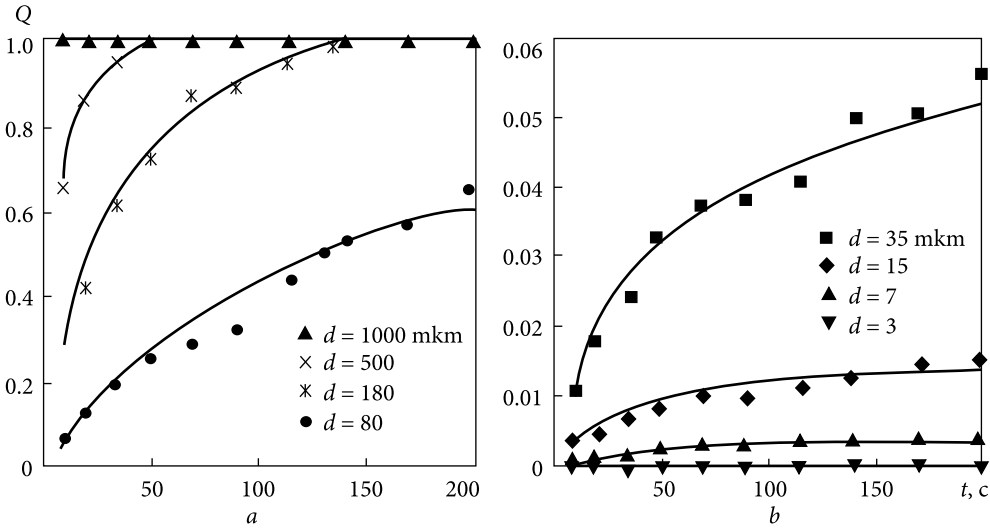


Fig. 1.11. Kinetic curves: a — large fractions; b — small fraction

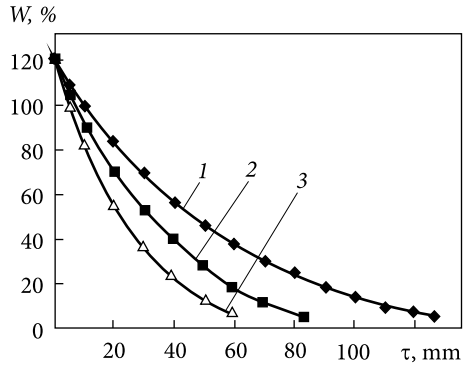


Fig. 1.12. Influence of the heat carrier temperature on dehydration of soybean-carrot composition: 1 — 70 °C, 2 — 100 °C, 3 — 120 °C. Mode parameters: $V = 2$ m/s; $d = 10$ g/kg dry air

The studies showed that the drying process of the binary mixture occurs in the 2nd period. As the evaporation zone inside the material deepens, the surface temperature increases and the rate of moisture transfer decreases. The duration of drying in the mode of the heat carrier 120 °C is reduced by almost twice compared to that for 70 °C.

Also, Zh.O. Petrova studied the influence of heat carrier temperature on the acid number (AN) of raw materials, which is an indicator of preservation and destruction of biologically active substances. At a drying temperature of 100 °C, AN increases to 5-8%. The shell around soybean and rape seed protects their fats from temperature exposure, which prevents the oxidative process. When soybean and rapeseed are ground, the oxidation process is more intense, AN increases with increasing material temperature. At the temperature of the crushed material 70 °C it increases to a critical level, 4.2-4.5%, and at 100 °C increases to 9-11%, which is unacceptable. It has been found that the preparation of mixtures of soybeans, rape seed and vegetables (Fig. 1.13) makes it possible to preserve fats as

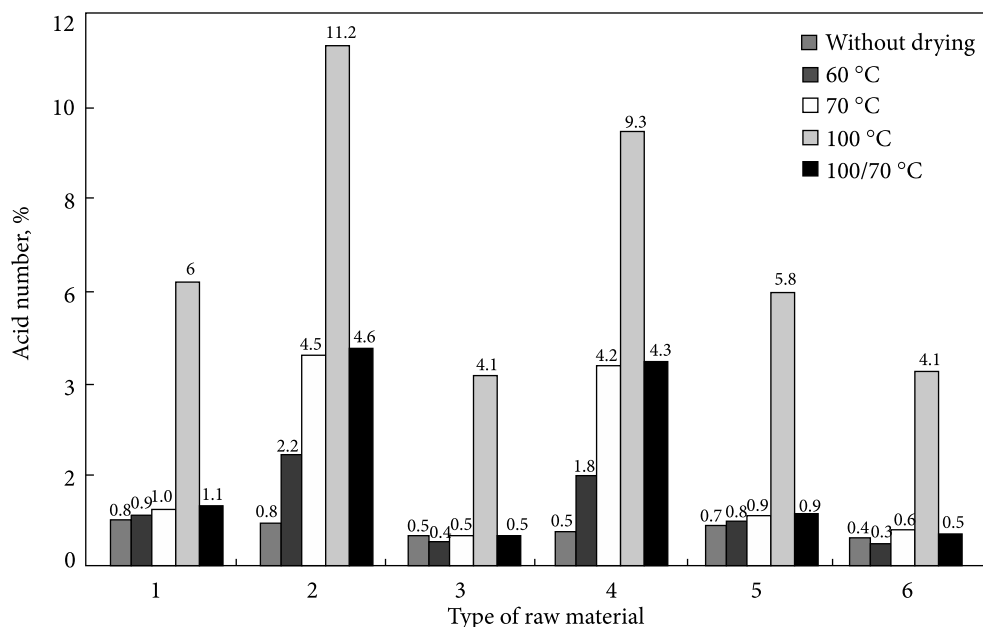


Fig. 1.13. Change in AN of PPRMs under the action of heat carrier temperature: 1 — rape seed; 2 — ground rape; 3 — soybeans; 4 — ground soybeans; 5 — rape-carrots; 6 — soy-based compositions: soy-carrot, soy-beet, soy-onion, soy-pumpkin

many as possible, as well as to develop drying regimes for PPRMs with a heat carrier temperature of 70 °C [54].

Drying distinguishes between natural (in the sun, in the shade) and artificial (thermal, sublimation, chemical, microwave) conditions [55].

For drying vegetables, fruit and medicinal plants, various drying installations are used (Table 1.1), which are classified by various signs [56]:

- by the method for supplying heat to the material: convective, conductive, sublimation, thermoradiation, high and ultrahigh frequency currents;
- by the air pressure in the drying chamber: atmospheric, vacuum, sublimation;
- by the nature of the installation: periodic and continuous action;
- the type of heat carrier : using heated air or superheated steam;
- by the nature of heat carrier circulation: with natural and forced supply of heat carrier , when centrifugal or axial fans are used;
- by the nature of heat carrier movement: direct-flow, counter-current and cross-flow of the heat carrier;
- by the design of the dryer: depending on the type of vegetable raw materials (Table 1.1);
- by the method for their heating: electric, steam, fire heating;

- by multiple use of heat carrier: single and multiple;
- the type of drying object: for solid, liquid and post-like products [56].

Heat drying is carried out in dryers with air heated to 60-200 °C. Conductive (contact) drying is a collision of a product with a hot surface of drums (drying of milk, mashed potatoes) [57]. Convective drying is carried out due to convection, heat transfer in a medium with inhomogeneous temperature distribution, which is realized due to the macroscopic elements of the medium during their movement in the drying chamber, where the drying agent is at the same time both a heat exchanger and a desiccant [57, 58]. The disadvantage of this method is the high energy expenses for the process and heating of heat carrier. The advantage of this method is a safe thermal effect on vegetable raw materials, ensuring maximum preservation of biologically active substances (BAS) and quality characteristics of the final product.

Microwave drying is a drying under high-frequency electromagnetic radiation. In this method, the heat supply is carried out using an electromagnetic field of ultra-high frequency (2450 MHz) [59]. The advantage of this method is its high productivity, versatility and easy management, but the main disadvantage is the high cost of electricity and energy consumption as well as partial loss of biologically active substances.

Sublimation drying is a kind of conductive method, based on the removal of moisture from frozen products by sublimation of water, ie the direct transition of ice into steam, bypassing the liquid phase, under conditions of deep vacuum [60]. During freeze-drying, the chemical composition, nutritional value, organoleptic properties of the product are preserved as much as possible, and the shelf life of the product can be increased up to 3 years. The method is used for dehydration of products of plant and animal origin. The disadvantages of this method are the

Table 1.1. Construction of dryers for vegetable materials [56]

Product	Construction of dryer
Vegetables, fruits and waste processing	Chamber, conveyor, tunnel, drum, sublimation
Bagasse	Drums, drums with pneumatic tubes
Grain	Mine, column, carousel, drum, etc.
Bread	Chamber, conveyor, tunnel
Pasta	Cabinet, chamber, tape, conveyor (with canes)
Medicinal raw materials	Chamber, tunnel, conveyor
Baking yeast	Cabinet, chamber, carousel, drum, vibrating, tape, pneumotubes, vacuum, sublimation
Fodder yeast	Rolling, spraying

high cost of the final product (by 7-8 times) and lower swelling rate as compared to convective drying.

Infrared or radiation drying is based on the heat transfer from an energy source by electromagnetic oscillations through a medium transparent to thermal radiation [55]. The advantage of radiation treatment is the cessation of the life of many species of putrefactive microflora and insect pests at relatively low doses. Technological disadvantages of infrared drying devices are: high uneven thermal impact on the irradiated surface, large losses of thermal radiation that extends beyond the treated surface and significant dimensions. In addition, the vapor of the evaporating liquid interacts with the surfaces of the radiation source and reflectors, which leads to their rapid oxidation and reduces the quality and reliability of the devices [61].

The disadvantages and problems described above were an incentive to look for alternative methods of pre-treatment and drying. The main goal of the modern food industry, including drying, is to produce high quality products with a minimum level of capital and operating costs. For this reason, special emphasis is placed on reducing operation time, reducing power consumption and minimizing the negative effects of processing [62-67].

In addition, combined drying methods are used, for example, convective and contact drying, high frequency electric drying and thermal convective or radiation drying, etc. [68].

1.3. Types of equipment for drying PPRMs

Drying of wet materials is both a thermophysical and technological process, in which the processes of heat and mass transfer are bound in one whole. At the same time structural-mechanical, physicochemical, biochemical and other properties of the dried material change. Proper scientifically sound organization of the drying process can ensure the production of material with the required technological properties at sufficient drying intensity and minimum heat and electricity consumption. The choice of drying method, optimal process mode and design of drying equipment is determined by the properties of the dried material, as well as the technology of its production [44].

Nowadays, there is a considerable choice of drying equipment (depending on the type of dried material). Convective, tunnel and belt dryers have proven to be the most effective for vegetables and fruits [56].

Convective-conductive dryers are the most common in the industry due to the simplicity of the device design and operation. Material to be dried is in the drying chamber in a stream of coolant (heated air), which is in direct contact with the material, and transfers heat to it, while absorbing moisture is removed from the raw material [56].

Convective chamber dryers are one of the simplest designs for drying various raw materials. They have the following advantages: simplicity of design and operation; versatility; maintainability, etc. However, the disadvantages are: high energy consumption, a high percentage of manual labor and uneven drying process in the chamber. The amount of manual labor is extremely difficult and expensive to change (this disadvantage is inherent in almost all food processing processes), but reducing energy consumption and equalization of temperature fields and moisture in the working chambers of convective dryers are of the main tasks facing designers and developers of techniques [69].

Fig. 1.14 presents a universal convective chamber dryer with air recirculation, manufactured by LLC «Techprom-Product» «Sadochok» (Ukraine, Vinnytsia) [70], with a drying area of 8.5 m², a sectional heater, finned stainless steel heaters. The average power consumption of the chamber dryer is 9 kW. Maximum load of raw materials is 100 kg. The duration of one drying cycle is 18-24 h. The maximum temperature of the drying agent is 65 ± 5 °C. The drying modes are optimal by temperature and moisture, set and maintained automatically. Dimensions: (not more) 1300 × 1160 × 2300 mm, weight: (not more) 340 kg.

The advantages of the presented dryer are durability, automation and versatility, but significant disadvantages are need of manual labor, the frequency of installation operation and high energy consumption for heating the heat carrier.

The Indian company «Optytech Engineers» presented a vegetable continuous dryer with a capacity of 2000 kg per day [71]. The metal part of the equipment contains a galvanized structure of all materials of the contact part made of PVC material SS-304 for the food industry. The process begins with a continuous supply of raw materials to the drying chamber (capacity 710 kg/day), where the material passes through a heated dry air zone. At stage 1, drying takes place at a drying agent temperature of 70-80 °C, at stage 2 — 45-55 °C. 85-90 % of moisture is removed during the whole process. The whole drying time of 1 batch of vegetables is 4-5 h. The machine is controlled via the automatic control panel, which allows one to set different parameters, such as heating temperature, air velocity time, exhaust temperature for all types of modes (Fig. 1.15).

Bucher DryCab vacuum drying cabinets [72] are the most common contact drying systems in the world for periodic drying of the product (Fig. 1.16). Drying cabinets are built in such a way that the heating plates can be in-



Fig. 1.14. Convective dryer with air recirculation

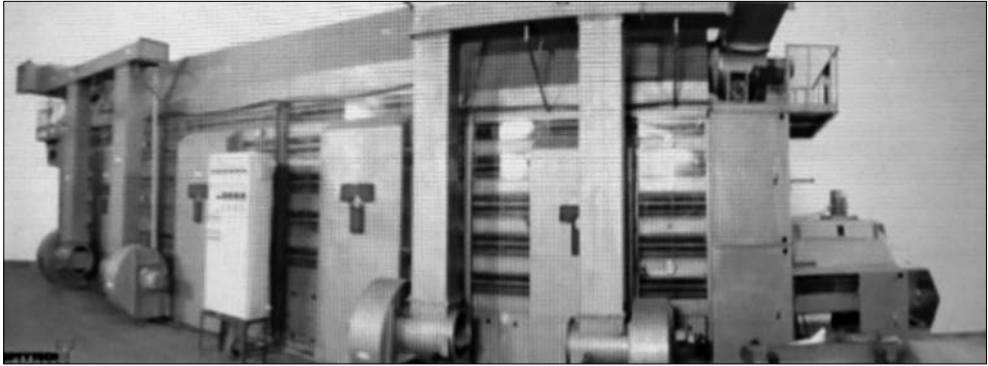


Fig. 1.15. Vegetable dryer of continuous action



Fig. 1.16. Vacuum drying cabinet

stalled in a horizontal position, above each other, with a minimum distance between them. Due to the use of a vacuum system, the drying process can be performed at low temperatures, thereby maintaining the quality of the dried material.

The working volume of the drying chamber is from 2.5 to 2500 l, the temperature range is from 20 to 150 °C, the power is 15-80 kW, the evaporation productivity is 0.5 to 250 kg/h of evaporated moisture.

The disadvantages of vacuum dryers include the high cost of the drying unit due to the complexity of its design and the need for additional equipment, in particular, a special condensing unit. Difficulties in controlling the drying process during the dryer operation, namely leakage through opening the hatches in the dryer violates the vacuum conditions (additional energy consumption). Although vacuum dryers have a number of advantages, because of their design complexity they are only used when required by specific technological features of material under processing.

Belt dryers work by the principle of continuous action and are used for drying fruits and vegetables cut into pieces of different configurations. The dryer has a chamber, inside which the material to be dried moves together with its carrying tape. Drying is performed with heated air or its mixture with flue gases at a mixture temperature of 70-170 °C. Air circulation is carried out by axial fans. The air penetrates the raw material from top to bottom and presses it to the belt conveyor. The dried material descends from the belt to the discharge conveyor. Such dryers are built with a belt width of up to 2–2.2 m and a length of 30–40 m [57].

Their disadvantage is an uneven drying through the layer thickness.

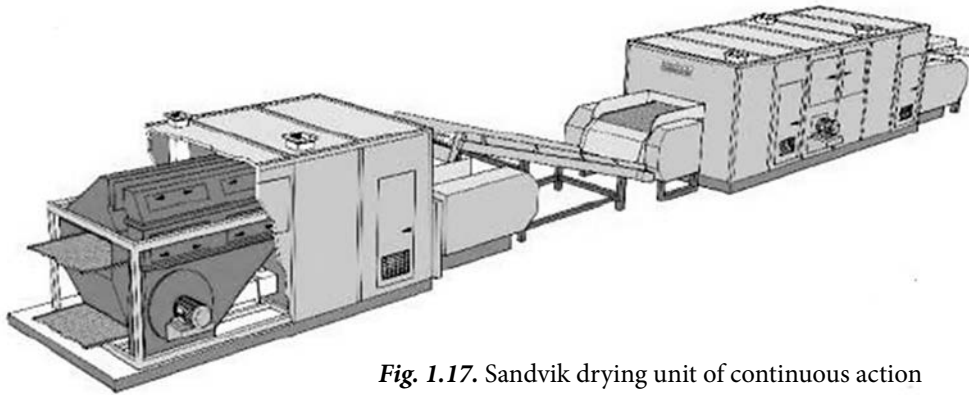


Fig. 1.17. Sandvik drying unit of continuous action

High-performance belt dryers, in which the material is mixed while poured from one belt to another, have high results in terms of uniformity of drying. In these dryers the heat consumption is from 5000 to 7500 kJ/kg of moisture [57].

A perforated tape is used in the Sandvik continuous belt dryer (Fig. 1.17) [73]. Average steam consumption of the Sandvik dryer is 1.67 kg of steam per 1 kg of evaporated water. The Sandvik dryer is capable of processing 2000 kg/h of carrot mass with an average moisture of 85% (exactly as provided by the initial technical and economic tests) and the final orange granules have a moisture of about 10%.

Belt dryers are widely used in the production of food powders. In belt (conveyor) dryers, the material is decomposed in thin layers on perforated sheets, sieves or tapes, which change its position when move. The product is dried in the form of a dense 7.5-15 cm thick layer. The air flow velocity in belt dryers is relatively small (1-3 m/s) [68].

Fig. 1.18 presents a conveyor dryer KSK-2 developed in the IET NAS of Ukraine with fire heaters on liquid fuel for drying vegetables, fruits and other plant raw materials that allow pouring from one conveyor belt to another [34].

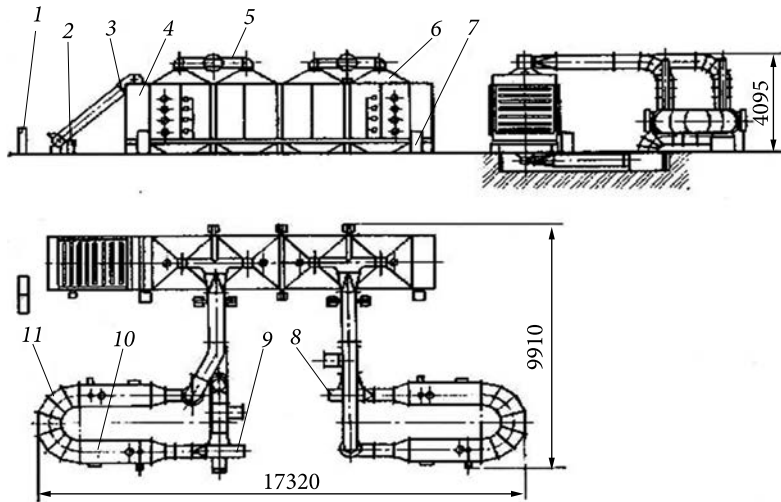


Fig. 1.18. Conveyor dryer KSK-2 developed in IET NAS of Ukraine for drying vegetables and fruits: 1 — control panel; 2 — autonomous drive station; 3 — loading conveyor; 4 — drying chamber; 5 — collectors; 6 — exhaust boxes; 7 — drive; 8, 9 — centrifugal fans; 10 — heat generators; 11 — air ducts

The dryer is a closed heat-insulated chamber in the middle of which 5 belt mesh conveyors made of stainless steel are located above each other in parallel. Each belt conveyor is offset relative to the other, along the length of the drying chamber, for pouring the product from one belt to another. The belts move opposite each other, their rate is adjustable [34].

The advantages of conveyor dryers are: ensuring the continuity of drying; possibility of smooth regulation of dryer productivity due to change of rate of separate conveyors; significant reduction in the installation area [68].

The disadvantage of belt dryers is an uneven distribution of air due to clogging of the heater surface, which leads to uneven distribution of temperature and moisture up to possible overheating of the material. Also in these dryers there is a problem of cleaning tapes from the stuck product, which leads to disturbance of temperature mode, periodic stop of the dryer and decrease in productivity [68].

Spray drying is the most common way to obtain products of microbiological synthesis from native solutions, as it provides drying of liquids in a few seconds [74]. Fig. 1.19, *a* shows a three-stage spray dryer A1-OR2Ch for drying milk and dairy products (CJSC «Kalinovsky Mashzavod», Vinnytsia region, Ukraine). Today, the Niro company offers 75 spray drying schemes.

Fig. 1.19, *b* shows four major dryers used in practice. The efficiency of different types of spray dryers is: 54% for a one-stage drying unit with a system of pneumotransportation; 62% for a two-stage drying unit with an instantizer; 75% for a

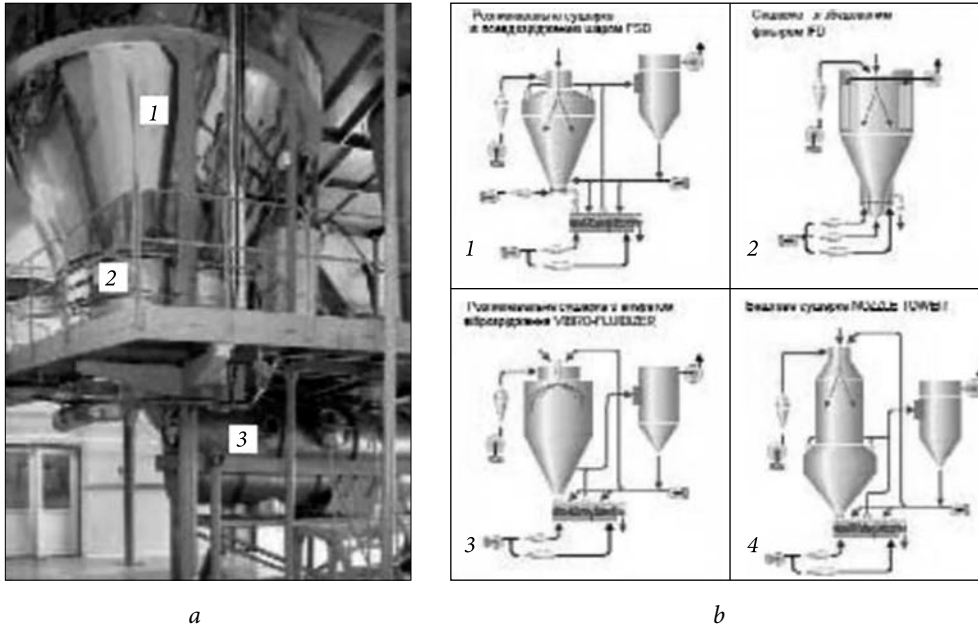


Fig. 1.19. Three-stage spray dryer A1-OR2Ch (a) with 1 — spray chamber, 2 — fluid bed and 3 — vibrofluidizer; (b) schemes of spray dryers of the Niro company

two-stage drying unit with a built-in fluidized bed apparatus and pneumatic conveying; 80% for a three-stage high-temperature drying unit with a built-in fluidized bed apparatus and an instantizer. These dryers can also be used for drying multi-tonnage products of microbiological synthesis for non-medical purposes [74].

