Досліджено технологічний процес сушіння фруктів у геліосушарці. Обґрунтовано режими роботи геліосушарки з дзеркальним концентратором та тепловим акумулятором, додатковим вологопоглинанням і в умовах природної циклічності. Визначено кінетичні параметри процесів вологовіддачі, що відтворюють часові залежності зміни кінетики сушіння фруктів, відносної вологості вхідного і вихідного потоків повітря та змодельовано часову залежність вологості вихідного потоку

Ключові слова: сонячна енергія, геліосушарка, температурно-вологісні поля, тепломасоперенесення, інтенсифікація, конвективне сушіння

Исследован технологический процесс сушки фруктов в гелиосушилке. Обоснованы режимы работы гелиосушилки с зеркальным концентратором и тепловым аккумулятором, дополнительным влагопоглощением и в условиях естественной цикличности. Определены кинетические параметры процессов влагоотдачи, отражающие временные зависимости изменения кинетики сушки фруктов, относительной влажности входящего и исходящего потоков воздуха, смоделировано временную зависимость влажности исходного потока

Ключевые слова: солнечная энергия, температурно-влажностные поля, гелиосушилка, тепломассоперенос, интенсификация, конвективная сушка

UDC 631.364:621.311.243
DOI: 10.15587/1729-4061.2018.122816

RESULTS OF RESEARCH INTO TECHNOLOGICAL PROCESS OF FRUIT DRYING IN THE SOLAR DRYER

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1. Introduction

Research into technological process of fruit drying by sun rays must involve studying energy parameters of the heat carrier, physical-mechanical properties of fruit as the object of drying, as well as selection and substantiation of operation modes. The development of new, and the improvement of existing, technologies and drying devices are regulated both by the intensities of heat moisture exchange between a heat carrier and the object of drying and by the intensities of heat moisture transfer inside the material. In addition, it is necessary to take into consideration changes between thermal-physical parameters of the fruit being dried and physical parameters of the environment. Solving the task on resource saving is complicated by the fact that fruits are characterized by high variability in thermal-physical, physical- mechanical, structural-mechanical, chemical properties. Therefore, it is an important task to substantiate the optimal operating mode of the solar dryer that underlies the improvement of technologies and techniques for fruit drying.

2. Literature review and problem statement

In paper [1], authors investigated characteristics of solar devices. The research was conducted for the standardized lighting conditions – spectral structure of radiation must conform to the standard AM 1.5; the intensity of irradiation is 1,000 W/m^2. Since such conditions are practically absent in nature, the establishment of specifications of solar thermal collectors is performed based on the irradiation of simulators of the solar energy flux. Operational characteristics of solar collectors are determined under regulated lighting conditions, temperature intervals, and flow rate of the heat carrier. These conditions arise from the requirements to the operation of solar collectors included in the heating and hot water supply systems where processes of heat generation and consumption are mostly split in time. Traditional solar dryers operate under the mode of a passive solar energy receiver and thus there are no standardized requirements to them.

The substantiation of the optimal operation mode of traditional solar dryer is proposed in paper [2], but it fails to address the issue of ensuring the optimal technological parameters of drying. Performance indicators of the solar dryer are affected by factors that have a varying degree of control. Among those factors that are controlled and managed are the temperature of the battery, the temperature of a heat carrier, heat carrier flow rate, heat carrier consumption, the area of an air collector, mass of the heat accumulating material, organization of heat carrier motion in a solar dryer. Those controlled but not managed include the initial moisture content of raw materials, dimension-mass characteristics of fruits, solar activity. The uncontrolled and unmanaged factors are the thermal-physical characteristics of fruits, physical parameters of the environment.

The specified factors are not accounted for in paper [2] when selecting the optimal operational mode of the solar dryer. Controlled factors are taken into consideration when processing results of the experiments as there is a certain dependence between parameters of each group and parameters of groups in general. For example, the mode of drying influences the pattern of a thermal field that describes the impact of structural and technological parameters on the process of drying fruits in a solar dryer.

Authors of paper [3] developed various designs of solar dryers, which meet the concept of passive solar energy installations. The current energy illuminance of the dryer with sun rays was measured using a pyranometer in the horizontal plane of the air collector only. However, the proposed procedure did not include the measuring of additional irradiation of the drying chamber in the plane of a vertical transparent wall. Given this, the derived values for pyranometer indicators do not match the total flux of direct and scattered radiation. At stable sunny weather, the measuring of direct and scattered radiation should be performed on both planes in the middle of each time interval. Note that over half an hour a change in the energy illuminance does not exceed a measurement error of 5 %, when using the standard meteorological pyranometer P 3×3.