The advantages of spray dryers are: high rate of the drying process; low temperature of the material during drying; obtaining the product in the form of a fine powder that does not require grinding, it is also well soluble. The material temperature does not exceed the temperature of the evaporated moisture (60-70 °C) and the temperature of the drying agent. The disadvantages are: relatively large size of the drying chamber (due to low velocity of the drying agent and low capacity of the spray chamber in terms of evaporated moisture (to 2-25 kg/(m³h)) as well as complexity of spray mechanisms and systems of dust collector and unloading [75].

The IET NAS of Ukraine has developed a two-stage method for spray dehydration [76]. At the first stage, a highly wet product is evaporated, the concentration of solute in the initial solution is 3.0-12.0% (yield 25-35%). At the second stage (spray chamber), the product is dried to the final moisture $W = 1.5-4.0\%$. Such a division of the process into stages creates opportunities for significant intensification of the heat and mass transfer process as a whole, allows one to utilize the heat of coolant used in the drying chamber, increase product yield by capturing the fine powder fraction in the evaporating chamber, that is, spray

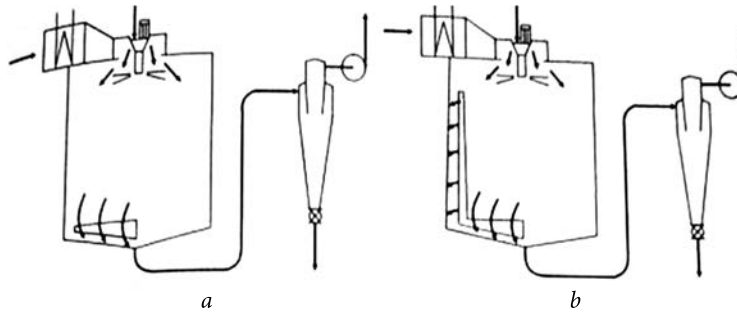


Fig. 1.20. Scheme of spray dryers with a flat bottom: (a) with a rotating unloading device on the chamber bottom; (b) with an air «broom» and a scraper mechanism on the chamber bottom

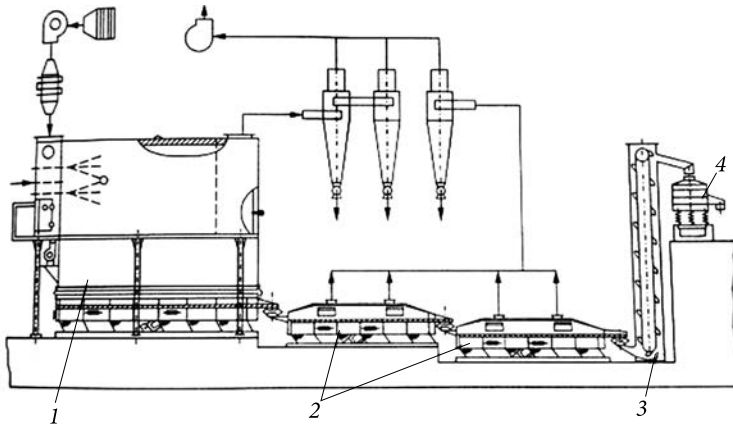


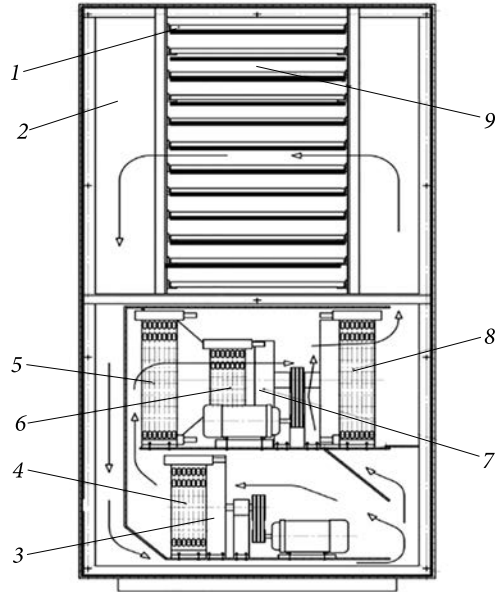
Fig. 1.21. Scheme of a drying unit with a horizontal spray chamber: 1 — spray nozzle dryer; 2 — vibratory convective dryer; 3 — elevator; 4 — vibrating sieve SV-0.9

concentrator. The IET has developed spray drying units with a flat bottom which has a slight inclination to the vertical axis of the chamber (Figs. 20, 21).

Such designs make maintenance easier due to the possibility of the operator to get inside the camera. A disadvantage consists in the fact that the unloading system often does not provide the required reliability, there are jams of dried powder inside the chamber, which makes it difficult to quickly evacuate the product. This is especially important when drying foods rich in fat.

Also, the IET NAS of Ukraine has developed a heat pump drying cabinet (Fig. 1.22) designed for drying thermolabile materials using heat pump cycles. It is possible to implement dehydration of various materials of plant and animal origin, synthetic materials and products, medicinal herbs and mushrooms, vegetables, fruits with the help of a heat pump drying unit. The advantage of the in-

Fig. 1.22. Heat-pump drying cabinet with infrared heaters: 1 — trays; 2 — drying cabinet; 3 — circulation fan; 4 — atmospheric heat exchanger (lower); 5 — freon evaporator; 6 — atmospheric heat exchanger (upper); 7 — fan; 8 — freon condenser; 9 — infrared heaters



stallation design is as follows: drying takes place in a closed circulation circuit with forced drying of the drying agent; part of the spent humid drying agent is delivered to the sucking circulation fan, where the heat of vapor condensation is utilized to be used for evaporation of the cooling agent.

Cooling and removal of moisture from the drying agent in the evaporator and its heating in the condenser occur under the conditions of the heat pump cycle in a compression refrigeration unit with additional infrared heating, which utilizes latent heat and liquefaction of drying agent vapor, and thus significantly reduces energy and reduces costs drying without loss of all useful properties of thermolabile materials. The source of energy for the operation of a heat pump dryer with a combined heat supply is electricity. The disadvantage of the heat pump dryer is that it is used for drying thermolabile materials only.

According to the multi-stage drying technology developed in the IET NAS of Ukraine, a three-zone tunnel drying unit TF 2.03 with three heat generators is used for drying vegetable raw materials with functional properties. The schematic diagram of the drying unit is presented in Fig. 1.23 [11].

The side labyrinths of the seal (5) are installed in the body of the drying unit in the form of flexible heat-resistant felt aprons. When moving, the carts from the nominal position along the length of the dryer create a maze of seals, which together with the cart doors stop the movement of air along the dryer, its discharge from the dryer and provides a rational scheme of blowing carts.

In the dryer walls there are two holes through which resistance thermometers are introduced inside the drying tunnel, which allows one to register the coolant temperature of each zone of the installation. Temperature in the zones is fixed by a KSP 4 recorder placed on the control panel. The heat generator is installed in an auxiliary room, it is connected to the fan and the dryer by an air duct. The heat generator is designed to heat the air supplied to the dryer. With the help of natural gas combustion, the air is heated. There is no direct contact between the combustion products and the heated air.

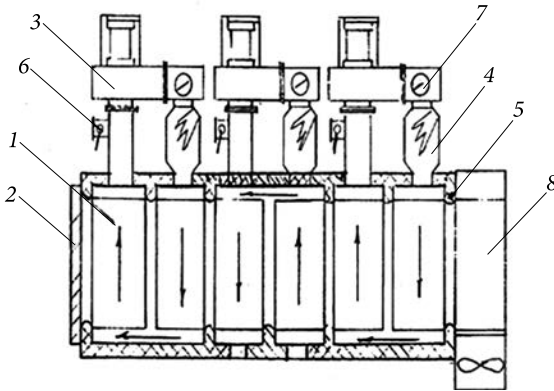


Fig. 1.23. Schematic diagram of a three-zone drying unit TF 2.03: 1 — drying area; 2 — gate; 3 — fan; 4 — heat generator; 5 — seals; 6 — latch with biofilter; 7 — exhaust latch; 8 — cooling zone

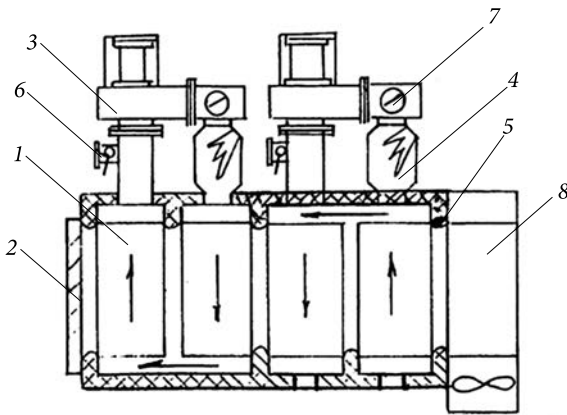


Fig. 1.24. Two-zone dryer with the heat generator TF 2.02: 1 — gate; 2 — drying area; 3 — heat generator; 4 — fan; 5 — seals; 6 — cooling zone; 7 — cooling fan; 8 — exhaust latch; 9 — latch with biofilter

The air heated in the heat generator (4) is supplied by a fan to the drying zone, where from left to right moves over the plant material that lies on trays. Further, in the space created by the dryer wall and the side surfaces of the trays, the coolant changes its direction by 180 deg and is evenly distributed along the height of the trays, blowing the chips from right to left. The coolant enters the fan (3) through the side recirculation channels. Instead of the part of the spent heat carrier which is thrown out, the identical part of fresh air moves in. Therefore, in the period of tray passing through drying zones, the direction of blowing shavings changes and additional conditions for its uniform drying are created. In the dryer casing there are lateral steel labyrinths of seals which create obstacles for the movement of air along the dryer and promote implementation of the described scheme of tray blowing.

Drying and cooling of the material are controlled remotely and are carried out from the control panel. In each zone of the dryer the temperature is maintained automatically, by means of self-recording regulating KSM potentiometers. Drying is realized according to the developed step modes: as an example, in the

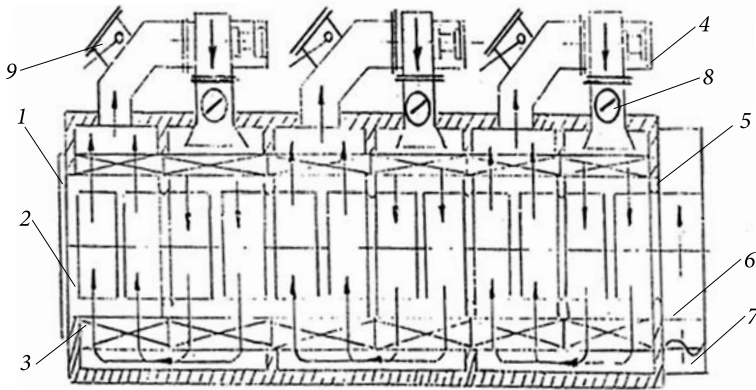


Fig. 1.25. Three-zone steam dryer TF 4.10: 1 — gate; 2 — drying area; 3 — heater; 4 — fan; 5 — seals; 6 — cooling zone; 7 — cooling fan; 8 — exhaust latch; 9 — latch with biofilter

1st zone temperature of the heat carrier is 100 °C at high moisture content of material; in the 2nd zone 80 °C; in the 3rd zone 60 °C [11].

According to the same principle of operation of the three-zone drying installation TF 2.03, the drying installation TF 2.02 was developed with two zones in the dryer (Fig. 1.24).

The drying unit of the tunnel (corridor) type TF 4.10 (Fig. 1.25) may consist of one, two, three or five drying zones, the number of which is determined by its capacity and the cooling zone [34]. Each drying zone has two half-zones, in either of which there are two trays. One tray is placed in the cooling zone.

The dryer is assembled from prefabricated metal sections that create a tunnel with zones. It is possible to make external brick walls of the dryer case. The case has the form of a tunnel, which consists of three drying zones and a cooling zone. Each zone has a ventilation unit for coolant circulation, which is installed outside. In order to ensure uniform drying/cooling of the product, distribution plates are installed along the height of the tray in the diffuser, through which the heat carrier enters the zone. An automatic regulator of steam flow is installed on the steam pipes, which supply steam to the heaters of each halfzone. The dryer is controlled from the control panel. When loading the following tray into the tunnel, the last tray with the dried and cooled product is rolled

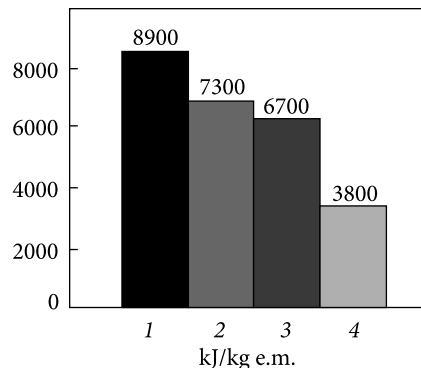


Fig. 1.26. Specific consumption of thermal energy in tunnel dryers for drying vegetables and fruits: 1 — MNIIP-1; 2 — B6-KF, Russia; 3 — Chachak, Serbia; 4 — SUM-2, IET, Ukraine

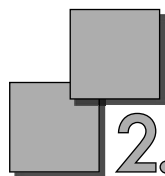
out of the cooling zone, thus the tray being loaded pushes the whole series of trays into the tunnel. In the walls of the dryer there are holes through which resistance thermometers are introduced to register the coolant temperature in each zone of the installation [34].

The advantages of steam dryers are versatility, automated control, environmental friendliness, lower energy consumption compared to the use of heat generators on fossil fuels. The disadvantage is an intensive deposition of salts (scale) on the surface of heating elements, which can lead to their burning, as well as to increase in the duration of processing of vegetable raw materials used for food purposes.

Comparison of tunnel dryers in terms of the specific heat consumption showed that dryers fabricated by the IET of NAS of Ukraine (Fig. 1.26), for which energy expenses are 3800 kJ/kg of evaporated moisture, are the most economical [34].

It follows that the known methods for PPRM processing are characterized by either high energy consumption and low productivity, or low quality of the product.

Mostly foreign and Ukrainian scientists study drying of soybean seeds or products of its processing in order to preserve the protein, and use energy-consuming drying methods. Therefore, an in-depth study in the field of heat and mass transfer processes and drying kinetics of phytoestrogenic soy-based raw materials is relevant today in order to reduce energy consumption for preliminary hygrothermal treatment of soybeans and the drying process, as well as ensuring maximum preservation of biologically active substances.



2. STUDY OF KINETICS OF THE PROCESS OF DRYING OF PPRMs AND MIXTURES BASED ON THEM

2.1. Research objects and experimental convection stand

The main object of the study was protein-containing PPRMs such as whole (with a shell) soybeans, which are colloidal capillary-porous bodies, in which there are all the characteristic forms of bonding of moisture with the material. Insufficient scientific information on the drying processes of protein-containing plant materials is the main basis for choosing the direction of research.

The botanical genus *Glycine* includes more than 40 species, half of which grow in tropical Africa. The species of cultivated soybean *G. hispida* L., which has 6 subspecies, has gained production value and distribution. In Ukraine, the Slavic subspecies *ssp. Slovonica* Kov. Ef Pinz is extended [77].

The high value of soy is determined primarily by the high content of complete protein, which by the aminoacid composition is close to animal proteins and so is well digested by humans.

It is also important that glycidin is the main protein of soy, which is able to coagulate during fermentation, which allows producing a large number of different foods from seeds and beans. Medical science has found that soy products contain antisclerotic substances which are very important for the elderly.

Of particular interest is soy as a source of vegetable protein due to its ability to lower cholesterol in patients with type II hyperlipoproteinemia [78]. It is rich in minerals and vitamins such as iron, zinc, copper, thiamine, riboflavin, niacin and pantothenic acid [79]. Most of these minerals and vitamins are well-known hemamins and are important for the formation of erythrocytes [80]. Lipids are contained in the form of simple fats, in soy 20% [81].

Soybeans contain phospholipids, vitamins and minerals. In addition, soy contains many minor substances, some of which, such as trypsin inhibitors, phytates and oligosaccharides, are known to be biologically active. The others, such as isoflavones, are simply recognized for their powerful ability to prevent cancer and other diseases [82].

On average, oil and protein together make up about 60% of dry soybeans. The rest consists of carbohydrates (about 35%) and ash (about 5%). Because the water content of stored mature beans is usually about 13% to ensure storage stability, wet-based soy contains about 35% protein, 17% oil, 31% carbohydrates and 4.4% ash [82].

The approximate chemical composition of soybeans is presented in Table 2.1. The cotyledons contain the highest percentage of both protein and oil, while the body has the lowest values of these components. Researchers [82] claim that the oil content in peel is so low that it can be viewed properly under a microscope. The hypocotyl axis has a cotyledon-like protein content, but its lipid content is about twice that of the cotyledons. Since cotyledon is the main component in the whole seed, its composition is very close to that of the whole seed, regardless of the large compositional difference between the structural parts.

A living organism is characterized by a higher degree of ordering of its constituent ingredients and a unique structural organization that provides both its phenotypic characteristics and a variety of biological functions. In this structural and functional unity of organisms, which is the essence of life, proteins (protein bodies) play a crucial role, which is not replaced by other organic compounds [83].

Proteins are complex organic molecules needed to build cells that perform hundreds of other diverse functions. They are involved in cell reproduction, enzyme formation, and the production of antibodies and hormones. Finally, in case of lack of energy in the body, proteins begin to break down and serve as a source of energy. That is why life without protein food is simply impossible [84]. Proteins contained in soybeans, by their amino acid composition, are the closest to the «ideal» protein composition, but given a large amount of fat, which is easily oxidized according to its biochemical properties, soy therefore has a short shelf life. Previous Petrova Zh.O.'s researches have established that the creation of plant carotene-based mixtures based on soybeans makes it possible to extend the shelf life of soybeans [11]. Therefore, there is a need for in-depth study of the drying process of soybeans in combination with carotene-containing raw materials in

Table 2.1. Approximate composition of soybeans and their structural parts [82]

Part of soybean	Percentage, %	Chemical composition, % of dry matter			
		Proteins	Lipids	Carbohydrates	Ash
Peel	8	9	1	86	4.3
Hypocotyl axis	2	41	11	43	4.4
Cotyledons	90	43	23	29	5.0
Whole bean	100	40	20	35	5.0

order to intensify the drying process and extend the shelf life of protein-containing PPRMs, which is of great practical and scientific importance.

On the basis of soy-vegetable compositions developed in the IET NAS of Ukraine, where vegetable components were carrots, pumpkin, onions, table beets, researches of the kinetics of drying process and definition of thermophysical properties of phytoestrogenic plant mixtures were carried out using carrots, spinach and sweet potato as vegetable components.

Researches carried out in the IET NAS of Ukraine on analysis of the chemical composition of raw materials, their properties and changes during technological processing, determined the optimal composition of the mixtures [7]. The most technological is a mixture with a ratio of raw materials 1:1. Increasing the part of carotene-containing raw materials leads to an increase in the moisture, which prolongs the drying time.

In the development of heat technology for soybean-vegetable mixtures, methods for intensification of mass transfer processes with a decrease in the specific heat consumption are of paramount importance [29]. The intensity of mass transfer mainly depends on the physical condition and nutrient content of plant raw materials. Soy-vegetable mixtures differ in their content of components from vegetable powders by high protein content and the presence of high percentage of lipids [7, 29].

By their nature, soy proteins are thermolabile and after overcoming the temperature range of 65-75 °C (in some literature sources from 60 °C) their destruction begins [83]. As in industrial conditions it is difficult to trace the beginning of the process of overheating inside the material layer, it is recommended to dry protein-containing vegetable raw materials at a coolant temperature not exceeding 60 °C. In the technological processing soybeans there is a need to use more «rigid» modes of hydrothermal treatment in order to inactivate unwanted enzymes and trypsin inhibitor proteins [85].

Before studying the kinetics of the drying process and determining the thermophysical properties of soybeans, carotene-containing raw materials (spinach and sweet potatoes) and soybean-vegetable mixtures, hydrothermal pre-treatment of soybeans was carried out to inactivate anti-food components according to the traditional methodology. Soybeans are thermostated at 60-70 °C for 60 min, then washed twice in water at 18-20 °C and then boiled in water for 20 min [86]. This hydrothermal treatment of soybeans allows one to inactivate the enzymes of the lipoxygenase complex and to increase the digestibility of proteins [86].

Spinach is one of the most important antioxidant vegetables, usually eaten after cooking fresh or frozen leaves. As-cut spinach leaves contain approximately 1000 mg of total flavonoids per kilogram. The possible presence of flavonoid compounds in spinach was first reported in 1943, but it took almost 20 years before the structure of flavonol isolated from spinach leaves was established as patuletin,

and the presence of spinacetin was confirmed [87]. In addition, the presence of several flavonol glycosides in methanolic spinach leaf extract has been reported. At least 10 flavonoid glycosides in spinach have been reported in [87]. These are glucuronides and acylated di- and triglycosides of methylated and methylene dioxide derivatives of 6-oxygenated flavonols [87]. Glucuronides are more water-soluble than glycosides and acylated compounds that remain in the tissue after boiling. Flavonoids and other phenolic components act as antioxidants due to their free radical scavenging properties and hydroxyl groups. Extensive conjugation throughout the flavonoid structure and numerous hydroxyl groups enhance their antioxidant properties, allowing them to act as reducing agents, donor or electron, donating agents, or singlet-oxygen. The results of the *in vitro* analysis of the oxygen radical absorption capability (ORAC) showed that among the various extracts of fruits and vegetables, the products with the highest ORAC activity include spinach, strawberries and blueberries using the DPPH radical and it was compared with Trolox, a synthetic analogue of vitamin E [87]. The most active products were derived from patuletin with 3,4-dihydroxyl group. The inclusion of a feruloid residue increased the activation of free radicals. During storage of spinach leaves there was observed a decrease in the overall activity of antioxidants. Boiling as-cut spinach leaves extracted approximately 50% of the total flavonoid content and 60% of vitamin C in cooking water; however, more flavonoid glucuronides were removed than other glycosides [87].

Spinach greens contain many macro- and microelements, mineral salts, B vitamins, and ascorbic acid. The leaves contain a lot of organic acids; young leaves of spinach contain (as related to dry material) 6.5% oxalic acid, which is not harmful to the human body. At high temperatures and according to the plant age, its content in old leaves rises up to 15.5%. Besides, heteroauxin was found in young spinach leaves and vitamin K in saponin seeds. Greens contain a high content of iron, as part of chlorophyll, which is similar to human hemoglobin and therefore 60% of iron is easily absorbed by the human body. Spinach also contains magnesium and iodine, which are essential for the growth and development of the human body, which makes this culture very important for the nutrition of Ukrainians on the post-Chernobyl territories. Fresh spinach leaves contain up to 80 mg/100 g of vitamin C and 2-9 mg/100 g of carotene [88-91].

Another raw material containing beta-carotene is sweet potato [92].

Sweet potato belongs to the heat- and light-loving crops of short daylight. There are many varieties of sweet potatoes, each of which has a distinctive appearance and taste. Common to all varieties of sweet potatoes is a number of useful properties that allow using the product in food, as well as a medicine to strengthen the body and prevent diseases [93].

In tropical countries, sweet potatoes are grown as a perennial plant. The weight of the tubers, in a few years, reaches 10 kg, but in temperate climates,

Table 2.2. Constituents of sweet potato: values per 100 g (3.5 oz.) edible portion [96]

Constituents	Units	Raw sweet potato	Cooked, baked with skin	Cooked, boiled without skin
Water	g	72.84	72.84	72.84
Energy	kcal; kJ	105; 439	103; 431	105; 439
Protein	g	1.65	1.72	1.65
Total lipid (fat)	g	0.30	0.11	0.30
Carbohydrate by difference	g	24.28	24.27	24.28
Fiber, total dietary	g	3.0	3.0	1.8
Ash	g	0.95	1.06	0.95
Calcium Ca	mg	22	28	21
Iron Fe	mg	0.59	0.45	0.56
Magnesium Mg	mg	10	20	10
Phosphorous P	mg	28	55	27
Potassium K	mg	204	348	184
Sodium Na	mg	13	10	13
Zinc Zn	mg	0.28	0.29	0.27
Copper Cu	mg	0.169	0.208	0.161
Manganese Mn	mg	0.355	0.560	0.337
Selenium Se	mcg	0.6	0.7	0.7
Vitamin C	mg	22.7	24.6	17.1
Thiamin B ₁	mg	0.066	0.073	0.053
Riboflavin B ₂	mg	0.147	0.127	0.14
Niacin B ₃	mg	0.674	0.604	0.64
Pantothenic acid B ₅	mg	0.591	0.646	0.532
Vitamin B ₆	mg	0.257	0.241	0.244
Folate, total	µg	14	23	11
Vitamin B ₁₂	µg	0	0	0
Vitamin A, IU	0.3 µg RE	20.063	21.822	17.054
Vitamin A, RE	µg RE	2.006	2.182	1.705
Vitamin E	mg-ATE	0.280	0.280	0.280

according to the experience of scientists, it can be cultivated only as an annual, since it is a heat-loving plant that cannot withstand low temperatures [93; 94].

Sweet potatoes are used in cuisines around the world. It is consumed raw, baked and cooked. In Uganda, dried sweet potatoes are used to make tea [94; 95]. People in Japan and China like to eat whole baked sweet potatoes. In winter,

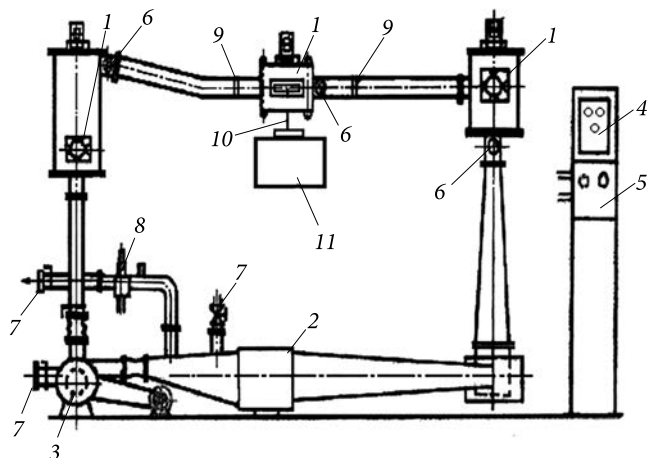


Fig. 2.1. Scheme of the experimental stand: 1 — drying chamber; 2 — heater; 3 — fan; 4 — temperature regulator; 5 — control panel; 6 — resistance thermometers; 7 — branch pipes with gates; 8 — psychrometer; 9 — special grids; 10 — bar of scales; 11 — scales

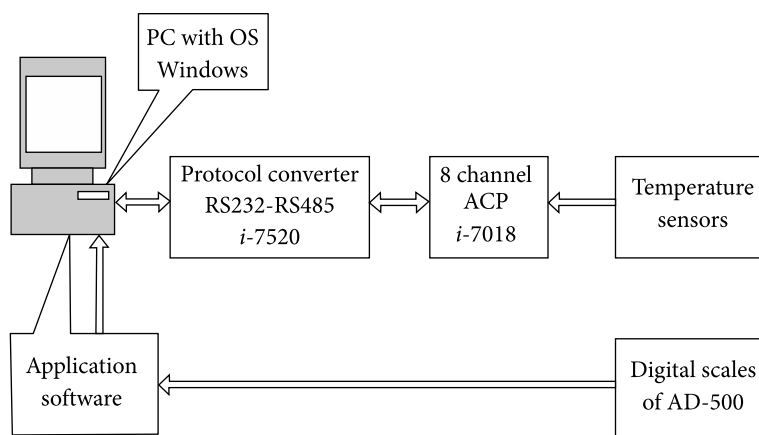


Fig. 2.2. Block diagram of automated collection and processing information from the convective drying stand

China prepares soup with ginger and sweet potatoes, which is considered warming. Koreans prepare transparent noodles from «sweet potato» [94; 95]. In some provinces of Eastern Congo, sweet potatoes are traditionally processed into flour, which is used as a basis for various foods and cakes. The chemical composition of sweet potatoes is presented in Table 2.2.

Carotenoids are most efficiently converted to retinol when there is a sufficient amount of easily digestible protein and fat. Therefore, it is advisable to combine carotene-containing plant raw materials with phytoestrogenic plant raw materials (with sufficient lipids) [97].

Analysis and experimental studies of the kinetics of the drying process of functional PPRMs were implemented on a convective experimental stand. A schematic diagram of the stand is presented in Fig. 2.1 [87].

Technical characteristics of the convective drying stand

Heat carrier temperature	30-150 °C
Heat carrier velocity	0.5-5 m/s

The convective experimental stand is equipped with a working chamber 1, heating zone 2, fan 3, potentiometer 4, control panel 5, scales 6, water vapor generator 7, regulating autotransformer 8, psychrometer 9 and Pitot tubes 10 with micromanometer 11. The design of the stand has a system of isolated air ducts with devices for heating and circulation of the heat carrier, drying chambers, systems of control and maintenance of heat carrier temperature, automatic collection and processing of information on the kinetics of drying material.

Part of the thermal preparation of air (2) has the form of a rectangular box, which houses a three-section electric heater with a capacity of 10 kW. To accurately maintain the set temperature, the heater is connected to an automatic control system, which consists of an electric temperature controller ERT-4 (4) and resistance thermometers TSM-50 (6).

The heat carrier moves by means of the centrifugal fan (3) of middle pressure. By adjusting the fan (3) speed on the control panel (5), a change in the velocity of the heat carrier is achieved. The exhaust/fresh air ratio can be adjusted using the valves on the nozzles (7).

The stand is equipped with an auxiliary equipment (Fig. 2.2):

- analog-to-digital converter *i-7018*;
- converter interface *i-7520*;
- personal computer.

This allows one to automatically implement the drying process using the developed application program «Sooshka». The research program provides registration of the basic patterns of drying PPRMs in a wide range of changes in technological parameters with the implementation of automatic collection and processing of information (about change in mass, sample temperature and kinetics calculations).

2.2. Regimes for PPRM drying

The basis of any technological processing of vegetable raw materials is their preliminary preparation. In our case, this is preliminary hydrothermal treatment. The quality and nutritional value of the final product depends on the correctness of its stages. During hydrothermal treatment, anti-food components are inactivated, and the structure and physicochemical properties of PPRMs change.

As described in Section 1, moisture in plant drying facilities is retained in various forms. At the biochemical level, semi-permeable cell membranes in the plant are a major barrier to the removal of cellular moisture. Therefore, to improve this process, it is necessary to increase cell permeability.

When processing soybeans under a long-term use of high temperatures, it is necessary to adjust the depth of protein denaturation. This is a very important stage of processing, since changes in denaturation can trigger a melanoidin reaction, which is the cause of irreversible binding of protein to amino acids. As a result, the color, taste and smell of the final product deteriorate. It is known that a slight denaturation preserves the nutritional biological value of proteins, but a strict hydrothermal treatment provides inactivation of anti-food components (especially inhibitors of trypsin).

Inhibitors of trypsin together with trypsin is a negative complex. They block the digestive processes in humans and slow down the absorption of nutrients. Existing method for trypsin inactivation consists in thermal denaturation and intensive mechanical grinding [29].

Heat treatment is a well-known method for destroying antifood components in raw soybeans [102]. All developed technologies are based on the principle of heating beans for a certain period of time, and sometimes additionally moistening them with steam. As a result, the nutritional value is improved and the contamination of seeds with microflora is reduced.

As shown in previous researches and described in detail in Zh.O. Petrova's candidate dissertation, the most effective treatment is heat treatment at elevated temperature and pressure: the intensity of moisture transfer in soybeans markedly increases. The content of trypsin inhibitor is determined by the casein procedure according to the A.P. Levitskyi method and consists in inhibiting the reaction of casein proteolysis by crystalline trypsin [29].

Loss of trypsin inhibitor activity is one of the purposes of moisture heat treatment. The trypsin inhibitor decreases when processing soybeans in an autoclave under a vapor pressure of 0.2 MPa (132 °C) with increasing processing time. This method made it possible to minimize the trypsin inhibitor (duration of treatment more than 20 min at a bean temperature of 100 °C), but affected the digestibility of proteins, which was below the maximum (Fig. 3.1) [103]. The value of digestibility of soy proteins about 90 % can be achieved by processing it in the autoclave under a pressure of 0.2 MPa for 12-13 min [104].

From the above, hydrothermal treatment (compliance with its regimes has a direct impact on the quality and nutritional value of the final product) is the most important technological operation before the drying process.

Fig. 2.3 presents the stages of improved preliminary hydrothermal preparation of soybeans for drying, based on previous studies at the IET of NAS of Ukraine [29, 86, 105].

At the first technological stage of soaking there is an unpleasant odor. This is due to alcohols (isobutanol, isopentanol, hexanol, decanol, heptanol) and volatile fatty acids (acetone, formic, butyric, isobutyric, isovaleric) in the main composition of soy aromatic substances. Soaking of soybeans is realized in a thermostat with water at $t = 60-70$ °C for 60 min, accompanied by activation of the lipoxy-

genase complex of enzymes. Then washed twice with water at $t = 18-20\text{ }^{\circ}\text{C}$ [86].

The graph of soybean temperature change during hydrothermal treatment [29] (Fig. 2.4) demonstrates that from the beginning of hydrothermal treatment up to 17-18 min the temperature of soybeans is $100\text{ }^{\circ}\text{C}$. At this thermal regime beans are boiled for another 15-20 min. At the stage of boiling (cooking soybeans for 20 min) enzymes are inactivated, as well as the lipoxygenase complex. Volatile and water-soluble decomposition products partially disappear as well.

As a result of preliminary hydrothermally pre-treated (HPT) soybeans, it was found that there is almost complete inactivation of anti-food components, in particular trypsin inhibitor [29].

This is followed by blending with carotene-containing vegetables to prevent oxidation of soybean fats [106], beans were combined with: 1) carrots; 2) spinach; 3) sweet potatoes.

The shelf life of spinach at a storage temperature of $0\dots 1\text{ }^{\circ}\text{C}$ and a relative moisture of 90-95% is only 2 days. Drying is one of the methods to extend the shelf life of spinach [11]. Before drying, spinach must be blanched to increase the tissue elasticity, inactivate enzymes, increase the permeability of the outer layers of the fruit, remove air from the tissues [11].

Spinach is in great demand among vegetable crops [107]. Folic acid, a widespread vitamin, was first found in spinach leaves [11]. This plant is recommended for consumption in cases of diseases of the nervous system, gastrointestinal tract, impaired growth in children, anemia, in the form of soups, puree it is prescribed for obesity. In folk medicine, the plant is used to enhance intestinal motility, strengthen the walls of capillaries. Spinach has antisclerotic and anti-inflammatory properties. It is recommended to consume spinach for children, pregnant women and patients with hypochromic anemia, diabetes and hypertension, hypoacid gastritis and enterocolitis, disorders of the secretory function of the thyroid and adrenal glands, as well as musculoskeletal rheumatism with painful sensations and pain [108, 109]. As a source of vitamins, spinach is used in diet therapy and in the so-called spring treatment.

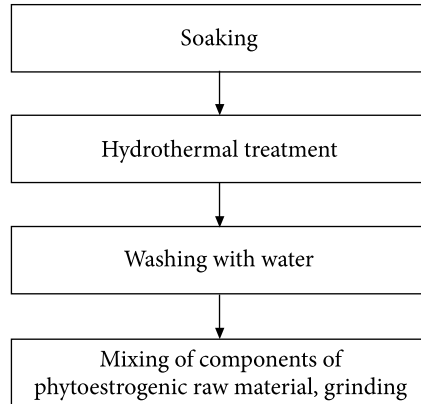


Fig. 2.3. The main stages of hydrothermal treatment of soybeans

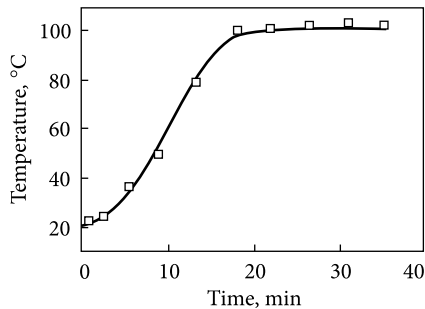


Fig. 2.4. Soybean temperature change during hydrothermal treatment

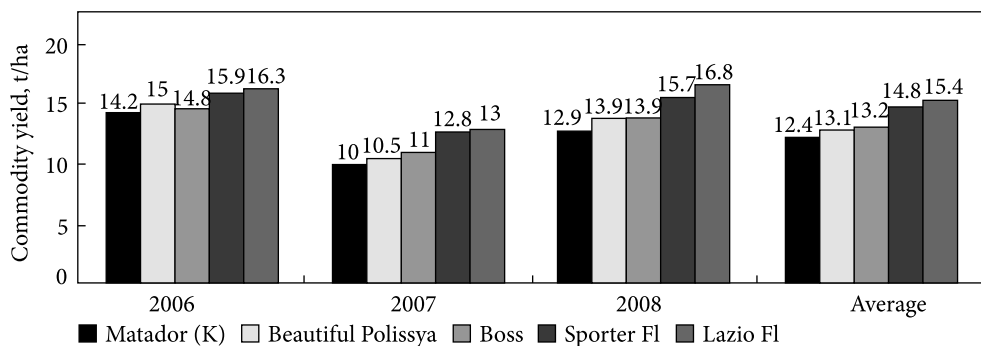


Fig. 2.5. The dependence of the yield of marketable green spinach on its varieties and hybrids

In terms of quality, varieties and hybrids of spinach are almost indistinguishable (Fig. 2.5). They contain a high content of ascorbic acid and a small amount of sugars [110].

Though in Ukraine this new plant is called «sweet potatoes», but its biological properties have nothing in common with our traditional potatoes [111]. The chemical composition of sweet potatoes includes much more useful vitamins, macro- and micronutrients for the human body [96].

Sweet potato, *Ipomea batatas* (L.) Lam. is a vegetable crop, which is not widespread in Ukraine, but is one of the most important and widespread tuberous crops in the world economy.

Sweet potato is grown in most tropical and subtropical countries of the globe, and most in China, India, Indonesia, Uganda, Nigeria and Vietnam. Also, from sweet potato tubers, flour, sugar, molasses and alcohol are produced; young leaves and stems are added in cooking to various salads, and from seeds a coffee surrogate is obtained. Sweet potato tubers are eaten raw, boiled, baked and fried, they are used as side dishes to meat, added to porridge. Souffle, jam and lozenges are made from varieties of sweet potato.

In China, sweet potatoes are called the fruit of longevity and are believed to prevent cancer, restore vascular elasticity, stimulate the activity of liver and kidneys, be useful in influenza as a tonic and source of vitamins. Sweet potatoes have a low glycemic index, so this root is safe for diabetics. Thus, sweet potatoes are a promising crop for growing in Ukraine with subsequent obtaining of products based on them of high nutritional value. Search and research for non-traditional types of agricultural raw materials, development of technology for their processing with maximum preservation of the content of biologically active substances in finished products is an important task in the creation of healthy and preventive products [112].

Carotenoids are more efficiently converted to retinol when there is a sufficient amount of easily digestible protein and fat. Therefore, it is advisable to

combine carotene-containing vegetable raw materials with protein-containing vegetable raw materials with a sufficient amount of lipids [8, 23, 97].

Spinach is one of the available sources of beta-carotene. It is added to salads, soups and desserts. Modern medicine classifies spinach as one of the five most useful products. Spinach contains: carotenoids, proteins, carbohydrates, as well as fats: saturated and unsaturated fatty acids, fiber, starch; vitamins A, E, C, H, K, PP, many B vitamins, beta-carotene; calcium, magnesium, sodium, potassium, phosphorus, iron, zinc, copper, manganese, selenium [11]. At a storage temperature of 0-1°C, relative moisture of 90-95%, the shelf life of spinach is 2 days. To extend the shelf life, spinach needs canning, one way of which is drying [11].

Before drying and adding to hygrothermally pre-treated soybeans, spinach was soaked in water for 15 min, the water temperature was 20—25 °C. This operation is mandatory, because then there is minimal loss of vitamins and other biologically active substances of spinach during drying. After hygrothermal treatment, soybeans were ground in a meat grinder produced according to GOST 4025-69 (nozzle D = 7 mm) and mixed with chopped spinach (3 × 3 mm). The most technological are mixtures with a component ratio of 1:1 [7, 29]. Increasing the content of carotene-containing raw materials leads to an increase in moisture, which increases the duration of drying. The initial moisture of the mixture was $W = 73.5\%$, the initial mass $m = 30$ g.

As mentioned earlier, soybeans contain a high amount of fats, which after the technological stage of grinding pre-hygrothermally treated soybeans are oxidized in a short time [105]. Therefore, further studies of PPRMs were performed on samples developed by soy-spinach and soy-sweet potatoes.

Studies of heat and mass transfer during drying of phytoestrogenic plant raw materials and protein-carotene-containing mixtures based on it were carried out using an experimental convective drying stand equipped with continuous automatic collection and information processing: change of mass, temperature in the middle of the layer and on the surface of the material layer developed application program «Sooshka», which allows calculating the data and building graphs based on them [113].

The experimental stand consists of a system of insulated air-wires with devices for heating and circulation of the heat carrier, drying chambers, measuring schemes and devices for control of process parameters and measurement of the magnitudes characterizing drying of the investigated material [97, 87].

The main parameters of the drying process are: coolant temperature (t), humidity of the heat carrier (d) and its velocity (V) [11, 30, 34, 35, 44, 114]. These parameters affect the duration of drying and the quality of the final material.

In processing of vegetable raw materials, the main indicator of the quality of the dried product is the maximum preservation of biologically active components and the functional value of the final product. Therefore, when developing

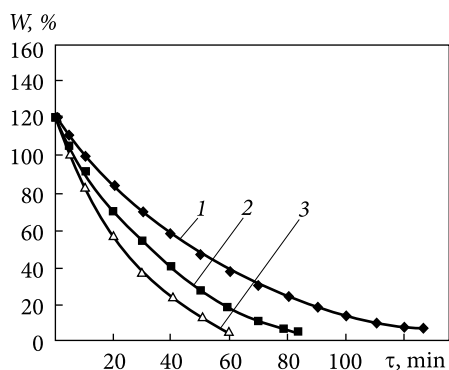


Fig. 2.6. Influence of heat carrier temperature on dehydration of soy-carrot composition. Mode parameters: $V = 2$ m/s, $d = 10$ g/kg dry air: 1 — 70 °C, 2 — 100 °C, 3 — 120 °C

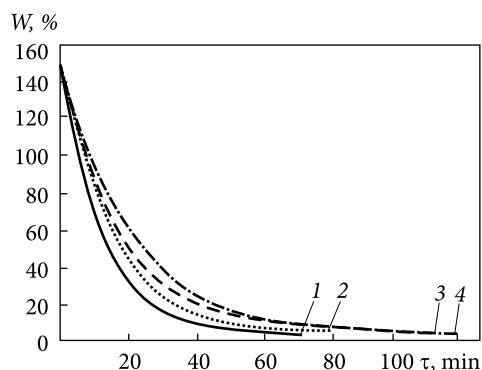


Fig. 2.7. Influence of heat carrier temperature on the kinetics of drying hydrothermally pre-treated ground soybeans. Mode parameters: $\delta = 15$ mm, $W = 4$ %; $V = 2.5$ m/s, $d = 10$ g/kg dry air 1 — 100 °C, 2 — 80 °C, 3 — 70 °C, 4 — 60 °C

optimal drying regimes for phytoestrogenic plant materials, it is recommended to be guided by the following requirements: reduction of drying time; ensuring minimal heat consumption for the process; ensuring the preservation of biologically active substances in the dried material [8, 30].