In paper [4], authors designed a solar dryer that meet the concept of an active solar energy installation. In it, a heat carrier passes between the bottom of the air collector and the upper layer of the heat accumulator. For a given solar dryer, it is actually possible to estimate temperatures of only two fluxes at the inlet to a drying chamber: direct, via the outlet of an air collector at closed valve and from the side of a heat accumulator, and vice versa. According to the described procedure, the efficiency of solar energy conversion can be estimated only based on the ratio of energy of direct flux at closed outlet of the battery to the energy illuminance of the air collector. However, such an estimation is always understated, because part of the heat generated by air collector is used for heating the upper layer of the heat accumulating material. Thus, the described procedure is too general. Therefore, the efficiency of heat accumulator's performance in the solar dryer can be estimated based on the results of comparison between parameters of the two processes of moisture removal under close weather conditions: with the accumulator, and without it.

Author of paper [5] analyzed the technological process of drying in solar dryers and substantiated their optimal modes of operation. According to the described procedure, the level of energy illuminance at the inlet to air collector was determined using a pyranometer, the temperature and moisture content of the incoming flow of air – by a thermometer and a moisture meter. At the inlet to a drying chamber only the temperature of the heated airflow and the moisture content were measured. The air flow rate was calculated based on the results of measuring the flow velocity inside the drying chamber. The authors reduced calculations to the levelling and stabilization of the drying mode under condition of changing illuminance enabled by to the backup electric heater, and at night – enabled by the bulk thermal battery. The work lacks calculation of relative humidity in the moisture content of the incoming and outgoing fluxes of the heat carrier.

In paper [6], authors proposed to use a solar dryer of the mine type with a parabola-cylindrical concentrator mounted onto it. However, when substantiating the modes of operation and estimating the kinetic and dynamic parameters, the authors failed to account for the theoretical moisture content in the original flow of the heat carrier, which would make it possible to describe the hourly changing of fruit mass Δm during drying.

Authors of paper [7] substantiated operation modes of the solar dryer based on the modeling of the process of removing moisture from fruit in the framework of the Stephan problem: the relations employ small temperature gradients. Specifically, in order to calculate energy and kinetic parameters of moisture removal, the temperature of a material T_m is taken equal to the temperature inside the dried material. However, for the thinly sliced apples with a thickness from 5 to 11 mm, the result of establishing the indicators of moisture removal cannot be considered equivalent enough. This is due to the fact that it is difficult to establish, in thin slices of fruit, the zone of heat and moisture release from the center point of material, being dried, to the surface by applying small temperature gradients. The use of the thicker slices is not allowed as it is regarded as a deviation from the technological requirements to fruit processing. That is why, during calculation, it is required to establish only the high indicators for the moisture removal process and to estimate them for the kinetics and dynamics of drying. Thus, the process of moisture removal can be estimated by the moisture content of air before and after the drying chamber, or by a change in the moisture content of separate fruit slices or in the mass of material being dried.

The substantiation of an optimal operation mode of the solar dryer that would ensure the maximal intensity of processes and minimal consumption of energy resources is an important task. The complexity of the process of drying fruits in a dryer is predetermined by the character of interrelated energy, kinetic, dynamic parameters, and heat-mass-exchange processes, as well as the high variability in the physical properties of fruit.

At the same time, still insufficiently studied is the issue of the accumulation of excessive heat at daytime and the amplification of slanting fluxes of morning and evening solar radiation on the receiving surface of air collector. Given this, it is expedient to use a heat accumulator and a flat mirror concentrator as part of the solar dryer design. Such a solution is rather effective and would make it possible to improve energy efficiency and technological process of fruit drying, as well as bring down energy costs. However, this would require additional field testing of the solar dryer with different configurations using a heat accumulator and a flat mirror concentrator, and without them, in order to substantiate its optimal operation mode and technological parameters.

Thus, a crucial aspect for making a decision on the use of the solar dryer for drying fruits is the substantiation of its optimal operating mode, which requires that the dried fruit raw materials should be obtained in accordance with the standards DSTU 4945:2008 "Fruits, vegetables, and products of their processing. Pycnometric method for determining the content of soluble dry substances."

3. The aim and objectives of the study

The aim of present study is the intensification of the process of dried fruit production using solar energy by employing an air collector, a flat mirror concentrator, and a heat accumulator, in the solar dryer of the mine type.

To achieve the set aim, the following tasks must be solved:

– to estimate operation characteristics (energy characteristics of the drying device, heat-mass exchange characteristics of the fruit drying process of) of the solar dryer under standard modes of solar irradiation and typical weather conditions;

– to explore the technological process of fruit drying in the solar dryer with a heat accumulator and a flat mirror concentrator depending on the technique and thickness of fruit slicing and physical parameters of the environment;

– to conduct field tests of the solar dryer.