In Petrova Zh.O.'s candidate dissertation «Development of processes for production of carotene-containing food products», the kinetics of the drying process of soy-carotene-containing mixtures (soy-carrot and soy-pumpkin) was studied at coolant temperatures of 80 °C, 100 °C, 120 °C, velocity $V = 2$ m/s and humidity $d = 10$ g/kg dry air.

Fig. 2.6 shows the kinetics of convective drying of soybean-carrot composition depending on the coolant temperature. The drying curves show that with increasing coolant temperature, the intensity of dehydration increases, the duration of the drying process of the material decreases: at 120 °C by 2.13 times compared to the process at 70 °C. But long-term use of high temperature drying causes undesirable melaidin reactions, so there is a need to develop and select technologically acceptable and less energy-intensive drying modes of soy-carotene-containing mixtures.

Phytoestrogenic plant material based on hydrothermally pre-treated soybeans is a complex object of drying in terms of structure, physicochemical and biochemical composition. On the basis of soy-vegetable compositions developed in the IET NAS of Ukraine, where vegetable components were carrots, pumpkin, onions and table beets, researches of the kinetics of drying process and determination of thermophysical properties of objects of phytoestrogenic plant mixtures on the basis of soy were carried out for carrots, spinach and sweet potatoes additives [8, 23, 86, 115, 116].

It is known that the temperature is the most common heat-technological parameter in processing of vegetable raw materials, and the drying process is one of the most important ways of preparing, canning and semi-finishing food.

The effect of coolant temperature was studied on samples of hydrothermally pre-treated soybeans ground in a meat grinder (nozzle $D = 7$ mm), material layer height 15 mm, coolant humidity $d = 10$ g/kg dry air and velocity $V = 2.5$ m/s (Fig. 2.7). From the comparison of the kinetics curves, the fastest is a one-stage drying mode at a coolant temperature of 100 °C.

Soy proteins are thermosensitive and after overcoming the temperature limit of 65 – 75 °C (in some sources from 60 °C) their destruction begins [83]. Since in industrial conditions it is difficult to track the beginning of overheating inside the material layer, it is recommended to dry protein-containing vegetable raw materials at a coolant temperature of not over 60 °C.

Fig. 2.7 presents the effect of coolant temperature on the kinetics of drying prepared soybeans. As can be seen, the shortest drying time of hydrothermally treated soybeans is at a coolant temperature of 100 °C.

As the heat carrier temperature decreases, the drying time increases accordingly. The longest duration was observed at a temperature of the heat carrier of 60 °C.

In order to preserve and increase the functionality of phytoestrogenic properties of plant raw materials, conditions for stabilization of plant ingredients have been developed. They involved hydrothermal treatment of soybeans and blending them to prevent enzymatic and non-enzymatic browning under drying. In addition, blending also prevents oxidation of soybean fats by carotenoids contained in spinach.

According to its natural properties, spinach contains a high percentage of free moisture, which is removed during drying. As seen in Fig. 2.8, spinach drying curves have a characteristic shape for colloidal capillary-porous materials. As the coolant temperature rises to 100 °C, the drying process intensifies by 17% relative to the coolant temperature of 60 °C. Taking in account that spinach has a large number of biologically active substances, which are destroyed at a coolant temperature of 100 °C, to intensify the process, blending of raw materials was developed and other temperature modes were studied.

Repeated experimental studies of the drying process were performed on hydrothermally pre-treated ground soybeans, carrots and soybean-carrot mixture at 70 °C, the results of which are shown in Fig. 2.9 [95].

Drying of HPT-soybeans requires a long time, which can negatively affect the energy consumption of the process. Soybeans in combination with carotene-containing raw materials in a ratio of 1: 1 are dried with less time. Thus, Fig. 2.9 shows that the drying time of carrots exceeds 2 h, while the drying time of soy-carrot mixture and mono-soy does not reach 2 h, and is within 1 h 18 min.

As known, saving operation time of technological equipment in production conditions is equivalent to reducing energy consumption. From the temperature

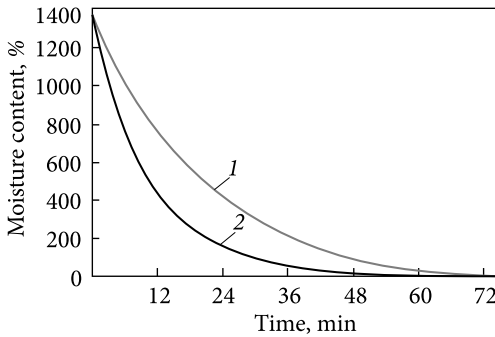


Fig. 2.8. Change in the moisture content in spinach at a heat carrier temperature of (1) 60 °C and (2) 100 °C over time. Mode parameters: $\delta = 15$ mm, $W = 4$ %; $V = 2.5$ m/sec, $d = 10$ g/kg dry air

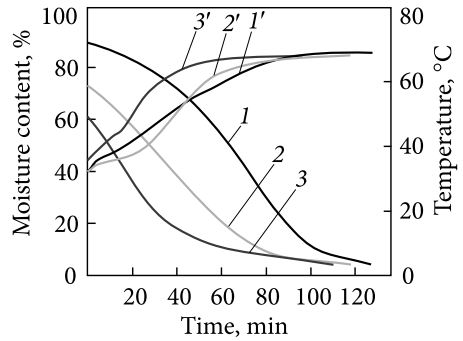


Fig. 2.9. Change in (1, 2, 3) moisture content and (1', 2', 3') temperature inside the layer of mono-materials and soy-carrot mixture over time. Mode parameters: (T) = 70 °C, $V = 2.5$ m/s, $d = 10$ g/kg dry air, $\delta = 15$ mm: (1, 1') carrot; (2, 2') soy-carrot 1:1; (3, 3') soy

curves 1', 2', 3' it can be seen that at the middle of the mixture layer (curve 2') temperature reaches required 70 °C at the 40th min, while in monocomponent layers merely after 60 min.

In developing heat technology for soybean and vegetable mixtures, the primary task is to use methods of intensification of heat and mass transfer processes in line with the reduction in the specific heat consumption [117]. The intensity of mass transfer depends in part on the physical state of plant raw materials and its chemical composition.

Soy-vegetable mixtures differ in composition from vegetables with a high amount of protein and a high percentage of lipids [29, 56].

The influence of the composition components on the kinetics of the drying process was investigated on a fundamentally new soybean-vegetable composition where the vegetable component was spinach.

Fig. 2.10 shows the effect of composition mixture mono-components on the kinetics of the drying process of phytoestrogenic soy-spinach mixture at a coolant temperature of 60 °C [95].

As seen in the figure, at a coolant temperature of 60 °C the most active heating of the material in the middle of its layer takes place in the soy-spinach mixture (curve 2') and lasts 40 min, which is twice more rapidly than for single soy (curve 3').

As a result of the combination of PPRMs (soybeans, $W_{in} = 62\%$) with carotene-containing raw materials (spinach, $W_{in} = 93\%$), there is observed intensification of the drying process of spinach by 10% and soybeans by 41%, which reduces energy consumption for the drying process.

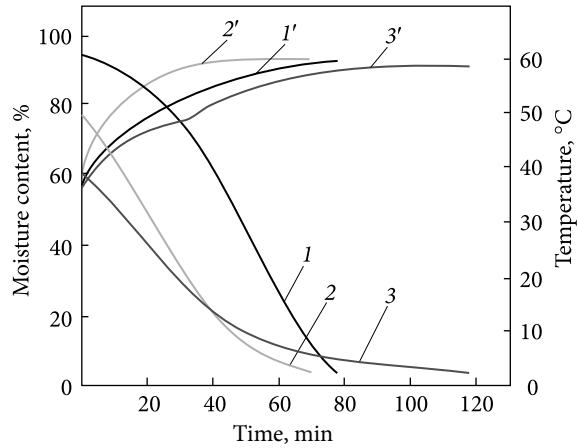


Fig. 2.10. Change in (1, 2, 3) moisture content and (1', 2', 3') temperature inside the layer of mono-materials and soy-spinach mixture over time. Mode parameters: $t = 60\text{ }^{\circ}\text{C}$, $V = 2.5\text{ m/sec}$; $d = 10\text{ g/kg dry air}$, $\delta = 15\text{ mm}$: (1, 1') spinach ($W_{in} = 93\%$); (2, 2') soy-spinach mixture ($W_{in} = 75\%$); (3, 3') soy ($W_{in} = 62\%$)

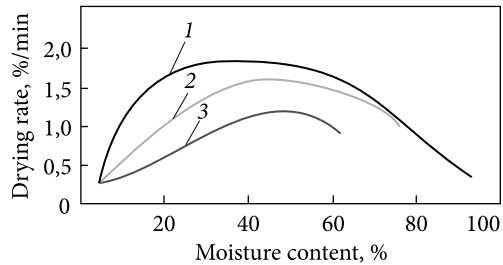


Fig. 2.11. Change in the drying rate of mono-materials and soy-spinach mixture (1:1) with changing the moisture content in the material. Mode parameters: $t = 60\text{ }^{\circ}\text{C}$, $V = 2.5\text{ m/s}$, $\delta = 15\text{ mm}$, $W_f^c = 4\%$; $d = 10\text{ g/kg of dry air}$: (1) spinach, (2) soy-spinach mixture, (3) soy

Drying rate curves (Fig. 2.11) show that the process of drying, i.e., removal of free and bound moisture, occurs in the 2nd period, in line with the falling rate. The mixture of components (maximum drying rate 1.6%/min) due to the addition of spinach, which has a maximum drying rate of 1.8%/min, gets dried 1.5 times more rapidly than the hydrothermally pre-treated crushed soybeans (drying rate 1.19 %/min).

Studies of the influence of components on the kinetics of drying process were also performed on samples of soy-sweet potato mixture, using as a vegetable component of Vietnamese sweet potato which was grown on soils in the Socialist Republic of Vietnam [8, 115]. Its initial moisture was $W_{in} = 51.6\%$, visually it had a purple skin and white flesh and contained a high amount of starch, as evidenced by darkening the white flesh in incisions for 20-40 min.

Sweet potatoes were cleaned and soaked in water at room temperature 20-25 $^{\circ}\text{C}$, cut into pieces of 30×30 mm, mixed with hot soybeans (immediately after hydrothermal treatment of soybeans) in a ratio of 1:1, then crushed in the meat grinder.

Sweet potato contains carotenoids, and therefore is suitable for use as a vegetable component in soy-vegetable mixtures. Due to the lack of information on the effect of soybeans and Vietnamese sweet potatoes and their mixtures on the nature of drying process, investigation of the drying process of soybean-sweet potato mixture is reasonable.

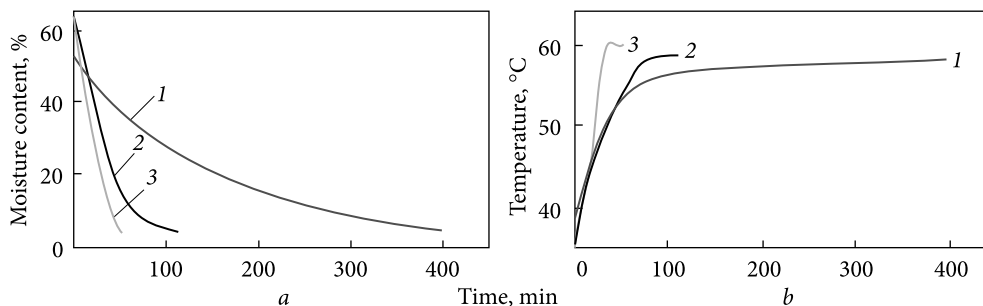


Fig. 2.12. Change in (a) moisture content and (b) temperature in the middle of layer of raw mono-material and soy-sweet potato mixture: 1 — sweet potato ($W_{in} = 52\%$), 2 — soy ($W_{in} = 62\%$), 3 — soy-sweet potato mixture ($W_{in} = 58\%$). Mode parameters: $t = 60\text{ }^{\circ}\text{C}$, $V = 2.5\text{ m/s}$; $d = 10\text{ g/kg dry air}$, $\delta = 15\text{ mm}$

Forms of drying curves in Fig. 2.12 are characteristic for colloidal capillary-porous materials.

The use of high-temperature drying mode above $65\text{--}70\text{ }^{\circ}\text{C}$ leads to the destruction of carotene containing sweet potatoes, so it is advisable to use the drying mode at a coolant temperature of $60\text{ }^{\circ}\text{C}$ [118].

In the course of research aimed at intensifying process of drying HPT crushed soybeans and stabilizing their fats, it was found that not only this aim is achieved by combining soybeans with Vietnamese sweet potato. The matter is that Vietnamese sweet potato, by its structural properties, is an object with a long drying time. In order to dry it to the required final moisture of 4–6 %, it is necessary to spend 6 h 40 min. Fig. 2.12 shows that when combining HPT-soybeans with Vietnamese sweet potato with a ratio of 1:1, there is observed a significant reduction in drying time by 8 times (equal to 50 min) relative to sweet potato.

The temperature curve (Fig. 2.12, b) indicates that inside the material layer intensive removal of free and bound moisture (up to the equilibrium moisture content of 12%) occurs at temperatures not exceeding $55\text{ }^{\circ}\text{C}$. The maximum drying rate of soy-sweet potato mixture is close to that for soybeans and is $1.45\text{ } \%/ \text{min}$. It can be assumed that this behavior of the mixture is due to the interaction of soybean fats with fat-soluble carotenoids of sweet potatoes.

From the curves of change in the drying rate depending on the moisture content in material (Fig. 2.13), it can be seen that drying takes place in the period of falling rate, period 2. The graphs confirm the feasibility of developing soy-sweet potato mixture (curve 3), characterized by higher drying rates (maximum drying rate $N_{max} = 1.45\text{ } \%/ \text{min}$).

It should be noted that the most important disadvantage of the drying process is its high energy consumption, up to 25% of all industrial energy. Current problems in the energy and environmental sectors, such as greenhouse gas emissions and resource depletion, are an extremely important issues in reducing energy consumption in all industries [34].

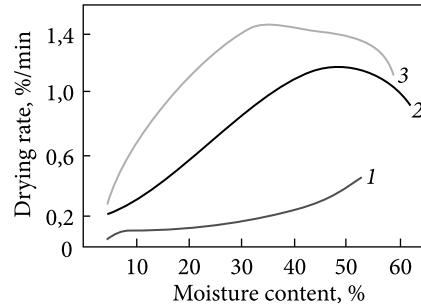


Fig. 2.13. Change in the drying rate of mono-materials and soy-sweet potato mixture (1:1) over time: 1 — sweet potato, 2 — soy, 3 — soy-sweet potato mixture. Mode parameters: $t = 60\text{ }^{\circ}\text{C}$, $V = 2.5\text{ m/s}$, $\delta = 15\text{ mm}$, $W = 4\%$; $d = 10\text{ g/kg dry air}$

Based on the studies of phytoestrogenic mixture of soybeans and spinach, the dependence of the Rebinder number on the moisture content in the material was calculated (Fig. 2.14).

Rebinder number (Rb) is a characteristic of the kinetics of the drying process. It determines the ratio of the amount of heat that must be spent on heating the material and evaporation of moisture for an infinitesimal period of time:

$$Rb = b \frac{\bar{c}}{r} = \frac{\bar{c}}{r} \left(\frac{d\bar{t}}{d\bar{W}} \right),$$

where c — the heat capacity of the material; r — the specific heat of vaporization.

The Rebinder number does not depend on the velocity and moisture content of the coolant and is only determined by the thermal drying mode.

As shown in Fig. 2.14, at the heat carrier temperatures of both $60\text{ }^{\circ}\text{C}$ and $100\text{ }^{\circ}\text{C}$ two maximums and two minimums are fixed for Rb in the moisture range 70-30%, but difference between Rb_{\max} and Rb_{\min} is far bigger for $100\text{ }^{\circ}\text{C}$, which confirms the «softness» of the temperature effect of the heat carrier on a thermolabile material at $60\text{ }^{\circ}\text{C}$.

The IET NAS of Ukraine has developed stepwise drying regimes for a soy-carrot mixture, which were repeated in the works [116; 119]. The coolant temperature changed during drying: in the beginning the coolant temperature was $120\text{ }^{\circ}\text{C}$, 15-20 min after the start of drying it was lowered to $100\text{ }^{\circ}\text{C}$ (curve 2, Fig. 2.15), and then after another 20 min — to $80\text{ }^{\circ}\text{C}$ and kept until the end of the drying process. Another step mode was also proposed: the coolant temperature is maintained at $120\text{ }^{\circ}\text{C}$ for 15-20 min and then lowered to $80\text{ }^{\circ}\text{C}$ (curve 3, Fig. 2.15).

As a result, the use of step modes has reduced the energy consumption of the drying process and the drying time, and most importantly, preserves the original quality of mixture components.

Based on this and similarity of the conditions of the conducted and calculated experiments, a study was carried out to develop a stepwise regime of $100/70\text{ }^{\circ}\text{C}$ for soy-carrot (1:1) mixture (Figs 2.16 and 2.17) [95].

As seen in Figs 2.15—2.17, drying of carotene-containing raw materials by the step mode $100/70\text{ }^{\circ}\text{C}$ is shorter (110 min, curve 1, Fig. 2.16) than for mono-

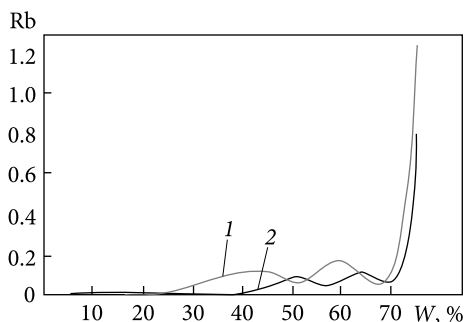


Fig. 2.14. Change in the Rebinder number during dehydration of soy-spinach mixture. Mode parameters: $V = 2.5$ m/s; $d = 10$ g/kg dry air; granule dimensions $4 \times 2 \times 3$ mm; soy/spinach ratio 1 : 1; coolant temperature: 1 — 100 °C, 2 — 60 °C

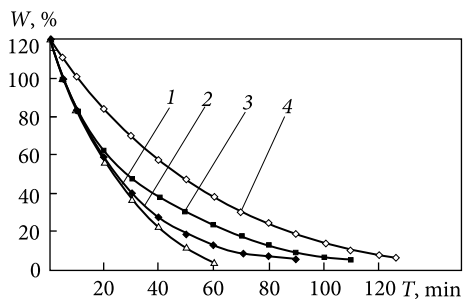


Fig. 2.15. Change in moisture content of soy-carrot mixture according to step modes of change in the heat carrier temperature. Mode parameters: $V = 2$ m/s; $d = 10$ g/kg dry air; 1 — 120 °C; 2 — $120/100/80$ °C; 3 — $120/80$ °C; 4 — 80 °C

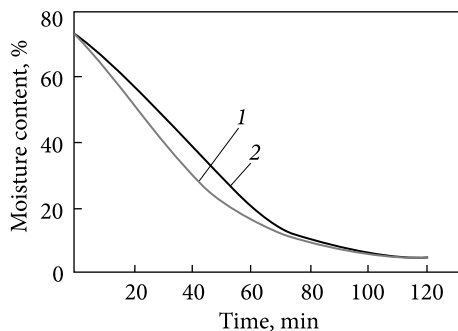


Fig. 2.16. Influence of heat carrier temperature 70 °C and $100/70$ °C on the change of moisture content in soy-carrot mixture during drying. Mode parameters: $\delta = 15$ mm, $W = 4$ %; $V = 2.5$ m/s, $d = 10$ g/kg dry air. 1 — $100/70$ °C, 2 — 70 °C

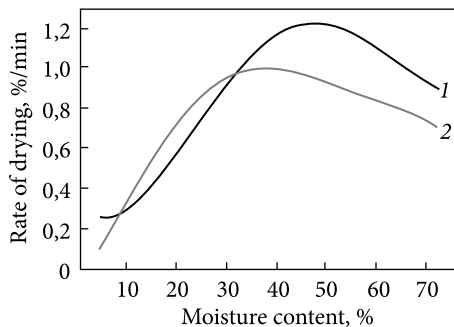


Fig. 2.17. Change in the drying rate of soy-carrot mixture under the influence of coolant temperature 70 °C and $100/70$ °C. Mode parameters: $\delta = 15$ mm, $W = 4$ %; $V = 2.5$ m/s, $d = 10$ g/kg dry air. 1 — $100/70$ °C, 2 — 70 °C

temperature modes at 70 °C (120 min, curve 2, Fig. 2.16) and 80 °C (125 min, curve 4, Fig. 2.15). In addition, the step mode $100/70$ °C exceeds the mono-mode 70 °C by the drying rate: its maximum rate is higher by 0.2% /min (Fig. 2.17). Its advantages over the step modes $120/80$ °C and $120/100/80$ °C are: lower energy consumption for heating the coolant and maintaining it at high temperature without a heat pump.

The step mode $100/60$ °C was developed for soy-spinach mixture, since spinach is a more thermolabile material, the use of which allows one to preserve nutrients, color and taste of the source components [95, 120]. Fig. 2.18 shows the change in moisture content of the soy-spinach mixture under the influence of the coolant temperature of 60 °C (curve 2) and $100/60$ °C (curve 1). As a result of

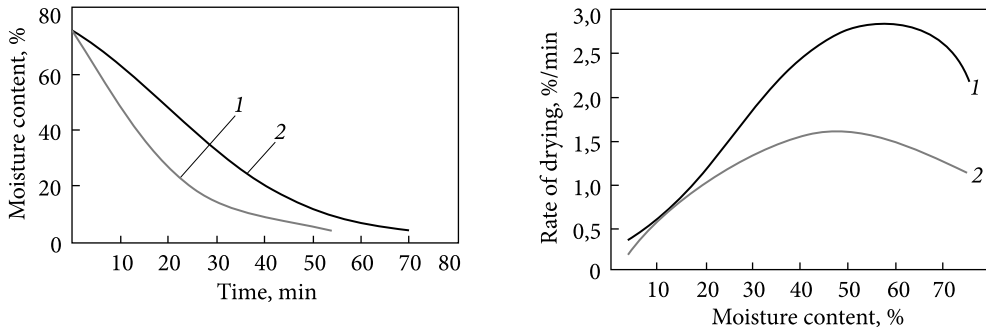


Fig. 2.18. Change in moisture content in soy-spinach mixture under the effect of coolant temperature 60 °C and 100/60 °C. Mode parameters: $\delta = 15$ mm, $W = 4$ %; $V = 2.5$ m/s, $d = 10$ g/kg dry air. 1 — 100/60 °C, 2 — 60 °C

Fig. 2.19. Changing the drying rate of soybean-spinach mixture under the influence of heat carrier temperature 60 °C and 100/60 °C. Mode parameters: $\delta = 15$ mm, $W = 4$ %; $V = 2.5$ m/s, $d = 10$ g/kg dry air. 1 — 100/60 °C, 2 — 60 °C

the development of a step mode for dehydration of phytoestrogenic soy-spinach mixture, the process is intensified by 21%.

The use of the step mode of 100/60 °C for HPT ground soybeans mixed with spinach can minimize energy consumption, as well as reduce the time of exposure to high temperatures of heat-sensitive proteins contained in soybeans, and prevent overheating in the middle of material layer.

The implementation of this step mode was as follows: at the beginning of drying, the coolant temperature was 100 °C. After 3-4 min, when the average temperature of the material layer approached the maximum allowable 60 °C (≈ 45 -50 °C), the heat carrier temperature decreased to 60 °C and remained the same until complete dehydration.

The resulting step-mode-derived mixture had a green color with a taste of raw materials.

Drying rate curves in Fig. 2.19 show that the using the step mode 100/60 °C allowed us to increase the average process rate and the maximum drying rate $N_{\max} = 2.8$ %/min (curve 1), which is 1.75 times higher than that for the mono-temperature mode 60 °C (curve 2).

Processing of soybeans requires high energy costs for drying. Studies on the change in moisture content and drying rate of soybean-carrot and soybean-spinach mixtures have shown that the stepwise regimes intensify the process in both cases.

Comparing the indicators from previous and repeated studies (Fig. 2.15), new ones on soybean-carrot mixture (Figs 2.16 and 2.17) and new data obtained from studies and use of the stepwise mode for soybean-spinach mixture (Figs. 2.18 and 2.19), one can see that spinach is an intensifying and stabilizing com-

ponent in drying of hygrothermally pre-treated soybeans. As a product of processing, soy-spinach mixture is not only less energy consuming compared to soy-carrot mixture, but is also a valuable source of nutrients, able to enrich and supplement the diet of people with vitamins and essential amino acids.

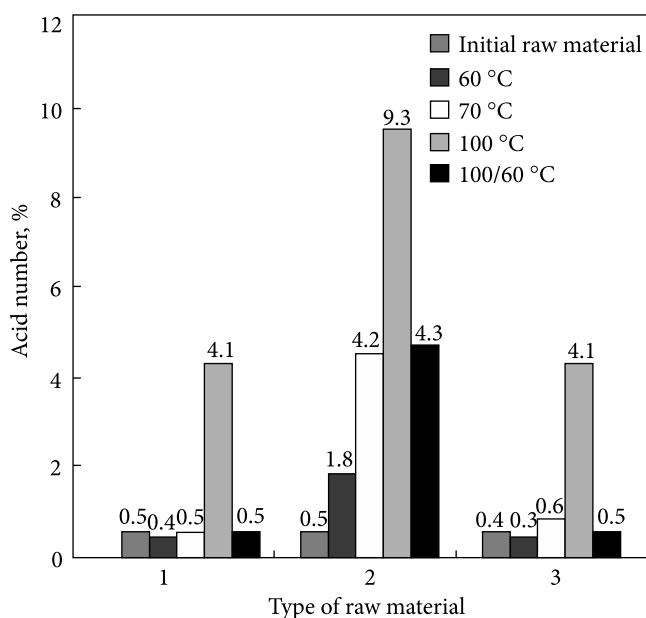
2.3. Qualitative characteristics of PPRMs and their carotene-containing mixtures

2.3.1. Changes in the acid number of PPRMs under the action of heat carrier temperature

For a protein-containing phytoestrogenic soybean-vegetable composition, another important quality characteristic is the change in acid number (AN) during drying. As known, AN characterizes the amount of free fatty acids contained in 1 g of fat and determined by the number of milligrams of caustic potassium required to neutralize them [122].

In studies of change in AN of PPRMs, under the action of coolant temperature a HPT soy-spinach mixture was selected and crushed.

Repetition of previous studies of AN change [11] confirmed that in whole soybeans during drying almost no change in AN is observed, but ground soybeans behave differently. When the material reaches a coolant temperature of 100 °C, AN = 9.3%. At 70 °C, the AN of crushed material gets a critical value of 4.2%, which is unacceptable. Previous studies in the IET of NAS of Ukraine have shown that overcoming the permissible value of 4% for AN causes hydration



of soy-vegetable composition fats. Based on this, coolant temperature for the drying process was chosen in accordance with the results for changes in AN (Fig. 2.20).

Fundamentally different results were obtained from the following studies on soybean-spinach mixture. From Fig. 2.20,

Fig. 2.20. Change in AN of PPRMs under the action of coolant temperature: 1— whole soybeans; 2 — ground soybeans; 3 — ground soy-spinach mixture

it is seen that due to the combination of soybeans with carotene-containing raw materials, in particular with spinach, change in AN occurs both in whole soybeans from 0.3 to 0.6%, and when using temperature of 100 °C exceeds the maximum allowable value 4.1%.

The obtained data allowed expansion of the permissible range of coolant temperatures and confirmed that the use of stepwise drying mode 100/60 °C is effective and safe for biologically active substances contained in the mixture of components [23].

2.3.2. Water holding capacity of PPRMs

The IET NAS of Ukraine has developed soy-carotene containing powders which contain a high content of nitrogenous substances from 29 to 32% of dry matter. They include proteins, nucleic acids; purines, as well as almost the entire amino acid composition.

The coefficient of swelling (K_s) is one of the most important characteristics of the quality of dried raw materials. It depends on the fiber content in the powders, but does not characterize the quality of protein-containing powders, and does not change with dispersion.

Powders that contain a large amount of protein are characterized by water holding capacity (WHC), determined by the centrifuge technique [100], which involves hydration of the mixture sample at certain conditions. The precipitate is centrifuged and dried. The value of WHC is equal to the mass ratio of evaporated water to dry solid residue. It is known that the pre-soaking time, rate, temperature and time of centrifugation do not significantly affect WHC (Table 2.3) [121].

Determination of WHC in composite protein-containing mixtures was performed using the technique of structuring protein products.

WHC is connected to the physicochemical properties of proteins that produce increased water absorption during dissociation of a protein molecule subunit during its deployment. The number of potential water-binding sites is theoretically increasing.

Table 2.3. Characteristics of carotene-containing powders [121]

Powder	Dry matter in centrifuge, %			WHC, %			Cellulose, %	WHC, %
	Temperature, °C			Temperature, °C				
	20	45	60	20	45	60		
Soy-carrot	2.3	2.9	3.1	2.4	2.6	2.6	8	58.1
Soy-pumpkin	2.0	2.5	3.1	2.8	2.9	2.7	10.1	61.2
Soybean	4.7	5.0	4.5	3.0	3.3	3.9	6.2	60.7
Carrot	3.2	3.4	4.2	5.2	5.3	5.4	11.1	85.0
Pumpkin	6.8	6.8	7.2	4.5	4.8	5.4	14.3	78.0

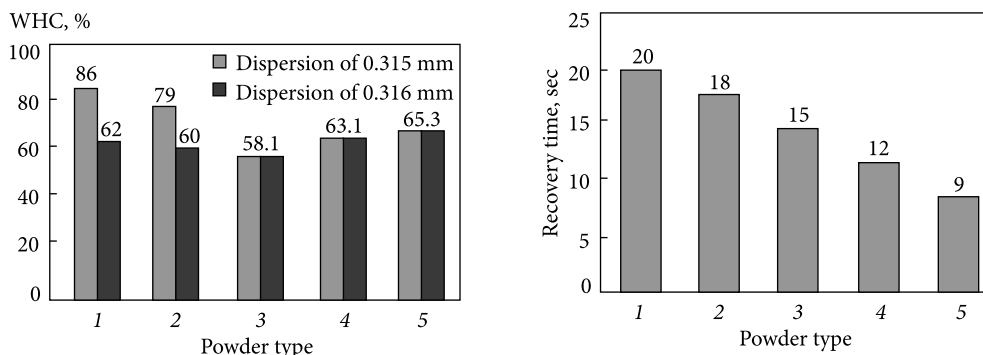


Fig. 2.21. Dependence of WHC of protein-carotene-containing mixtures and their components on the dispersion: 1 — spinach, 2 — sweet potato, 3 — soybean, 4 — soy-spinach mixture (1:1), 5 — soy-sweet potato mixture (1:1)

Fig. 2.22. Results of recovery of protein-containing phytoestrogenic powders: 1 — dry milk protein, 2 — bean-carrot, 3 — pea-carrot, 4 — oat-carrot, 5 — soy-spinach

According to the results of research (Fig. 2.21), the WHC of protein-containing carotene mixtures is 58.1-65.3% [121]. Dispersion is important only for the WHC of vegetable powders.

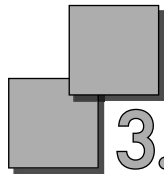
When the dispersion of spinach powder is over 0.315 mm, WHC = 86 %, and at a dispersion of 0.16 mm, WHC = 62%. For sweet potato dispersion over 0.315 mm, WHC = 79%, and at a dispersion of 0.16 mm, WHC = 60%.

2.3.3. Recovery of protein-containing phytoestrogenic powders

As a result of the research of drying processes, soy-spinach powder was obtained. The third important characteristic of the quality of the obtained powders, which is required for their further use, is their recovery (Fig. 2.22). Since soy is a high-protein raw material, dry milk protein was used as a reference for comparison. It was recorded that dry milk protein is restored in 20 sec, and soy — spinach powder in 9 sec (most rapidly of the existing protein-containing phytoestrogenic powders).

It is known that vegetable powders have a high rate of recovery in a short time, so the developed powder mixtures based on soybeans and vegetables recover faster than the standard ones. Soy-spinach mixture recovers faster due to the properties of spinach, which is a mixture component acting as an intensifier of the stage of dispersing the mixture in water.

Powders that contain two mutually reinforcing components are characterized by high quality recoverability [123]. This creates conditions for the use of plant functional powders in the production of dairy, bakery, confectionery, pasta and many other products through provision them with new technological properties, and saturation of products with functional components [124].



3. HEAT AND MASS TRANSFER DURING PPRM DRYING

3.1. Calculation of duration and rate of PPRM drying

Calculation of the kinetics of heat and moisture exchange during the drying of the phytoestrogenic mixture was carried out according to the V.V. Krasnikov method [44].

The studies on drying kinetics of different materials of plant origin using various drying methods (convective, conductive, combined, infrared, fluidized bed, etc.) conducted by Ukrainian and foreign researchers [68] have established the following pattern: during drying of a certain material having a primary moisture W_{in} , at any mode of drying, the quantity $N\tau$ remains independent and corresponds to the current moisture W .

Mathematically, this can be represented as follows:

$$N_1\tau_1 = N_2\tau_2 = \dots = N_n\tau_n = (N\tau)_W = const, \quad (3.1)$$

where: N_1, N_2, \dots, N_n are the drying rate in the first period (in the absence of the first period — the maximum drying rate) for different modes; $\tau_1, \tau_2, \dots, \tau_n$ are the current drying time during which the moisture changes from the initial moisture W_{in} to moisture W .

In accordance with the basics of the similarity theory and dimensional analysis [125], $N\tau$, as a stable set of values characteristic for the drying process, can be called a generalized value or a generalized drying time.

In particular, for the first drying period:

$$(N\tau)_W = W_{in} - W. \quad (3.2)$$

In the general case, for the second drying period:

$$(N\tau)_W = W_{in} - W + W_x = const. \quad (3.3)$$

where W_x is the experimental value which depends on the material properties.

3. HEAT AND MASS TRANSFER DURING PPRM DRYING

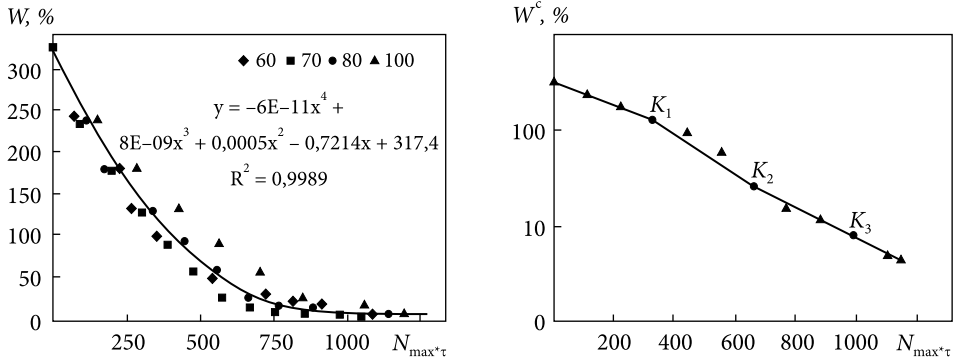


Fig. 3.1. Generalized kinetics curve of drying of soy-spinach mixture depending on the heat carrier temperature: 60 °C; 70 °C; 80 °C; 100 °C

Fig. 3.2. Generalized drying curve of phytoestrogenic mixture in a semi-logarithmic coordinate system

Operation with this quantity, which is related to the generalized drying time, gives a generalizing character to the study of the drying process. Due to the large number of different N and τ combinations, the same $N\tau$ value can be obtained at different N and τ , i.e., a fixed value $N\tau$ corresponds rather to a large number of similar sets than to the 1st defined set of initial quantities. Therefore, during studies of the drying process using $N\tau$, a large number of different cases are analyzed, which are united by some generalization of process parameters. The larger the value N , the shorter the drying time τ that is needed to reach a given moisture W , but according to (1.2) or (1.3) for all possible N for this W , the $N\tau$ remains constant. From the above: if we set the summary time $N\tau$ on the abscissa axis, and the current moisture W on the ordinate axis, then all the experimental drying curves of this material obtained at one initial moisture W_{in} , but at different modes (family of curves), transferred to a new coordinate system $W-N\tau$, may be combined into a single curve called the generalized drying kinetics curve.

When constructing the curve, the data presented in Section 3 and obtained in experiments with different temperature modes were generalized, taking into account the velocity and water content in both the heat carrier and material layer.

The drying curve of soy-based PPRMs is presented in Fig. 3.1. As seen, at high moisture of the material, points that correspond to different drying modes are located near the generalized curve. As the current moisture decreases, the scattering of the points increases, but within the error.

The generalized curve for the kinetics of drying soy-spinach mixture allows determining the relative drying coefficients of the second period.

The relative drying ratio % does not depend on the mode of processing and is determined only by the formula for connection of moisture with the structure and density of material.

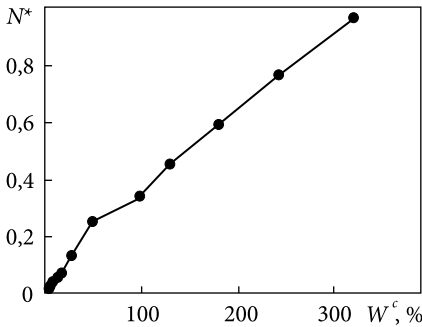


Fig. 3.3. Generalized drying curve for a phytoestrogenic mixture

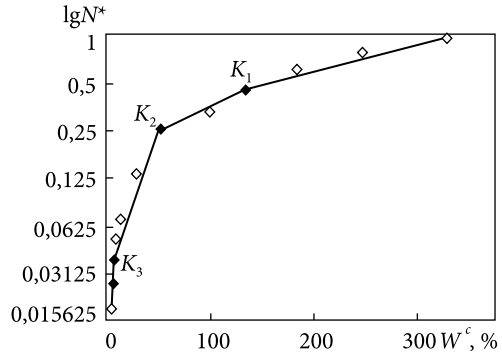


Fig. 3.4. Generalized drying curve for a soy-spinach composition in semi-logarithmic coordinates

Table 3.1. Relative drying coefficients for a soy-spinach mixture

Material	Range of critical moisture content, %	Relative drying coefficients		
		χ_1	χ_2	χ_3
Soy-spinach	131-50	0.00117	0.000807	0.000904
	50-14			
	14-4			

The relative drying coefficients are determined from the generalized curve by the following expressions:

$$\chi_1 = \frac{\lg(W_{K_1} - W_p) - (W_{K_2} - W_p)}{N_{\max} \tau_1}; \quad (3.4)$$

$$\chi_2 = \frac{\lg(W_{K_2} - W_p) - (W_{K_3} - W_p)}{N_{\max} \tau_2}; \quad (3.5)$$

$$\chi_3 = \frac{\lg(W_{K_3} - W_p) - (W_{K_4} - W_p)}{N_{\max} \tau_3}; \quad (3.6)$$

where $W_{K_1}, W_{K_2}, W_{K_3}, W_{K_4}$ — moisture content of the material in points K_1, K_2, K_3, K_4 — equilibrium moisture content of the material, %; τ_1, τ_2, τ_3 — duration of the first, second and third parts of the drying process, min.

The constructed generalized drying curve of the phytoestrogenic mixture shows that the drying process takes place in the second period (Fig. 3.2).

The curve is represented by broken lines, which indicates a complex nature of the second period: it consists of four parts of drying, each of which is characterized by its drying ratio, calculated by formulas (3.4-3.7) and listed in Table 3.1.

When calculating the relative drying coefficients for this phytoestrogenic mixture, the equilibrium moisture was 6.02 % at the heat carrier parameters $d = 10$ g/kg dry air and temperature 20 °C (according to our researches).

It is known that the drying rate in each part of the period is represented by a straight line in a semi-logarithmic coordinate system, i.e., the actual drying rate curve is replaced by a curved line.

After graphical differentiation of the generalized curve of drying kinetics presented in Fig. 3.2, a generalized drying rate was obtained (Fig. 3.3), which is determined by the following expression:

$$N^* = \left| \frac{dW}{d\tau} \right| \div N = \frac{dW}{Nd\tau} = tg(W, N\tau) = f(W) \quad (3.7)$$

N^* does not depend on drying mode and is a function of moisture [94].

Fig. 3.3 shows that the generalized drying rate curve is represented by smooth inclined curves. In order to describe the dependence N^* on W , the generalized drying rate curve was constructed in semi-logarithmic coordinates.

Fig. 3.4 shows that in semi-logarithmic coordinates, the generalized drying rate is presented with a broken line consisting of four straight lines. The law of changing due to the transition from one part to another changes as well, which indicates a difference in the kinetics and dynamics of drying in different periods of the drying process.

The value of N^* in different parts of the drying process in the second period without taking into account the heating period of the material is determined by the empirical dependences presented in Table 3.2.

The overall duration of the drying process τ_T (without taking into account the heating period) consists of the drying duration in the first period τ_1 and in the 1-st τ_1 , 2-nd τ_2 , 3-rd τ_3 parts of the second period:

$$\tau_T = \tau_1 + \tau_1 + \tau_2 + \tau_3. \quad (3.8)$$

The drying duration in the first period is equal to

$$\tau_1 = 0. \quad (3.9)$$

in the 1st part of the second period:

$$\tau_1 = \frac{1}{\chi_1 N} \lg \frac{W_{K1} - W_p}{W_{K2} - W_p}. \quad (3.10)$$

in the 2nd part of the second period:

$$\tau_2 = \frac{1}{\chi_2 N} \lg \frac{W_{K2} - W_p}{W_{K3} - W_p}. \quad (3.11)$$

Table 3.2. Generalized drying rate of soy-spinach mixture

Range of critical moisture content, %	Generalized drying rate
131-50	$N^* = 0.0116e^{0.7529W}$
50-14	$N^* = 0.0046e^{1.0113W}$
14-4	$N^* = 0.0031e^{1.205W}$

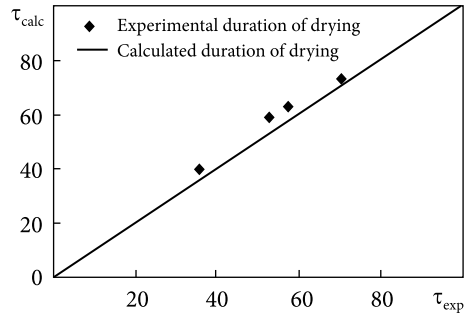


Fig. 3.5. Comparison of experimental and calculated duration of PPRMs drying on a convective stand

And in the 3rd part of the second period:

$$\tau_3 = \frac{1}{\chi_3 N} \lg \frac{W_{K_3} - W_p}{W_{K_4} - W_p}. \quad (3.12)$$

The overall duration of the process:

$$\tau_T = \frac{1}{N} \left(\frac{1}{\chi_1} \lg \frac{W_{K_1} - W_p}{W_{K_2} - W_p} + \frac{1}{\chi_2} \lg \frac{W_{K_2} - W_p}{W_{K_3} - W_p} + \frac{1}{\chi_3} \lg \frac{W_{K_3} - W_p}{W_{K_4} - W_p} \right). \quad (3.13)$$

In formula (3.13) the values of critical moisture content W_{K_1} , W_{K_2} , W_{K_3} , W_K and relative coefficients χ_1 , χ_2 , χ_3 are taken from the generalized drying curve in semi-logarithmic coordinates.

The overall duration of drying of the phytoestrogenic mixture is calculated by the formula (3.4):

$$\tau_T = \frac{1320}{N}. \quad (3.14)$$

Fig. 3.5 shows a comparison of the experimental τ_{exp} and calculated τ_{calc} for drying PPRMs at different temperatures of heat carrier (60, 70, 80, 100 °C).

The value of τ_{calc} calculated by formula (3.14) is close to the experimental. The error of the experimental results as compared to the calculated ones does not exceed 5%.

3.2. Numerical modeling of heat and mass transfer during PPRM drying

Numerical modeling of the convection process for drying of colloidal capillary-porous material (soy raw material) is performed on the basis of finite-difference solution of the system of heat and mass transfer equations [35, 124], which consists of:

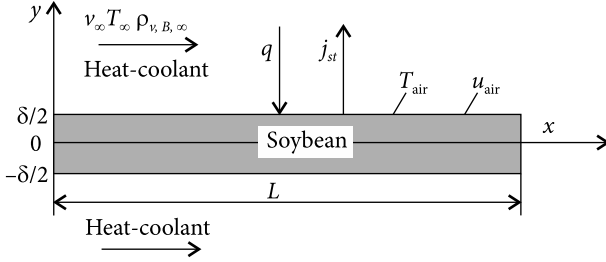


Fig. 3.6. Scheme to the physical model of the convective drying

mass transfer equation

$$\frac{\partial u}{\partial \tau} = K_{11} \nabla^2 u + K_{12} \nabla^2 T \quad (3.15)$$

heat transfer equation

$$\frac{\partial u}{\partial \tau} = K_{21} \nabla^2 u + K_{22} \nabla^2 T, \quad (3.16)$$

where u , kg/m^3 , is the specific moisture content in the material; T , K is temperature; τ , sec , is the time, ∇^2 is the Laplace operator.