4. Materials and a procedure for the substantiation of operation modes of the solar dryer

4. 1. Substantiation of the technological circuit and structure of the solar dryer

Heliothermal installations have been widely applied in the agricultural sector. For example, when drying plant raw materials, specifically fruit, solar energy is actively utilized in the drying industry. A given type of dehydration is fully applicable for the region of western Polissya (forest zone) (the city of Korets, Rivne oblast, Ukraine). In particular, scientists from the National Agricultural University of Lviv (the city ofLviv, Ukraine) at the Department of Energy designed a solar dryer, which is an active system for using solar energy [8]. A detailed description of the design and the work principle of the solar fruit dryer is given in paper [9]; the structural-technological circuit of the solar dryer with a heat accumulator and a flat mirror concentrator is shown in Fig. 1.

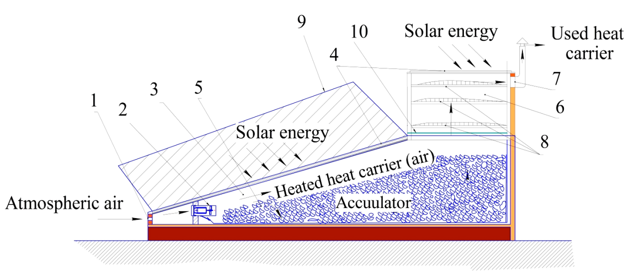

Fig. 1. Structural-technological circuit of the solar dryer with a heat accumulator and a flat mirror concentrator: 1 – inlet channel; 2 – fan; 3 – air duct; 4 – air collector; 5 – heat-accumulating material (gravel-based); 6 – drying chamber; 7 – return channel; 8 – sieves; 9 – flat mirror concentrator; 10 – valve

To conduct the experiments, the solar dryer was equipped with measuring instruments and sensors. Specifically, energy illuminance, amplified by the flat mirror concentrator, was determined using the pyranometer PELENG SF-06. The rate of heat carrier was defined applying the digital thermoanemometers UT 362 and Testo 425.

The ambient temperature, heat carrier temperature, heat accumulating material temperature was measured simultaneously by the digital regulator-meter PT-0102-8 and by the Pt100 resistance thermometers.

Relative air humidity was determined by the digital air moisture meter WCM-1 with the humidity sensor EE HC 200 and the Assmann's aspiration psychrometer. Heat carrier in the drying chamber was measured by the digital thermohygrometer PT-0102 with the Pt100 resistance thermometers. To determine the temperature of the material being dried we used digital multimeter UT-70B with thermocouples of chromel-copel THK of type L. Moisture content of fruits was determined using the hydrometer BFS-1A.

Design of the proposed solar dryer combines in one unit an air collector and a heat accumulator. We did not investigate experimentally relationships between time dependences of change in energy, kinetic and dynamic parameters for the designed installation. Specifically, it is impossible:

– to conduct separate tests for the mirror concentrator and the air collector employing a standard procedure;

– to calculate dynamic properties of the bulk heat accumulator;

– to determine kinetic parameters of the moisture release processes, which represent time dependent changes in the kinetics of fruit drying $W(\tau)$, relative humidity of the incoming φ_i and outgoing φ_o flows of air, moisture content of the outgoing flow $\varphi(\Delta m)$;

– to establish dynamics of the mass exchange processes that describes the intensity of moisture content of incoming X_i, outgoing X_o, and the simulated dynamics of mass exchange processes $X(\Delta m)$ of air flows during drying and hourly change in the mass of fruit Δm.

The parameters specified must be determined experimentally during field tests of the energy unit in a solar dryer in the following configuration:

– operation mode of the solar dryer in combination with a mirror concentrator and a heat accumulator;

– stabilization of drying with additional moisture absorption;

– operating mode of the solar dryer under regime of natural cycles.

Thus, the designed solar dryer must be field tested with energy unit of different configurations. It is also necessary to choose effective methods to control the course of energy transformations and mass exchange processes. Given the variability of weather-dependent parameters, measuring instruments must work under the mode of continuous measurements, must enable the visualization and archiving of the results, in order to subsequently process them using the methods of mathematical statistics. We propose that effectiveness of the solar dryer should be substantiated based on the specific energy intensity of moisture removal.

4. 2. Substantiation of technological parameters of the material being dried

Fruit drying in a solar dryer over 24 hours is characterized by a periodic irregularity in the arrival of a solar energy flux. Heat-mass exchange characteristics of the drying process, energy characteristics of the solar dryer, and the properties of fruit vary during 24 hours depending on weather and season. Thus, it is required to separately substantiate kinetic and dynamic properties of the object of drying, or to explore the drying process.

In order to estimate moisture content of fruit, relative magnitudes are typically used, where all relations define the arbitrary mass of a material, rather than the unit of volume accepted in gases. They include humidity and moisture content.