The coefficients included in the system of equations have the form:

$$K_{11} = a_m; K_{12} = a_m^T; K_{21} = \frac{\gamma \varepsilon a_m}{C_p \rho}; K_{22} = \frac{\lambda}{C_p \rho} + \frac{r \varepsilon a_m^T}{C_p \rho},$$

where a_m , m^2/sec is the moisture diffusion coefficient in colloidal capillary-porous material; a_m^T , $\text{kg}/(\text{m} \cdot \text{K} \cdot \text{s})$, is the moisture thermal diffusion coefficient; ρ , kg/m^3 is the effective material density; λ is the effective thermal conductivity; C_p , $\text{J}/(\text{kg} \cdot \text{K})$ is the effective heat capacity; r , J/kg , is the specific heat of moisture evaporation; ε ($0 < \varepsilon < 1$) is the phase transformation coefficient, which determines the proportion of water vapor flow relative to the total flow of liquid and vaporous moisture.

The system of heat and mass transfer equations in the form of (3.15), (3.16) is usually used when the coefficients of thermal conductivity and diffusion can be approximately considered to be constant.

For numerical modeling of the convection drying process, a sample of rectangular soybean raw material with a thickness of δ , is placed in the drying chamber. The sample surfaces are washed with a heat carrier, i.e., with dry heated air having a temperature of T_∞ and relative concentration of water vapor $\rho_{v,B,\infty}$ (Fig. 3.6). The air flow velocity in the drying chamber moving in the longitudinal direction has a value v_∞ . The relative concentration of water vapor is defined as the ratio of the partial density of water vapor to the density of the vapor-air mixture.

The physical model of the drying process involves transfer of heat by convection from the heated air flow to the surface of the layer of material to be dried. The

water vapor formed as a result of drying the material is removed by the heat carrier stream. The main transfer of heat and moisture occurs in the direction perpendicular to the material surface. In the case of small sample thickness δ , heat and mass flows in the longitudinal direction may be neglected. Therefore, the problem of heat and mass transfer is considered in an approximate one-dimensional formulation [126]. If the temperature gradients in the thickness of the material are relatively low, you can also ignore the transfer of moisture by thermal diffusion. In this case $K_{12} = 0$; $K_{22} = \lambda/C_p\rho$. Under these conditions, equations (3.15) and (3.16) are simplified and take the forms:

$$\frac{\partial u}{\partial \tau} = a_m \frac{\partial^2 u}{\partial y^2}; \quad (3.17)$$

$$\frac{\partial T}{\partial \tau} = a_T \frac{\partial^2 T}{\partial y^2} + \frac{r\varepsilon \partial u}{C_p\rho \partial \tau}; \quad (3.18)$$

where $a_T = K_{22} = \frac{\lambda}{C_p\rho}$ is the effective coefficient of thermal conductivity of a colloidal capillary-porous material.

The initial conditions for nonstationary equations (3.17) and (3.18) are distribution of temperature T and specific moisture u inside the material at $\tau = 0$. The air velocity is also a known quantity v_∞ along with temperature T_∞ and the relative humidity of heat carrier φ_∞ . To formulate the boundary conditions, it is assumed that the heat and mass transfer proceeds symmetrically relative to the x axis. In this case, the system of equations (3.17) and (3.18) is considered only in the range $0 \leq y \leq \delta/2$ (Fig. 3.7), and at $y = 0$ the conditions of symmetry are set as follows:

$$\left. \frac{\partial u}{\partial y} \right|_{y=0} = 0; \quad \left. \frac{\partial T}{\partial y} \right|_{y=0} = 0.$$

On the surface of the sample to be dried, the boundary conditions must determine the balance of moisture removed from the material and entering the heat carrier, as well as the balance of heat coming from the heat carrier to the material and spent on heating the material and evaporating moisture from the surface. The total flow of liquid and vapor coming from the middle of the material to the

surface is defined as $j_{\hat{a}_a} = -a_m \left. \frac{\partial u}{\partial y} \right|$. From the material surface to the heat carrier,

moisture is transferred in the form of vapor by diffusion. The density of this flow is calculated by expression $j_i = -D_{va}\rho_a \left. \frac{\partial \rho_{v,\hat{a}}}{\partial y} \right|$, where D_{va} is the diffusion coefficient for water vapor in air.

Therefore, the boundary condition to equation (3.17) for the heat and mass transfer on the surface has the form:

$$-a_m \left. \frac{\partial u}{\partial y} \right|_{y=\delta/2} = -D_{va} \rho_a \left. \frac{\partial \rho_{v,\hat{a}}}{\partial y} \right|_{y=\delta/2}. \quad (3.19)$$

The heat flux flowing from the heat carrier to the material surface is equal to $q_a = -\lambda_a \left. \frac{\partial T}{\partial y} \right|_{y=\delta/2}$, where λ_a is the coefficient of thermal conductivity of air. The heat flux density transferred from the surface into the material is calculated as $q_m = -\lambda \left. \frac{\partial T}{\partial y} \right|_{y=\delta/2}$. The density of heat flux expended on the evaporation of moisture from the surface is proportional to the flux density of the liquid moisture, i.e.

$$q_{ev} = -r(1 - \varepsilon_{air}) a_m \left. \frac{du}{dy} \right|_{y=\delta/2}.$$

Expression $(1 - \varepsilon_{air})$ determines the proportion of the flow of liquid moisture in the total flow of moisture coming from the middle of the material to the surface. Therefore, the boundary condition to equation (3.18) on the heat and mass transfer surface has the form:

$$-\lambda \left. \frac{dT}{dy} \right|_{y=\delta/2} - r(1 - \varepsilon_{air}) a_m \left. \frac{du}{dy} \right|_{y=\delta/2} = -\lambda_a \left. \frac{dT}{dy} \right|_{y=\delta/2}. \quad (3.20)$$

To calculate the heat flux density and water vapor flux density on the surface of the material from the heat carrier, the expressions are used:

$$-D_{va} \rho_a \left. \frac{\partial \rho_{v,\hat{a}}}{\partial y} \right|_{y=\delta/2} = \beta (\rho_{v,\hat{a},air} - \rho_{v,\hat{a},\infty}); \quad (3.21)$$

$$-\lambda_a \left. \frac{\partial T}{\partial y} \right|_{x=\delta/2} = \alpha (T_{air} - T_{\infty}), \quad (3.22)$$

where α , W/(m²K) is the heat transfer coefficient; β , kg/(m²s) is the mass transfer coefficient, T_{air} is surface temperature for heat and mass transfer, $\rho_{v,\hat{a},air}$ is the relative concentration of water vapor in the heat carrier near the surface of the material.

To calculate the heat transfer coefficients α , the corresponding criterion equations for the Nusselt number are applied to the sample surface to be dried $Nu = \frac{\alpha L}{\lambda_a}$, which are given in [127] and correspond to the flow regime of the heat carrier. The flow regime is determined by the Reynolds number $Re = \frac{v_{\infty} L}{\nu_a}$, calculated using the velocity of the heat carrier flow v_{∞} . Mass transfer coefficient β can be calculated by ana-

logy between heat transfer and mass transfer, from an approximate ratio $\beta \approx \frac{\alpha}{C_a}$, which is considered to be valid provided that the Lewis number is close to unit

$$\left(\text{Le} = \frac{D_{v,a}}{a} = 1 \right).$$

To apply these boundary conditions, it is necessary to establish a relationship between the value $\rho_{v,\hat{a},\text{air}}$ and the specific moisture content on the material surface $u_{\text{air}} = u_{y=\delta/2}$. To do this, it is advisable to use isotherms of sorption/desorption, which establish the relationship between the equilibrium moisture content and the relative moisture φ . If the moisture content exceeds the maximum hygroscopic value for the condition $\varphi=1$, quantity $\rho_{v,\hat{a},\text{air}}$ is calculated by the relationship between the partial pressure of saturated water vapor and the temperature which corresponds to the material temperature. Otherwise, for the moisture content on the surface u_{air} and temperature $T_{\text{air}} = T_{y=\delta/2}$, the corresponding value of relative moisture near the surface φ_{air} is calculated. Then, the value $\rho_{v,\hat{a},\text{air}}$ is determined [128]. To do this, the ratio is formed:

$$\rho_{v,\hat{a}} = \frac{\rho_v}{\rho_v + \rho_a} = \frac{p_v / R_v}{p_v / R_v + p_a / R_a},$$

where p_v ; p_a are the partial pressures of water vapor and dry air, respectively; R_v and R_a are gas constants for water vapor and dry air. To determine the values p_v and p_a , it is necessary to use ratios $p_v = \varphi_{\text{air}} \cdot p_{v,\text{sat}}(T_{\text{air}})$; $p_a = p_0 - p_v$, where p_0 is the total pressure of the vapor-air mixture, which corresponds to atmospheric pressure, $p_{v,\text{sat}}(T_{\text{air}})$ is the saturated vapor pressure at temperature T_{air} .

The phase conversion coefficient on the heat and mass transfer surface ε_{air} depends on the moisture content of this surface. This dependence is determined experimentally. But in the first approximation we can assume that $\varepsilon_{\text{air}} \approx 0$, if the moisture content of the material surface exceeds the maximum hygroscopic value, which corresponds to the relative moisture near the surface $\varphi_{\text{air}} = 1$. If the moisture content is lower than the specified value, it is accepted as $\varepsilon_{\text{air}} \approx 1$ [129].

For the numerical solution of the system of equations (3.17) and (3.18) with boundary conditions (3.19)-(3.22), the finite difference method is used. For this purpose, a uniform grid is constructed with a step of $\Delta y = \delta/(2n)$, where n is the number of steps along the y -axis. Grid nodes are located in the middle of the intervals into which the calculation area is divided. The system of equations (3.17) and (3.18) in the method of finite differences acquires the form:

$$(u_{k,i} - u_{k-1,i}) / \Delta \tau = a_m (u_{k,i+1} - 2u_{k,i} + u_{k,i-1}) / \Delta y^2; \quad (3.23)$$

$$(T_{k,i} - T_{k-1,i}) / \Delta \tau = a_T (T_{k,i+1} - 2T_{k,i} + T_{k,i-1}) / \Delta y^2 + \frac{r\varepsilon}{C_p \rho} (u_{k,i} - u_{k-1,i}) / \Delta \tau; \quad (3.24)$$

where $\Delta\tau$ is the step time; k is the number of steps; i is the step number along y . In the given system of difference equations the implicit time scheme [130] according to which approximation of derivatives by spatial variable y is performed for the current time step k . Equations (3.23) and (3.24) are formed in each internal node of the calculation grid.

The numbering of grid nodes is performed so that the node with the number $i = 1$ be the closest to the plane of symmetry $y = 0$ of internal grid node. Herein, node with number $i = n$ will be the internal node closest to the heat and mass transfer surface at $y = \delta/2$. Nodes with numbers $i = 1 \dots n$ are internal calculation nodes of the grid. In the considered difference scheme, additional (external) nodes with numbers $i = 0$ and $i = n + 1$ are also used at a distance $\Delta y/2$ below and above plane of symmetry, respectively.

Boundary conditions in the finite difference form are:

$$-a_m \frac{u_{k,n+1} - u_{k,n}}{\Delta y} = \beta(\rho_{v,B,\text{air}} - \rho_{v,B,\infty}); \quad (3.25)$$

$$-\lambda \frac{T_{k,n+1} - T_{k,n}}{\Delta x} = \alpha \left[\left(\frac{T_{k,n+1} + T_{k,n}}{2} \right) - T_\infty \right] + r(1 - \varepsilon_{\text{ПОВ}}) \beta(\rho_{v,B,\text{ПОВ}} - \rho_{v,B,\infty}); \quad (3.26)$$

$$u_{k,0} = u_{k,1}; \quad (3.27)$$

$$T_{k,0} = T_{k,1}. \quad (3.28)$$

The relative concentration of water vapor in the heat carrier near the surface of the material $\rho_{v,B,\text{air}}$ is defined as a function of the surface temperature $T_{\text{air}} = (T_{n+1} + T_n)/2$ and its moisture content $u_{\text{air}} = (u_{n+1} + u_n)/2$ by the method discussed above.

To solve the system of difference equations (3.23) and (3.24), the run method is used [130]. Consider this on the example of system of difference equations (3.23) given in the form:

$$Au_{k,i+1} - Bu_{k,i} + Au_{k,i-1} = F; \quad (3.29)$$

where $A = a_m \Delta\tau / \Delta y^2$; $B = (2A + 1)$; $F = -u_{k-1,i}$.

The relationship between functions $u_{k,i}$ and $u_{k,i-1}$, which belong to the neighboring nodes of the difference grid, is specified as

$$u_{k,i-1} = P_{i-1} \cdot u_{k,i} + Q_{i-1}. \quad (3.30)$$

Expression (3.30) is substituted into equation (3.29), which after the transformation looks like

$$(A \cdot P_{i-1} - B) \cdot u_{k,i} = -Au_{k,i+1} + (F - A \cdot Q_{i-1}).$$

From the last expression $u_{k,i}$ is determined:

$$u_{k,i} = -\frac{A}{(A \cdot P_{i-1} - B)} u_{k,i+1} + \frac{F - A \cdot Q_{i-1}}{(A \cdot P_{i-1} - B)}. \quad (3.31)$$

As follows from the comparison of expressions (3.20) and (3.19),

$$P_i = -\frac{A}{(A \cdot P_{i-1} - B)}; \quad Q_i = \frac{F - A \cdot Q_{i-1}}{(A \cdot P_{i-1} - B)}.$$

The coefficients are calculated from the given expressions P_i and Q_i in each grid node ($i = 1 \dots n$). To determine P_0 and Q_0 , it is necessary to use the boundary condition (3.27), from which $P_0 = 1$; $Q_0 = 0$.

After calculating the coefficients P_n and Q_n , related to the node n , the moisture content in the node $n + 1$ is determined. For this, the relation (3.30), generated for the node number n , is substituted into the boundary condition (3.25) $i = n$:

$$u_{k,n} = P_n \cdot u_{k,n+1} + Q_n.$$

From the obtained expression, $u_{k,n+1}$ is defined:

$$u_{k,n+1} = \frac{Q_n - \beta \cdot \Delta y (\rho_{v,B,air} - \rho_{v,B,\infty}) / a_m}{(1 - P_n)}$$

The following values $u_{k,i}$ for $i = n \dots 0$ are calculated using relationship (3.30). The system of equations (3.24) is solved similarly.

According to the above method, numerical modeling of the convection drying process of a crushed soybean layer is performed. A rectangular sample of soybean raw material is considered: length $L_1 = 100$ mm; width $L_2 = 50$ mm and thickness $\delta = 15$ mm. The coolant (heated air) temperature at the entrance to the drying chamber is $t_\infty = 60$ °C, and its relative humidity $\varphi_\infty = 7\%$. Under these conditions $\rho_{v,B,\infty} = 0.00858$. Air flow velocity in the drying chamber $u_\infty = 2.5$ m/sec. The initial mass of the sample is $m_{in} = 33.78$ g. Mass of dry material (after complete removal of moisture) $m_d = 12.79$ g. The initial temperature of the soybean layer varies linearly from 37.1 °C in the middle of the sample ($y = 0$) to 46.7 °C on its surface ($y = \delta/2$). The initial specific moisture content is $u_0 = 280.0$ kg/m³. Thermophysical properties of crushed soybeans are accepted according to the recommendations [131]. Sorption/desorption curves for determining the equilibrium moisture content in crushed soybeans depending on the relative moisture are presented in [11].

Numerical simulation is performed in the calculation range $0 \leq y \leq \delta/2$ (F. 3.6), which is divided into $n = 100$ steps along the transverse coordinate. The length step of the difference grid along the y coordinate $\Delta y = \delta / (2n) = 0.075$ mm and the time step is $\Delta \tau = 1$ sec.

3. HEAT AND MASS TRANSFER DURING PPRM DRYING

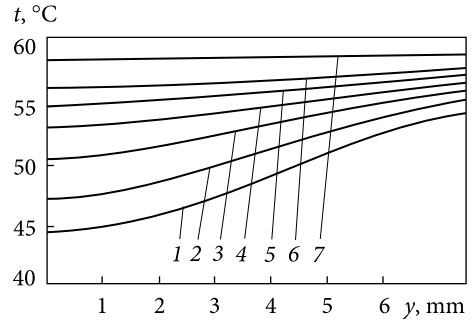
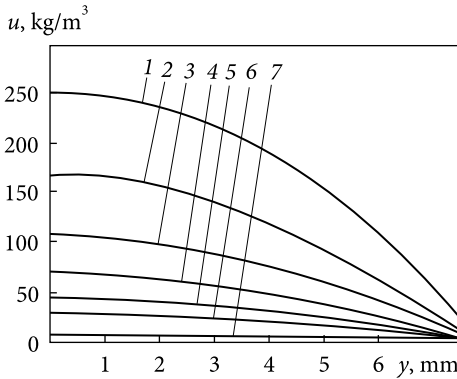


Fig. 3.7. Change over time of distribution of specific moisture through the sample thickness during drying for: 1 — 10 min; 2 — 20 min; 3 — 30 min; 4 — 40 min; 5 — 50 min; 5 — 60 min; 7 — 90 min

Fig. 3.8. Change over time of temperature distribution through sample thickness during drying for: 1 — 10 min.; 2 — 20 min; 3 — 30 min; 4 — 40 min; 5 — 50 min; 6 — 60 min; 7 — 90 min

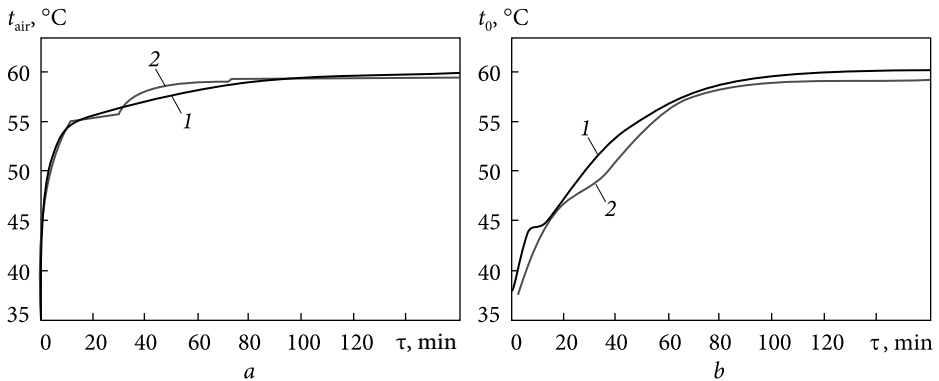


Fig. 3.9. Temperature change over time (a) on the surface and (b) in the center of the soybean layer during drying: 1 — results of numerical simulation; 2 — experimental data

The results of solving the difference equations for mass transfer (3.23) and heat transfer (3.24) in the form of distributions over the thickness of the sample of specific moisture content $u(\tau, y)$ and temperature $T(\tau, y)$ at different points over time during drying are shown in Figs 3.7 and 3.8. As seen from these figures, for the first 10 min of the drying process, the specific moisture content on the material surface ($y = 7.5$ mm) decreases from the initial value 280.0 kg/m^3 to 25.0 kg/m^3 . Moisture content in the material center ($y = 0$) during this time hardly changed. That is, at the initial stage of drying, the process is the most intense on the sample-surface. The soybean layer temperature in the first 10 min rises from $46.7 \text{ }^\circ\text{C}$ to $54.5 \text{ }^\circ\text{C}$ on the surface and from $37.1 \text{ }^\circ\text{C}$ to $44.5 \text{ }^\circ\text{C}$ in the center. It follows that heating of the sample at the initial stages proceeds intensely through its thickness.

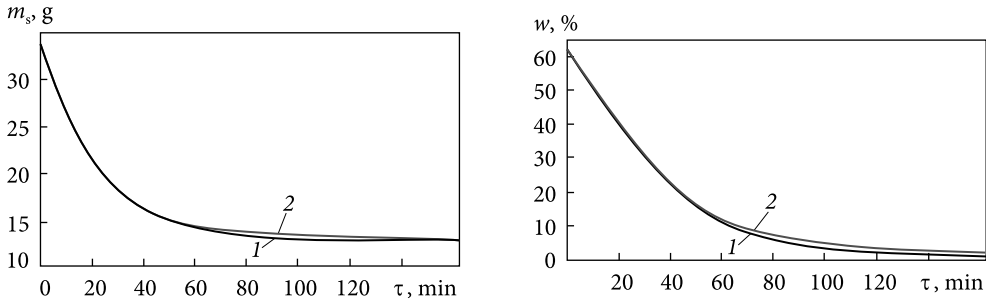


Fig. 3.10. Soybean layer mass change over time during drying; 1 — results of numerical modeling; 2 — experimental data

Fig. 3.11. Time dependence of the relative moisture in soybean layer during drying: 1 — results of numerical modeling; 2 — experimental data

Over time, the distribution of specific moisture content and temperature through the material thickness becomes more uniform. The intensity of heat and mass transfer gradually decreases.

The results of numerical modeling of the temperature regime of drying were compared with experimental data. Fig. 3.9 shows the change over time of the soybean layer surface temperature (*a*) and the temperature in the sample center (*b*). Curves 1 correspond to the results of numerical modeling, and curves 2 — to the experimental results. As can be seen in Fig. 3.9, *a*, 80 min after the start of drying, the surface temperature t_{air} reaches 59 °C and then changes much more slowly. In the sample middle, temperature changes markedly within 120 min from the beginning of drying (Fig. 3.9, *b*).

Comparing curves 1 and 2 in Fig. 3.9, *a*, one can see that the discrepancy between the calculated and experimental data on the surface temperature for heat and mass transfer does not exceed 1.5 °C. Somewhat more significant is the discrepancy between the calculated and experimental data on the temperature inside the sample (Fig. 3.9, *b*). But in general, the results of numerical simulations of the drying process temperature are quite agreeable with the experimental data.

An important integral characteristic of the drying process is the time dependence of the sample mass. Fig. 3.10 (curve 1) shows the results of calculating the change over time of the soybean sample mass during drying, determined by integrating the specific moisture content in the sample through its thickness, taking into account the symmetry relative to the $y = 0$ axis and the dry material mass:

$$m_3(\tau) = 2 \cdot L_1 \cdot L_2 \cdot \int_0^{0,5\delta} u(\tau, y) dy + m_c$$

These results are compared with the experimental data shown in Fig. 3.10 (curve 2).