The humidity of a material is determined from the ratio of the mass of moisture (vapor) in a material, kg, to the mass of the entire wet material:

$$w=\frac{m_{\mathrm{m}}}{m},\ \text{kg/kg};\ d=\frac{m_{\mathrm{m}}}{m},\ \text{g/kg}$$

or

$$W=\frac{m_{\mathrm{m}}}{m}\cdot 100,\ \%. \qquad (1)$$

The moisture content of a material is derived from the ratio of the mass of moisture in a material, kg, to the mass of the dry material:

$$u=\frac{m_{\mathrm{m}}}{m-m_{\mathrm{m}}}$$

or

$$U=\frac{m_{\mathrm{m}}}{m-m_{\mathrm{m}}}\cdot 100\,\%,\ \text{kg moisture/kg dry substance}. \qquad (2)$$

Using the specified relationships, it is possible to express relation between humidity and moisture content in the following form:

$$w=\frac{u}{u+1}$$

or

$$u=\frac{w}{1-w},\ \text{kg moisture/kg dry substance}. \qquad (3)$$

For the case of freshly sliced apple and pear, initial humidity is taken to be equal to W_n=80.2 %. However, since the fruit are put to the dryer after blanching, the initial humidity of the batch changes in different experiments with the difference not exceeding 5 %.

Based on the difference in the results of weighing the full sieves G_n and empty sieves: $m=G_n-G_0$, a mass of the batch is determined. Over the first and subsequent hours, the mass of the product reduces, which is taken to be equal to the difference in weight measurements:

$$\left.\begin{aligned}\Delta m_1&=G_n-G_1,\\ \Delta m_2&=G_1-G_2,\\ \Delta m_n&=G_{n-1}-G_n.\end{aligned}\right\} \qquad (4)$$

As a result of the current weighing, it is more convenient to calculate moisture content instead of humidity because when comparing two consecutive values there is no need to reduce them to a common denominator. For example, prior to the initial humidity W_n=80.2 % (w_0=0.802), the moisture content is equal to:

$$u_0=\frac{w_0}{1-w_0}=\frac{0{,}802}{1-0{,}802}=4{,}051\ \text{kg moisture/kg dry substance}.$$

Moisture mass m_m and dry substance mass m_s for the batch of mass m_0=5.5 kg are, respectively:

$$m_{\mathrm{m}}=w\cdot m_0=0{,}802\cdot 5{,}5=4{,}411\ \text{kg};$$

$$m_s=\frac{m_{\mathrm{m}}}{u}=\frac{4{,}411}{4{,}051}=1{,}089\ \text{kg}.$$

Current moisture content U is derived from:

$$U_1=u_0-\frac{G_0-G_1}{m_s},\ \text{kg moisture/kg dry substance}. \qquad (5)$$

where G_0 and G_1 are, respectively, the initial and the resulting weight of sieves with fruit, kg.

For the solar dryer, energy expenditure for moisture transfer is typically estimated based on a change in enthalpy and in moisture content of the flow of heat carrier along the path from the inlet to the air collector to the outlet from the drying chamber. Enthalpy of the inflow is equal to the enthalpy of air in the environment

$$i_a=c_o\cdot T_a+(c_{\mathrm{v}}\cdot T_a+r_0)\cdot X_a,\ \text{kJ/kg}, \qquad (6)$$

where c_o is the specific heat capacity of outside air, kJ/(kg·K); T_a is the outside air temperature, K; X_a is the moisture content of outside air, kg/kg; c_v is the specific heat capacity of water vapor in the outside air, kJ/(kg·K); r_0 is the latent heat of water vaporization, kJ/kg.

The moisture content of air at the outlet of air collector is equal to that at the inlet, because the increase in enthalpy in the air collector is determined only at the expense of higher temperature of the outflow T_i:

$$i_{ac}=c_{hc}\cdot T_i+(c_v\cdot T_i+r_0)\cdot X_i,\ \text{kJ/kg}. \qquad (7)$$

After the drying chamber, temperature T_o does not exceed temperature T_i, and due to the moisture Δm_m lost by the fruit, moisture content X_o is larger. That is why enthalpy of the outgoing flow is defined through its relative humidity and temperature T_o:

$$I_{dc}=c_{hc}\cdot T_o+(c_v\cdot T_o+r_0)\cdot X_o,\ \text{kJ/kg}, \qquad (8)$$

where c_{hc} is the specific heat capacity of heat carrier, kJ/(kg·K); c_v is the specific heat capacity of water vapor, kJ/(kg·K); r_0 is the latent heat of water vaporization, kJ/kg; T_i, T_o are, respectively, temperature of the incoming and outgoing heat carrier, K; X_i, X_o are, respectively, moisture content of the incoming and outgoing heat carrier, kg/kg.

The moisture content of heat carrier can be determined:

$$X_i=X_o=0{,}622\cdot\frac{\frac{\varphi_i}{100}\cdot p_{\mathrm{sva}}}{P-\frac{\varphi_o}{100}\cdot p_{\mathrm{svdc}}},\ \text{kg/kg}, \qquad (9)$$

where φ_i, φ_o are, respectively, relative humidity of the incoming and outgoing heat carrier, %; p_{sva} is the saturated vapor pressure in the inflow at a given temperature of the air, Pa; p_{svdc} is the saturated vapor pressure in the drying chamber at a given temperature of the air, Pa.

Theoretical air humidity, calculated based on the loss of mass of the fruit, is derived from formula:

$$\varphi_{\mathrm{sc}}(\Delta m)=\frac{p_{\mathrm{v}}}{p_{\mathrm{sv}}}\cdot 100,\ \%, \qquad (10)$$

where p_{sv1} is the pressure of saturated vapor in the material being dried at a given temperature of the air, Pa.

The partial pressure of vapor p_{v1} with mass M_1 in the hourly volume of the outflow of heat carrier is determined from the Clapeyron-Mendeleev equation:

$$p_v=\frac{M_1}{\mu}\cdot\frac{R\cdot T}{V_h},\ \text{Pa}, \qquad (11)$$

where M_1 is the total mass of vapor in the outflow, kg; R is a universal gas constant, R=8.31 kJ/mol·K; μ is the molar mass of water in vapor, kg/mol; V_h is the volumetric hourly consumption of heat carrier, m^3; T is the temperature of heat carrier, K.

Theoretical moisture content of the outflow, calculated based on the loss of mass by the fruit, is derived from formula:

$$X_o(\Delta m)=0{,}622\frac{\varphi_{sc}(\Delta m)\cdot p_{sv}}{p-\varphi_{sc}(\Delta m)\cdot p_{sv}},\ \text{kg/kg}, \quad (12)$$

where p is the pressure of saturation in the outgoing flow, which is taken from tables for the assigned air temperature, Pa.

The total duration of raw material drying τ, which depends on the structural-technological parameters of a solar dryer, kinetic and dynamical properties of the material being dries, and physical parameters of the environment, can be determined from [10]

$$\tau=\frac{W_i-W_{e.}}{N}+\frac{1}{K}\cdot\ln\left[\frac{W_c-W_e}{W_r-W_e}\right]+$$
$$+\frac{\Delta m\cdot c_f\cdot\left(T_{f2}-T_{f1}\right)+h_l\cdot\rho_f\cdot\left(\sum S_s\right)\cdot c_f\cdot\left(T_o-T_i\right)}{S_{dc}\cdot\upsilon_{hc}\cdot\rho_{hc}\cdot c_{hc}\cdot\left(T_o-T_i\right)/\tau_h-(S_{ac}\cdot E)-S_{sd}\cdot K\cdot\left(T_{dk}-T_a\right)-V_{ha}\cdot\rho_{ha}\cdot c_{ha}\cdot\left(T_{ha2}-T_{ha1}\right)/\tau_d}, s, \quad (13)$$

where τ is the duration of fruit drying, s; W_i is the initial moisture content of fruit, %; N is the rate of drying, %/s; K is a factor of drying, s; W_r is the resulting moisture content of fruit, %; W_c is the critical moisture content of fruit at a critical point in the process of drying, %; W_e is the equilibrium moisture content of fruit for the assigned mode of drying, %; E is the energy illuminance, W/m^2; τ_h is the duration of heating of the drying chamber, s; S_s is the area of sieves, m^2; S_{ac} is the area of air collector, m^2; S_{dc} is the area of the drying chamber, m^2; υ_{hc} is the heat carrier velocity, m/s; ρ_f, ρ_{hc}, ρ_{ha} are the density, respectively, of fruit, heat carrier, and a heat accumulating material, kg/m^3; c_{hc}, c_f, c_{ha} are the specific heat capacity, respectively, of heat carrier, fruit, and a heat accumulating material, J/(kg·K); T_{f1}, T_{f2} are the temperature of fruit, K; T_{ha1}, T_{ha2} are the temperature at the inlet of the heat accumulator and at its outlet, K; S_s is the area of sieves, m^2; S_{sd} is the solar dryer area, m^2; T_{dk} is the heat carrier temperature in the drying chamber, °C; T_a is the ambient temperature, K; K is a coefficient of heat transfer through the casing of a solar dryer, W/(m^2·K); τ_{d} is the duration of discharge of the heat accumulator, s; h_{l} is the height of the layer of fruit material on sieves, mm; V_{ha} is the volume of heat accumulator of the solar dryer, m^3.