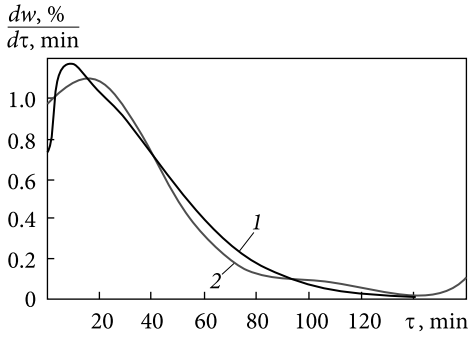


Fig. 3.12. Dependence of the rate of change in the relative moisture of sample on the time: 1 — results of numerical modeling; 2 — experimental data

As seen, for the first 80 min of the drying process, the soybean mass decreases due to evaporation of moisture from the initial value of 33.78 g to 13.5 g.

Comparison of numerical simulation results with data calculations indicate their satisfactory agreement.

Another important integral characteristic of the drying process is the change over time in the relative moisture in the material $w(\tau)$, which is calculated by the

$$\text{formula: } w = \frac{m_3 - m_c}{m_3} \cdot 100\% .$$

Its dependence on time is shown in Fig. 3.11. The nature of the w change is generally similar to the change in m_3 . For the first 60 min of drying, $w(\tau)$ varies quite intensively, from 62 % to 11 %. Then its change slows down.

This value is also determined from the experiment. As seen in Fig. 3.12, within the time interval $0 < \tau < 60$ min the calculated results and experimental data agree quite well. Then, at the stage of drying, there appeared a slight discrepancy.

The time derivative of the relative moisture in the material $\frac{dw}{d\tau}$ is also determined. It characterizes the rate of change over time of the relative moisture $w(\tau)$ and is measured as a percentage per minute. The time dependences of this value, obtained by the results of numerical simulations and the experimental data are shown in Fig. 3.12.

The figure shows that, according to numerical simulations in the interval $0 < \tau < 10$ min, the rate of $w(\tau)$ change over time increases and at $\tau = 10$ min reaches a maximum value of 1.19 %/min. The increase is due to increasing the relative concentration of moisture in the air near the material surface, $\rho_{v, b, \text{поб}}$. The value of $\rho_{v, b, \text{поб}}$ determines the intensity of vaporous moisture transfer from the surface of the soybean layer to the coolant. Its growth is associated with intense heating of the material surface at the initial stage of drying. Then it gradually decreases, which is a consequence of the decrease in the specific moisture content on the material surface. Under these conditions, the rate of removal of vaporous moisture from the material surface to the coolant slows down. This also explains the decrease in the rate of change of the relative moisture over time, $\frac{dw}{d\tau}$ (Fig. 3.12, curve 1).

Experimental results for determining the rate of change over time in the relative concentration of moisture in the material are shown by curve 2 in Fig. 3.12. Accord-

ing to experimental studies, the maximum rate, $\frac{dw}{d\tau}$, was achieved at $\tau = 14$ min and equaled 1.1%/min. Further experimental values of $\frac{dw}{d\tau}$ began decreasing, which in general qualitatively coincides with the data of numerical simulations.

From the analysis of numerical simulation data in line with the results of comparing the calculated data with experimental data, we can conclude that the proposed numerical model satisfactorily describes the process of convection drying of crushed soybeans and can be used to calculate the mode parameters of this process.

3.3. Specific heat of PPRM evaporation

One of the problems in drying vegetable raw materials is that due to the influence of light and heat treatment, oxygen in biologically active substances (BAS) leaves the material. The main purpose of processing soybeans by drying is to preserve phytoestrogens as many as possible and prevent oxidation of fats. To inactivate the anti-food components of soybeans improve the quality of the preliminary hydrothermal treatment of raw materials, soybeans are soaked, washed, boiled and washed again, which results in increasing protein digestibility and destruction of anti-food components [86].

It is known that moisture evaporation is an energy-intensive process. From the literature, a study of the drying process of various materials of plant origin showed a significant difference between the actual values of specific heat consumption for moisture evaporation and the values of specific heat consumption for pure water evaporation [132]. Due to the fact that in drying plant materials, the increase in energy costs is associated with the complicated permeability of cell membranes to water and the complexity of the water removal process (due to interaction with soluble components of cell juice and skeletal molecules) and due to lack of related data in the literature, it is important to investigate the effect of creating protein-containing phytoestrogenic functional compositions from plant raw materials on the specific heat consumption required for evaporation of the water present in the compositions.

The calorimetric method was used as a basis for experimental studies. It is based on simultaneous continuous measurement of the decrease in the sample mass and the amount of heat spent on the evaporation of moisture during isothermal drying. The experiments were carried out using the modernized installation for synchronous thermal analysis DMKI-01 created in the IET NAS of Ukraine [98, 133], which includes a calorimetric platform with deep cylindrical cells, which makes it possible to study powder materials.

A picture of the microcalorimeter is shown in Fig. 3.13.

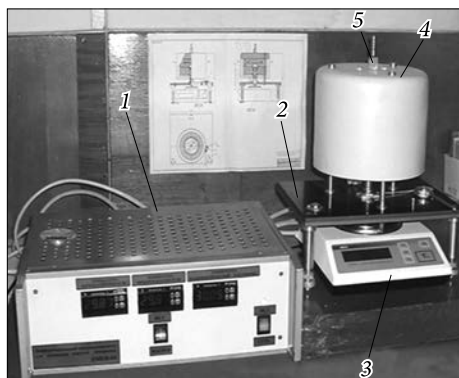


Fig. 3.13. Appearance of the differential microcalorimeter DMKI-01: 1 — electronic unit; 2 — platform; 3 — analytical balance; 4 — casing of the thermal unit; 5 — thermal unit

The microcalorimeter of the DMKI-01 model belongs to differential thermogravimetric calorimeters. Differential calorimetry and gravimetric analysis are combined to determine the specific heat of vaporization. The microcalorimeter is used as a non-standard means for measuring evaporation of both free and material-bound moisture [98, 99].

The objects to be studied were crushed HPT soybeans, spinach, carrots and their functional mixtures with a ratio of 1:1. Beans and vegetables were chopped to an approximate size of $4 \times 2 \times 3$ mm. Conductive drying of samples with the same initial mass of 0.3 g was carried out in the working chamber of the calorimetric unit at a constant temperature of 60°C in conditions close to isothermal, until the equilibrium moisture of the samples. The drying temperature of 60°C was determined as recommended for pre-treated protein-containing raw materials. The mass of dry matter in the sample was determined by drying in the working chamber at a constant temperature of 105°C to a constant mass.

The specific heat of water evaporation from the sample material was determined from the time of reaching thermodynamic equilibrium inside the calorimetric chamber and then at the current time according to the following formula:

$$r_i = \frac{\int_{\tau_{i-1}}^{\tau_{i+1}} q(\tau) d\tau}{m(\tau_{i-1}) - m(\tau_{i+1})},$$

where r_i is the specific heat consumption for evaporation over time from τ_{i-1} to τ_{i+1} , kJ/kg; τ_{i-1} and τ_{i+1} are the current time, sec; $q(\tau)$ is the heat flux inside the working chamber as a function of time, J/sec; $m(\tau_{i-1})$ and $m(\tau_{i+1})$ are the sample mass, kg, at times τ_{i-1} and τ_{i+1} .

The measurement results are shown in Figs. 3.14 and 3.15. From Fig. 3.14 it is seen that at the beginning of drying the specific heat of moisture evaporation from carrots and soy-carrot compositions is almost by 4-5% greater than that for pure water. As a result of mixing components during drying, starting from a moisture of 65%, an integrated thermal effect is registered in the mixture during the evaporation process [134].

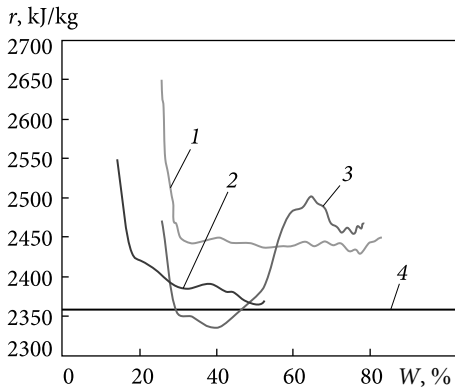


Fig. 3.14. Dependence of the reduced heat of water evaporation from soy-carrots mixture and its components on their relative moisture during drying: 1 — carrots, 2 — soybeans, 3 — soy-carrot mixture, 4 — water

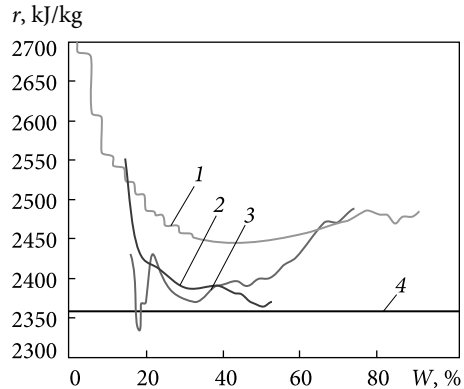


Fig. 3.15. Dependence of the reduced heat of water evaporation from soy-spinach mixture and its components on their relative moisture during drying: 1 — spinach, 2 — soybeans, 3 — soy-spinach mixture, 4 — water

A similar effect is also observed on the soy-spinach mixture (Fig. 3.15). This is probably the reaction of soybean fats with fat-soluble carrot/spinach carotenoids, but a more precise determination of the nature of this reaction requires additional biochemical studies of the interaction of components [134].

3.4. Thermogravimetric properties of PPRMs

As described in the previous sections, in the crushed state and under thermal action, BASs lose their activity owing to the influence of light and oxygen, while soybean and vegetable fats are oxidized. To preserve and improve the functional properties of protein-containing PPRM, HPT of raw materials was used, followed by mixing them with a component ratio of 1:1.

As known from the literature, there is a significant difference between the actual values of specific heat consumption for their dehydration and the heat of evaporation of pure water [135]. The increase in energy consumption for the drying process of plant materials is associated with the removal of water bound with molecules and ions of cellular fluid as well as biopolymers of the material skeleton [136-138].

The aim of our study was to determine whether the heat of dehydration and thermal stability of soybeans are affected by the formation of a composite mixture with carrots (or spinach), in particular with a ratio of soybeans to carrots (or spinach) 1 : 1.

3. HEAT AND MASS TRANSFER DURING PPRM DRYING

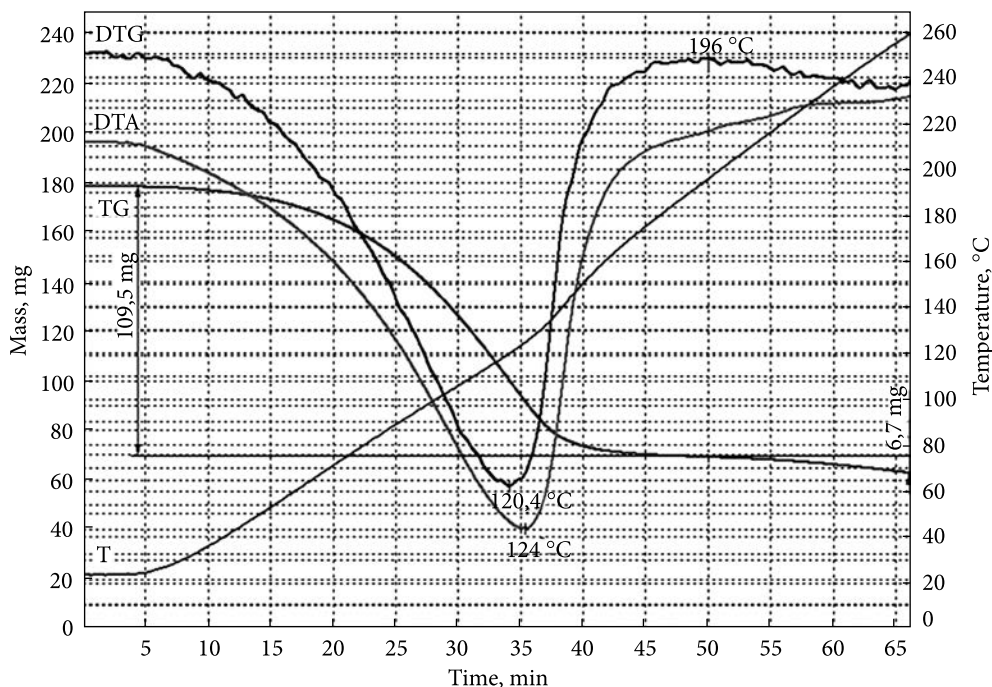


Fig. 3.16. Soybean derivatographs. Sample mass 178.6 mg

The studies were performed using a derivatographic method which combines thermogravimetry (TG) with classical differential thermal analysis (DTA). This method allowed us to study the state of mono-substances and compositions under conditions of programmable heating [132]. Qualitative and quantitative analysis of the processes that took place under heating of the samples at a constant rate is performed using derivatograms, that is, a set of curves of changes in: temperature of the sample (T), its mass (TG), mass change rate (DTG) and DTA curve, due to which it is possible to identify thermal processes.

The studies were carried out on a Q-1000 derivatograph of the Paulik-Paulik-Erdey system (IOM, Hungary) [109] in the range of 25...250 °C at a heating rate of 3.6 K/min in an atmosphere of still air. An inert substance in the reference crucible was alumina. The temperature scale was corrected by the melting point of benzoic acid (122.4 °C) [139]. The temperature deviation did not exceed ± 0.5 K. With using the derivatograph computer created in the Delphi programming medium, the obtained data were collected and processed. Samples before the study were ground in a meat grinder and crushed in a mortar to a single-fraction state of particles. Samples were placed in an open conical platinum crucible from the derivatograph complete set.

Figs. 3.16-3.20 demonstrate the obtained derivatographs.

3.4. Thermogravimetric properties of PPRMs

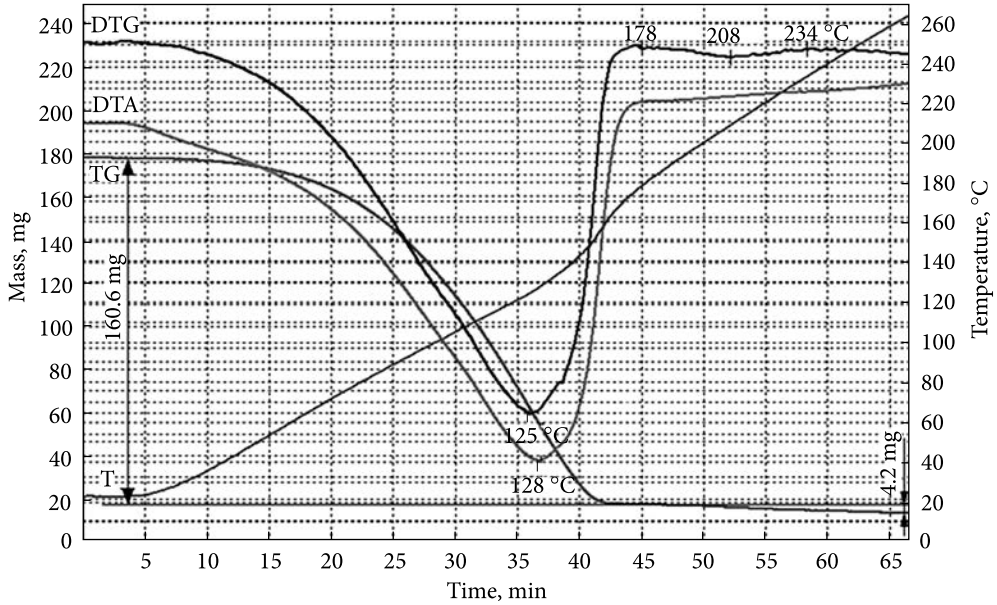


Fig. 3.17. Spinach derivatographs. Sample mass 178 mg

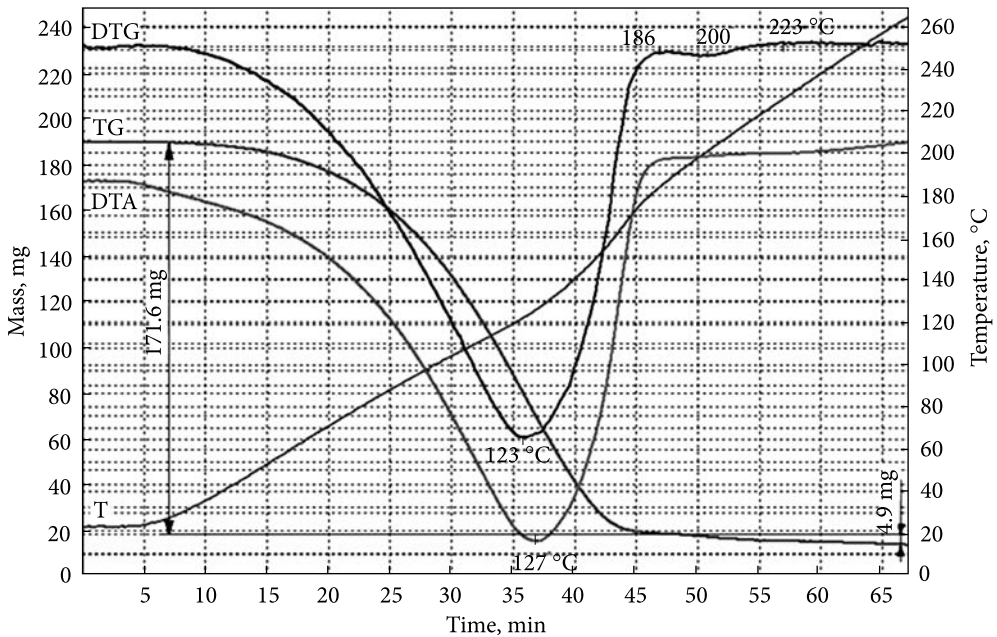


Fig. 3.18. Carrot derivatographs. Sample mass 190 mg

3. HEAT AND MASS TRANSFER DURING PPRM DRYING

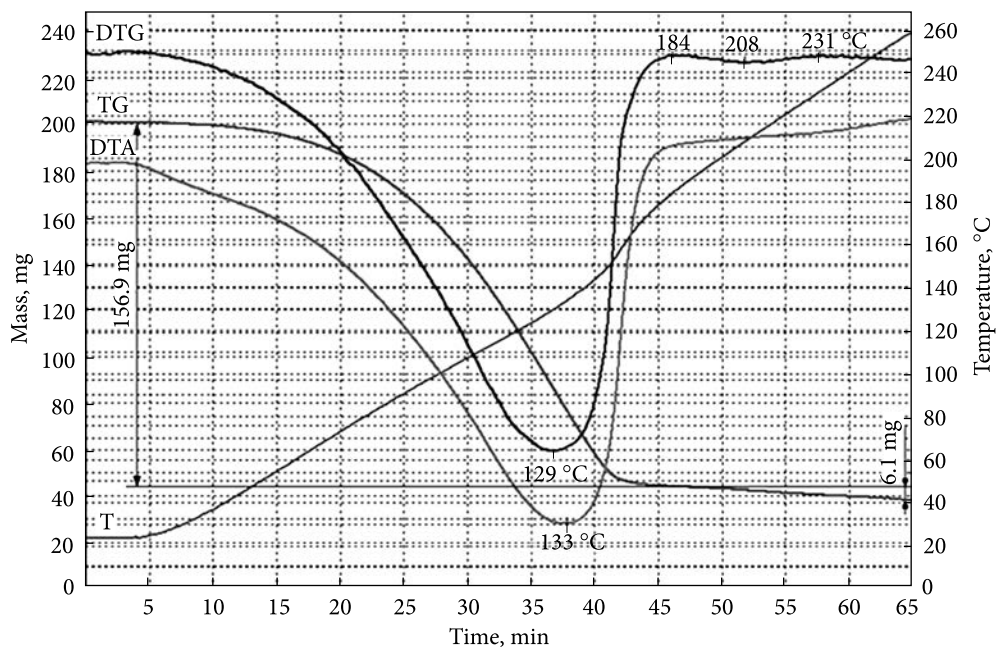


Fig. 3.19. Derivatograph of soy-carrot mixture. Sample mass 201 mg

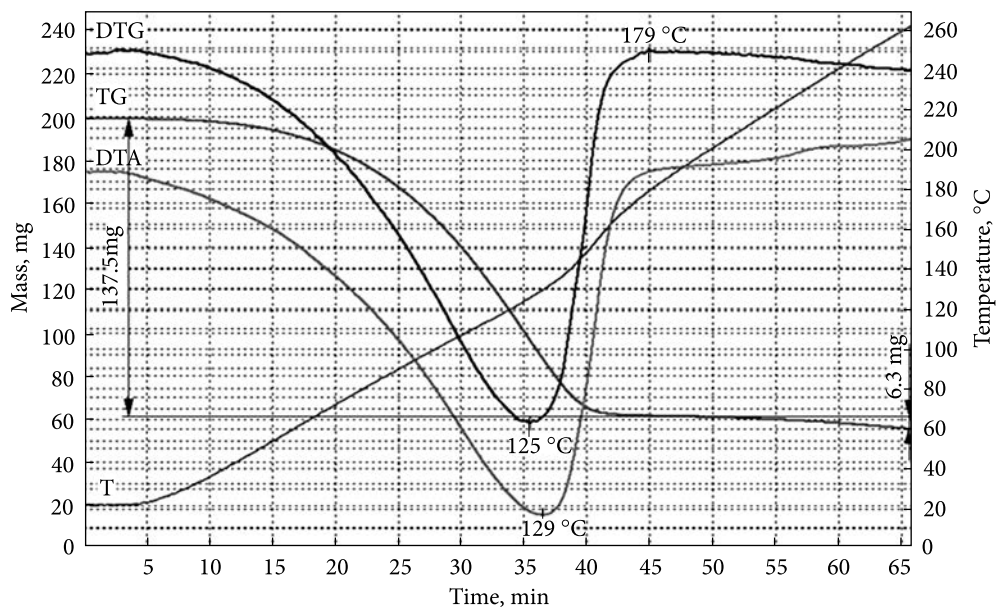


Fig. 3.20. Derivatograph of soy-spinach mixture. Sample mass 199 mg

Upon analyzing the obtained graphs for derivatives, it can be stated that the removal of water, as evidenced by the change in the mass of objects (TG curves), with simultaneous heat absorption (DTA curves) begins from 22-24.0 °C. As the temperature rises, the rate of dehydration increases and reaches a maximum at the appropriate temperature (Table 3.3). After passing the maximum points, the tested samples of raw monomaterials and mixtures reach their maximum moisture content. At this stage only bound water remains. It is known that the temperature of the maximum water removal rate (DTG) or heat absorption (DTA) in the range of 22-196 °C does not divide water into free and bound [134]. The rate of water removal after the peak goes to zero and this means the complete dehydration of samples. The appropriate rate of water removal is dependent on the material structure and chemical composition. Accordingly, its highest value relates to spinach, the lowest — to HPT soybeans (Table 3.3).