The humidity, which matches the equality of pressures of saturated vapor near the surface of a material and in the volume of ambient air, is called equilibrium humidity. For a given mode of drying

$$W_e=K_1\left(T_{\text{o}}\right)+K_2\left(T_{\text{o}}\right)\left[\lg\left(\frac{1}{1-\varphi}\right)\right]^{1/2}, \quad (14)$$

where W_p is the equilibrium humidity of fruit during desorption process, %; φ is the relative air humidity, $\varphi=\frac{P_{\text{v}}}{P_{\text{sv}}}$; P_{sv} is the partial pressure of saturated vapor, kPa; P_v is the vapor partial pressure, kPa.

K_1 and K_2 are coefficients, which are determined for each of the specific regions:

$$K_1=7{,}11+0{,}044\cdot T_{\text{o}}; \quad (15)$$

$$K_2=10{,}41\cdot T_{\text{o}}^{0{,}166}. \quad (16)$$

Equilibrium humidity of fruit for the second region (from 30 to 13 %) is determined

$$W_e=7{,}11+0{,}044\cdot T_o+$$
$$+10{,}41\cdot T_o\cdot\left[\lg\left(\frac{1}{1-\varphi}\right)\right]^{1/2}. \quad (17)$$

Thus, energy costs for the moisture transfer in a solar dryer are estimated by change in enthalpy and moisture content along the path of a heat carrier flow from the inlet to the air collector to the outlet from the drying chamber.

4. 3. Preparation of fruit for drying

We investigated the moisture content of fruit at a laboratory setup under conditions of 6 experiments. Different varieties of fruit were studied: apple of the variety Semyrichka, pears of the varieties Stolovka and Cure – with the initial humidity W_i=70.3÷85.2 %. Mass of the batch of raw fruit materials per a solar dryer loading is 5.5 kg.

First, we investigated influence of the blanching technique on the fruit drying process. Preparation of raw materials included: sorting, washing fruits, cutting by rings and slices with a thickness of 5÷11 mm. The sliced fruits were blanched using the following techniques: blanching in a solution of sugar for 3 minutes (1 l of water – 10 g of sugar); blanching in a solution of salt for 3 min (1 l of water – 10 g of salt); without any treatment. Upon blanching, the fruits on sieves were placed in the drying chamber. In the course of drying we continuously measured moisture content of fruit. The end of drying was established by weighing the batch until constant mass was reached. We determined the duration of drying and the reduction in mass for each variant.

During another experiment, we determined the effect of cutting thickness on the fruit drying process. Preparation of raw materials included: washing fruit, cutting in rings and slices with different thickness: rings, 5 mm; slices, 8 mm; rings, 11 mm; slices, 5 mm; slices, 6 mm; rings, 7 mm.

The fruit properly dried in a solar dryer must meet the requirements of State standard DSTU 27548-87 “Methods for determining the moisture content of fruit” [10].

5. Results of examining a technological process of fruit drying in a solar dryer

5. 1. Weather conditions in the course of examining the operation of a solar dryer

We studied the work of a solar dryer during period of ripening for most fruit, the months of July and August, typical for steady sunny weather. Fruit drying takes at least two days. However, due to natural weather-dependent factors, a full match among parameters of solar energy flux, temperature and humidity of the ambient air, illuminance, as well as the strength of wind, over two consecutive sunny days is unlikely. The objective criterion for the influence of one or another parameter on the final result is the comparison between time dependences in the corresponding magnitudes. For example, the day of July 15 was sunny, a little cloudy: from 10:00 a.m. to 2:00 p.m. the energy illuminance of the collector grew from 635 to 824 W/m^2, and at 4:00 p.m. it declined to 658 W/m^2 [11].

The flux of solar energy at 10:00 a.m. on July 16 was less than that over the previous day, and at 3:00 p.m. it leveled at 843 W/m^2, while at 6:00 p.m. it decreased to the level of 203 W/m^2. Thus, on July 15, 1.5 m^2 of the air collector surface received 8.25 kW·h of energy, and on July 16, slightly less – 7.75 kW·h. On July 16, at 01:00 p.m. we tested a flat mirror concentrator, which amplified natural illuminance of the collector to a maximum value of 1,295 W/m^2.

By using numerical integration of the results of measurement of intensity during 50 hours of drying on July 15÷17, 2017, it was established that over three days, the area of 1.5 m^2 of the air collector surface received 20.1·1.5=30.2 kW·h, or 108.5 MJ of thermal energy. At evaporation of 2.792 kg of moisture, energy efficiency of the process is 10.7 kW·h/kg, or 38.8 MJ/kg. Actual working conditions of the solar dryer for the performed series of experiments are summarized in Table 1.

Table 1

Summarized conditions and results of experimental drying of apple and pear in the solar dryer over the period of July 15 – September 3, 2017

No. of entry	Date	Duration, hours	Configuration		$\sum H_\beta$,	Energy efficiency
			HA	MC	kW·h/MJ	MJ/kg
1	15–17.07	50	+	+	30.15/108.5	47.6
2	15–21.07	119	–	–	–	0
3	28–31.07	74	–	–	34.2/123.1	44.1
4	7–10.08	77	–	–	30.7/110.5	39.6
5	10–12.08	50	+	+	31.2/74.8	26.8
6	15–17.08	50	+	+	23.0/81.3	29.1
7	31–3.09	98	–	–	26.6/95.8	35.7

Test of the solar dryer started at 12:00 a.m. for summer Kyiv time in the city of Korets, Rivne oblast, Ukraine, located on meridian 27° eastern longitude, which is 3° to the west of Kyiv ($\Delta\psi$=3°). At this settlement (the serial number of day in a year is m=197, correction for the ellipticity of the earth's orbit is E=–6 min), the solar noon arrives:

$$\tau_0=(12+1)\ \text{h}+(E-4\Delta\psi)\ \text{min}=$$
$$=13\ \text{h}+[-6+4(-3)]\ \text{min}=12\ \text{h}\ 42\ \text{min}.$$

Thus, the beginning of the experiment, July 16, hour 12 is matched with local solar time τ=+42 min, that is, 42 minutes before solar noon. The estimated duration of sunlight under condition of cloudless weather is 15 h 54 min for a horizontal plane, and 14 h 24 min for the air collector, tilted at the optimal angle to the horizon β=40°.

5. 2. Operation modes of the solar dryer

5. 2. 1. Work of the solar dryer in combination with a mirror concentrator and a heat accumulator

Operation mode of a solar dryer always depends on weather conditions, which are rarely repeated. A conclusion about the effectiveness of a specific regime can be drawn only based on the analysis of results from several studies. We shall consider the operation mode of the solar dryer in combination with a flat mirror concentrator and the air-gravel accumulator.

Using the concentrator made it possible to reach the following maximal energy illuminance of the air collector: July 15 – 1,269 W/m^2; July 16 – 1,184 W/m^2 (843 without the concentrator); July 17 – 1,147 W/m^2.

The values of energy illuminance of the air collector, hourly averaged, are shown by a bar chart in Fig. 2.

The shape of temperature curves corresponds in general to the daily schedule of arrival of solar energy and the temperature of the environment.

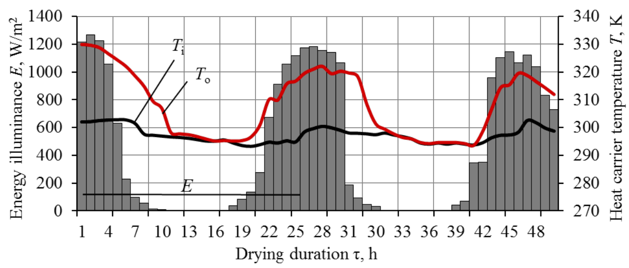

Fig. 2. Energy parameters of the solar dryer operation over the period of 15–17.07.2017: T_i, T_o are, respectively, the temperature of the incoming and outgoing heat carrier, K; E is the energy illuminance, W/m^2

The kinetics of fruit drying is represented by the time dependences of humidity $W(\tau)$ and the relative humidity of the incoming φ_i and outgoing φ_o air flows (Fig. 3). Hourly change in the moisture content of fruit was experimentally determined by the moisture meter BFS-1A. Results of the measurement of relative humidity of the incoming flow in Fig. 3 are shown by a solid black curve, that of the outgoing – by a red curve. Dotted line shows the simulated time dependence of humidity of the outgoing flow $\varphi(\Delta m)$, calculated based on the hourly change in fruit mass Δm under assumption that it is completely diffuses in the flow-through air stream.

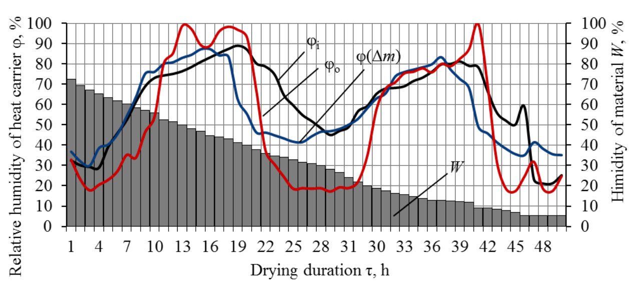

Fig. 3. Kinetic parameters of the processes of moisture release in the solar dryer over the period of 15–17.07.2017: φ_i, φ_o are, respectively, the relative humidity of the incoming and outgoing flows of heat carrier, %; W is the humidity of the material being dried, %; $\varphi(\Delta m)$ is the simulated time dependence of the humidity of outgoing flow of heat carrier, %

Fig. 4 shows results of the calculation of moisture content of the incoming X_i, outgoing X_o, and the simulated (for the released mass) $X(\Delta m)$ air flows. It also shows a bar chart for the hourly decrease in the fruit mass, calculated based on the experimentally measured values for its moisture content

$W(\tau)$. The specified hourly values Δm are numerically equal to the rate of drying, which is a much more sensitive parameter for the moisture transfer.