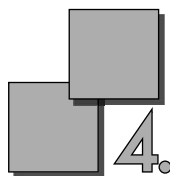
After dehydration, there is a moderate decrease in sample mass (TG). According to the table, the rate of thermal destruction (combustion) is the highest for soy-spinach mixture, and the lowest — for spinach. At this stage, there is an instant complete destruction of sugars, proteins and nutrients contained in protein-containing phytoestrogenic mixtures. The temperature difference ΔT (between the temperatures of maximum rate of water removal and thermal destruction (combustion), derived from the curves of DTG and DTA, is associated with the influence of thermal conductivity of vegetable raw materials (samples) on the electric mobile force of the measuring thermocouple [140].

Table 3.3. Results of analysis of soybean, carrot, spinach and soy-carrot, soy- spinach mixtures

Material	Moisture, %	Water removal				Thermal destruction		
		Interval, °C	Maximum rate, °C	Average rate, %/s	Energy of tissue dehydration, J/g	Interval, °C	Maximum rate, °C	Average rate, %/s
Soybean	61.19	24-196	120.4	0.023	2505	196-247	—	0.020
Spinach	90.28	22-178	125	0.037	2609	178-234	208	0.107
Carrot	90.32	23-186	123	0.035	2501.7	186-223	200	0.156
Soy-carrot mixture	78.06	24-184	129	0.031	2503.35	184-231	208	0.11
Soy-spinach mixture	69.09	22-179	125	0,027	2545.4	179-240	—	0.026

3. HEAT AND MASS TRANSFER DURING PPRM DRYING

According to the method described in [141], the heat expended on dehydration of the samples was estimated (Table 3.3). As can be seen from the table, most of the energy is spent on dehydration of spinach [142]. Table 4.1 informs that water removal from spinach and soy-spinach mixture starts at 22 °C, while in carrots, soybeans and soy-carrot mixtures at 23, 24 and 24 °C, respectively. The heat consumption for dehydration of carrots is slightly lower. However, the specific heat consumption in the dehydration of mixtures of carotene-containing components with soybeans is much smaller than the cost of dehydration of mono-components of the mixture. It should be noted that the specific heat of dehydration was recorded in non-isothermal conditions and the values obtained should be considered averaged over the temperature range of 25-179 °C. The specific heat determined from derivatographic studies correlates with the results obtained in the study of the specific heat of water evaporation from these materials in a differential microcalorimeter of evaporation.



4. HEAT TECHNOLOGY FOR OBTAINING PHYTOESTROGENIC POWDER FROM SOYBEANS AND SPINACH

4.1. Development of energy-efficient heat technology for obtaining powder from PPRM

With the development of scientifically sound concepts of recipes in food production, as well as the demand for diversity in food products, there is a tendency to expand the market of food ingredients. Most of the ingredients come in the powder form and therefore this technology is extremely important. The two main aspects are that plant powders are of biological origin and are consumed by humans for food. The main aim for processing vegetable raw materials is extension of the shelf life due to dehydration and maximum preservation of all BAS. It is proved that the stability and functional properties of vegetable raw materials before its use are maintained in the form of powder (Fitzpatrick and Lilia, 2005) [143].

The shelf life of vegetables mainly depends on their type. For example, leafy vegetables (spinach) have a limited shelf life, but root vegetables reach a shelf life of many months. Variations in the combination of root, legume and leaf in the mixture can be the basis for prolongation of the shelf life of the dried product. Therefore, there are technologies for combining vegetable raw materials in the composition.

Analysis of protein deficiency, dynamics of cultivation and the impact of soybeans on human health and longevity showed a positive trend of increasing demand for soybeans and soybean products. High energy consumption in enterprises where drying processes are implemented (energy consumption per process 10-12% of total energy consumption), all of the above leads to insufficient development of heat technologies for processing protein-containing vegetable raw materials, resulting in a product with a short shelf life, degraded properties and taste, and are the root causes for the development of energy-efficient heat technologies.

4. HEAT TECHNOLOGY FOR OBTAINING PHYTOESTROGENIC POWDER FROM SOYBEANS

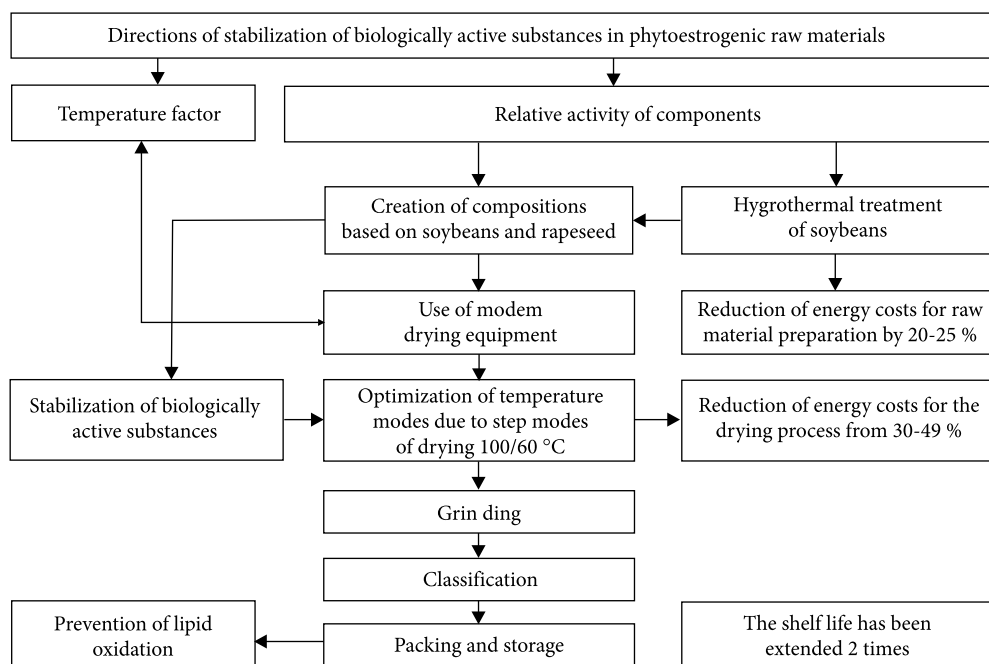


Fig. 4.1. The main directions of BAS stabilization in PPRM

Optimal modes for processing of PPRMs are presented in Fig. 4.1 [117], which shows that the most influential on the quality of the obtained powders is the temperature and stabilization of biologically active substances.

Soybeans contain a high per cent of fat, so during its processing and storage it is necessary to provide conditions that prevent oxidation. For this purpose soy was blended with vegetable raw materials which contain natural stabilizers of lipids.

Previous studies have shown that the creation of plant composite mixtures can reduce energy consumption in the preparation of raw materials for drying in the range of 20-25 %; application of step modes reduces the energy consumption within 30-49%; compliance with all technological regimes makes it possible to double the shelf life of powders [144].

4.2. Technology for obtaining phytoestrogenic powders from soybeans and spinach

A heat technology for obtaining phytoestrogenic powder from soybeans and spinach has been developed in [145], which allowed prolongation of the shelf life of phytoestrogenic powder to one year. Soybeans in the crushed state without addition of spinach are oxidized in a short time and cannot be stored for more than 3 months without stabilizers of unnatural origin [86]. The technological scheme of obtaining phytoestrogenic powder is presented in Fig. 4.2.

4.2. Technology for obtaining phytoestrogenic powders from soybeans and spinach

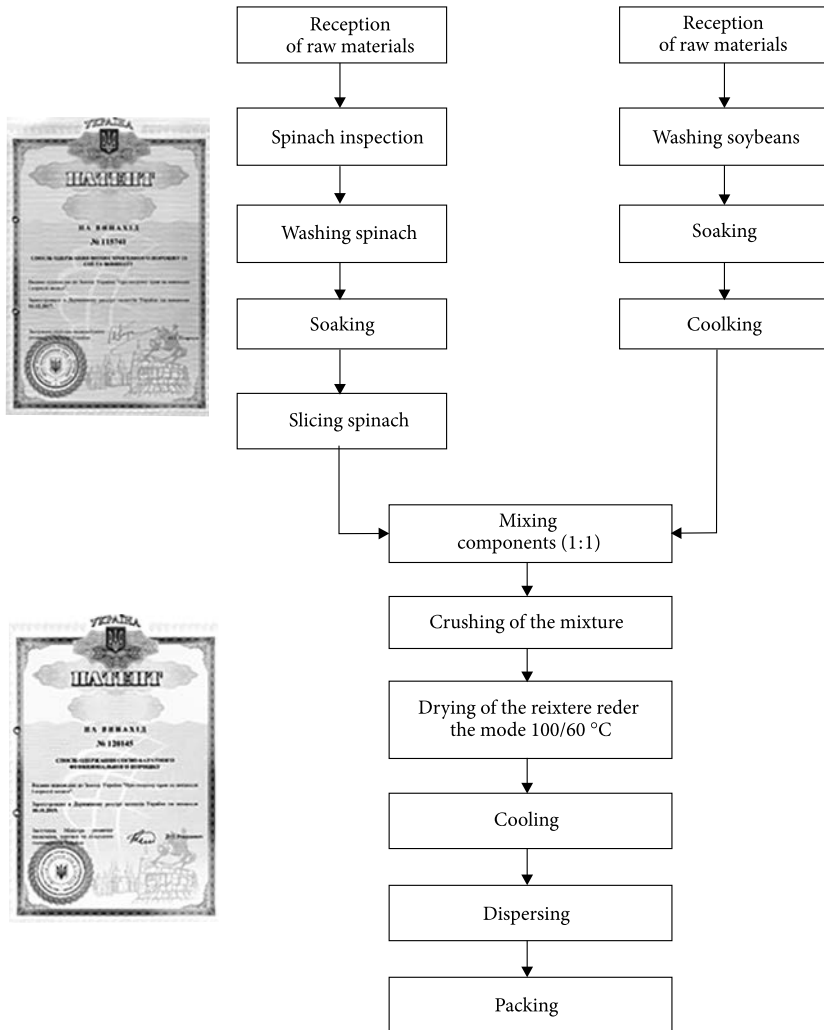


Fig. 4.2. Technological scheme of obtaining phytoestrogenic powder from soybeans and spinach

The most important technological stage is the preliminary preparation of raw materials. In the beginning, whole soybeans enter the bean washing machine through the receiving hopper. Then soybeans are soaked in water at 50 °C for 1 h. At this stage, the oligosaccharides are removed. After soaking, soybeans are boiled at a temperature of 100 °C for 20 min (to inactivate anti-food components). Then the hot beans are fed to the stage of mixing and grinding the components.

Spinach is inspected and served for washing and soaking. The duration of soaking is 15-20 min. After that, the raw material is sent for slicing, then inspect-

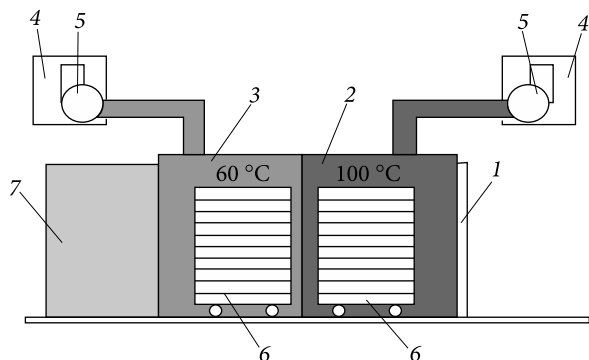


Fig. 4.3. The scheme of convective drying of PPRMs in a two-zone dryer with heat generators on biomass at the operating parameters: $V = 2.5$ m/s, $d = 10\text{--}15$ g / kg bm, t (drying zone 1) = 100 °C, t (drying zone 2) = 60 °C, $\delta = 15$ mm: 1 — drying gate; 2 — drying zone 1; 3 — drying zone 2; 4 — heat generator; 5 — fan; 6 — trays; 7 — cooling zone

ed, if necessary, cut by hand to a given size, and dosed to the stage of mixing with soybeans at a ratio of 1:1 and subsequent grinding of the mixture.

The obtained crushed mixture of soybeans and spinach is unloaded on the pallets of trays of a two-zone drying unit, where a two-stage drying process of $100/60$ °C is realized, dried to a final moisture of 4-8% and cooled at 20 °C.

The dried mixture is dispersed on a hammer mill and fed to the semi-automatic packing machine, where it is packaged in bags.

In order to implement the method for production of phytoestrogenic powder from soybeans and spinach, a production line and a list of technological equipment [146] of mainly Ukrainian production has been proposed.

For drying functional raw materials according to the proposed technology, a two-zone tunnel dryer TF 2.02 with two heat generators was used [11, 34]. In the dryer casing there are steel labyrinth of seals in the form of flexible heat-resistant felt aprons, which block air movement along the casing and its outlet and so provide proper blowing over the trays by the scheme described in Section 1.

A scheme of convective drying of PPRMs in a two-zone dryer with heat generators on biomass is shown in Fig. 4.3.

Through two openings in the walls, thermometers of resistance are introduced in the dryer tunnel, which allows registration of the heat carrier temperature in a separate zone. The obtained temperature indicators from drying zones are fixed by the recorder of the KSP 4 type on the control panel.

The heat-generator for air heating is located outside and connected to the dryer via an air duct. Air heating is provided by combustion of natural gas. There is no contact between the heated air and combustion products.

The air heated in the heat generator (4) is blown by a fan into the drying zone, where the raw material on trays is blown from left to right. Then, at the dryer wall plane and the side surfaces of the trays, the coolant turns 180 deg and is distributed evenly over the entire height of the trays, blowing the dried shavings from right to left.

Next, through the side recirculation channels, the coolant enters the fan (5). A certain part of the used heat carrier goes outside, and the equivalent part of fresh air is supplied to replace this part. Therefore, the direction of blowing the dried shavings during tray movement through drying zones changes, which creates additional conditions for uniform drying. The described scheme allows maintaining a warm-moist mode in each drying zone.

Control of drying and cooling of the dried material is remote, carried out from the control panel. On the mnemonic, which is provided with the control panel, the illuminated dots mark all the working mechanisms of the drying area.

In all zones of the drying installation, temperature is supported automatically by means of self-recording regulating KSM potentiometers. Control of the automatic regulator on using gas by the heat generator is provided by two options. Potentiometers of each zone ensure an automatic mode, and manual one is performed through buttons of remote control. The drying area is served by one operator. The drying operation is performed according to the developed step modes.

Therefore, in the first zone, at the stage of high moisture of material, the coolant temperature is 100 °C and then the cart moves to the next zone with a temperature of 60 °C. After that, the dry material enters the cooling zone (7) [146].

It was found that when storing soybean monopowder for 3 months, its AN approaches a critical value (4%), while soybean powder with carotene-containing raw materials is stored for 9-10 months (Fig. 4.4).

4.3. Areas of using phytoestrogenic powder from soybeans and spinach

Soybeans are rapidly gaining popularity in the diet of people worldwide. Soy-based protein products are a perfectly balanced source of essential amino acids, which is an efficient supplement to cereal proteins and can completely replace animal protein. There are over 50 types of processed soy products [3], the most common of which are:

- *Soy protein concentrate*: obtained by processing soy flour via removing the water-soluble non-protein components. In terms of amino acids, soy concentrate exceeds soybeans and soy flour. Digestibility of protein concentrate is 80-86%, the same as that of traditional milk protein.

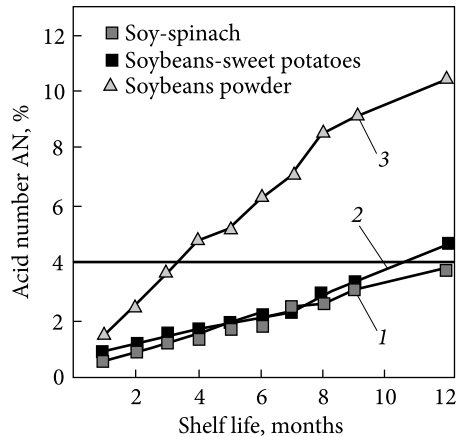


Fig. 4.4. Changes in AN during storage of PPRM

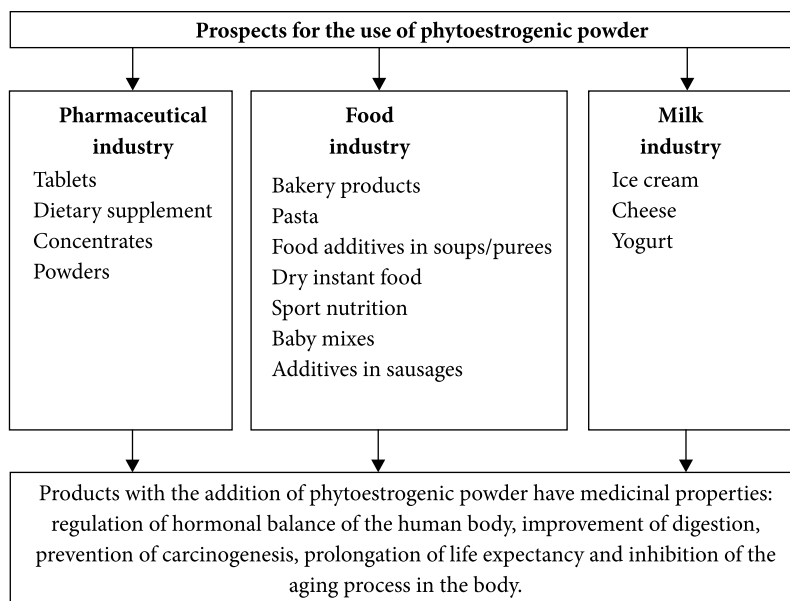


Fig. 4.5. The main promising areas of phytoestrogenic powder application

- *Soy isolate*: obtained by chemically removing protein from skimmed meal. The digestibility of soy isolate proteins is higher than that of soy flour protein. Trypsin inhibitor activity in soy protein isolates is 5–6 %, in soy flour — 10–11 %.

- *Meat and milk substitutes*: obtained from soybeans, by shape, smell and taste are similar to meat/milk. Meat substitutes are used in soups, supplements to sausages, grill and others; and dairy ones are used in the production of cheese, ice cream, etc.

- *Tofu (soy cheese)*: obtained from soy milk, after its coagulation. The resulting coagulant is squeezed, then stored in water in a refrigerator or an airtight container.

Spinach is becoming popular as the base of a healthy diet and vitamin saturation. By the natural properties, it does not have a pronounced pleasant taste, nevertheless there are a huge number of recipes for dishes that include spinach.

A wide range of applications of soy and soy products in various sectors of the pharmaceutical, food and dairy industries indicates the importance of the positive effects of phytoestrogens on the human body (Fig. 4.5).

Folates and spinach carotenoids stabilize soybean lipids. As a result of this combination, a dried composite phytoestrogenic powder can be stored for up to 10-12 months.

Functional properties of soybean products are important for baking, food concentrates, confectionery and pasta industries (Table 4.1). Consumption of

4.3. Areas of using phytoestrogenic powder from soybeans and spinach

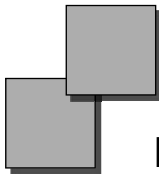
Table 4.1. Functional properties of soy products [3]

Functional property	Mode of action	Types of soy-used products	Soy product
Solubility	Dissolution of proteins, depends on pH	Beverage concentrates	Flour, concentrate, isolate, soy milk
Water absorption and binding	Binding of water by hydrogen, capture of water	Bakery products, cakes, fondant, flour confectionery	Flour, concentrate, texture, tofu
Viscosity	Thickening, water binding	Concentrates of soups, sauces, ready fillings for buttery bakery and flour confectionery	Flour, concentrate, isolate
Gelation	Formation of protein matrix, hardening	Lozenges-marmalades, mousses, creams	Concentrate, isolate
Stickiness	Protein that acts as a binding material	Pasta	Flour, concentrate, isolate
Elasticity	Disulfide bonds in deformable gels	Baked goods	Flour, isolate
Emulsification	Formation and stabilization of fat emulsions	Food concentrates for lunch, cakes, fillings and decorations for confectionery	Flour, concentrate, isolate
Fat absorption	Binding of free fats	Donuts, confectionery masses: praline, jelly, cream	Flour, concentrate, isolate, texture, tofu
Binding of flavoring substances	Absorption, capture, selection	Food concentrates of lunch dishes, desserts, bakery products	Flour, concentrate, isolate, texture, tofu
Foaming	Formation of a film to capture gas	Whipped creams, desserts, muffins from whipped protein	isolate
Color control	Bleaching (lipoxygenase)	Bakery products	Flour, tofu

soy-containing products by these industries prevents obesity, metabolic disorders thanks to low caloric content and NV of soy foods.

The addition of phytoestrogenic powder can improve the structural properties of dough.

By following the correct technological modes for the production of phytoestrogenic powder from soybeans and spinach, one can get a valuable product with functional properties, which is able to enrich the products of baking, food concentrate, dairy, confectionery and pasta industries.



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Монографія присвячена вирішенню проблеми енергозбереження та розробки ресурсоощадної теплотехнології переробки соєвих бобів та їх сумішей з каротиновмісною сировиною на функціональні фітоестрогенні харчові порошки. Розглянуто сучасні дослідження та способи переробки фітоестрогенної сировини. Представлено дослідження тепломасообмінних процесів під час конвективного сушіння та дослідження теплофізичних і фізико-хімічних властивостей фітоестрогенної сировини та її білково-каротинових сумішей. Розроблено інноваційну теплотехнологію отримання фітоестрогенних порошків на основі сої, що рекомендовано до використання у фармацевтичній, молочній та харчовій промисловостях.

Видання призначено для працівників підприємств харчової промисловості, студентів закладів вищої освіти, магістрів та аспірантів інженерно-технічних спеціальностей.

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ІНСТИТУТ ТЕХНІЧНОЇ ТЕПЛОФІЗИКИ НАН УКРАЇНИ

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