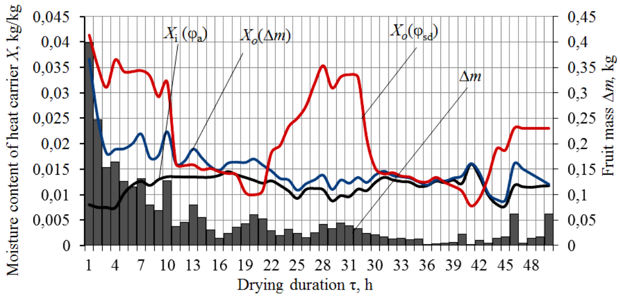

Fig. 4. Dynamics of processes of mass transfer in the solar dryer over the period of 15–17.07.2017: $X_i(\varphi_a)$, $X_o(\varphi_{sd})$ are, respectively, the moisture content of the incoming and outgoing flows of heat carrier, kg/kg; Δm is the hourly change in the mass of material being dried, kg; $X_o(\Delta m)$ is the simulated time dependence of moisture content in the outgoing flow of heat carrier, kg/kg

The moisture content curve of the outgoing flow (Fig. 4) indicates that the main part of moisture is removed during daytime, with an elevated temperature of the drying agent in full agreement with classical models of drying. Instead, the moisture content of the simulated flow $X(\Delta m)$ is more sensitive to local changes in the rate of drying, as evidenced by the correlation of positions of the respective deviations.

5. 2. 2. Stabilization of drying with additional moisture absorption

The tests of the solar dryer with the same configuration were repeated on 10–12 and 15–17 of August, 2017, at almost cloudless weather. In order to prevent possible condensation of moisture, we dried the outgoing flow after midnight when the its humidity exceeded 95 %. In front of the drying chamber we placed a container with crushed crystals of preliminary dried Glauber salt. Glauber salt was in advance heated with sun rays in a flat tin box in the open air without bringing it to the melting point.

As calculated, the air collector's surface on 10–12.08.2017 received 31.2 kW·h, or 123.1 MJ of solar energy, which is slightly larger than in the first experiment, conducted on 15–17.07.2017 – 30.2 kW·h and 108.5 MJ, respectively. Note that the study on 15–17.08.2017 did not employ the mirror concentrator, which is why the arrival of solar energy was significantly less than in the first experiment – 23.0 kW·h, or 81.3 MJ. Despite this, the duration of drying in the second rerun was the same – 50 hours. Results of the study on 10–12.08.2017 are shown in Fig. 5–7.

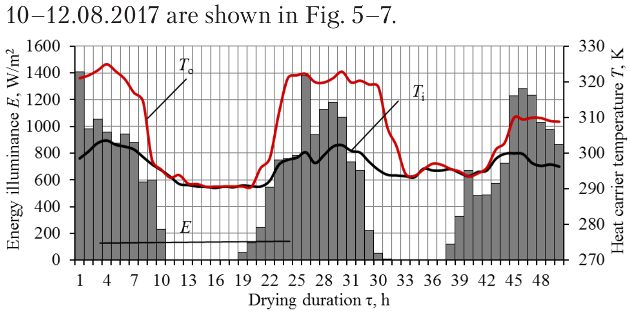

Fig. 5. Energy parameters of the solar dryer operation over the period of 10–12.08.2017

Additional drying of the incoming flow in both repeated experiments made it possible to avoid the condensation of moisture at night. It allowed us to remove moisture from the central layers of the material being dried to the surface layers during periods of intensive or slow moisture removal. The intensity of moisture removal is shown in bar charts $W(\tau)$ and $\Delta m(\tau)$ (Fig. 6, 7).

In addition, due to the lower relative humidity of the ambient air, drying from hour 13 to hour 19 (1:00 a.m. to 06:00 a.m.) proceeded more intensively than in the first experiment.

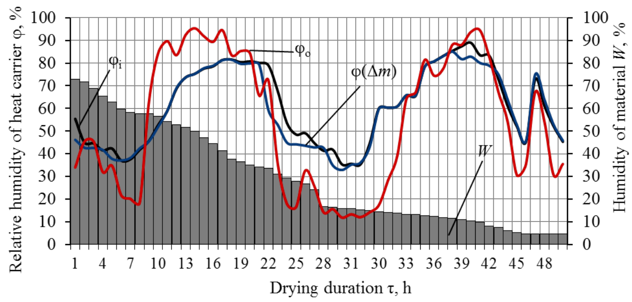

Fig. 6. Kinetic parameters of the moisture release processes in the solar dryer over the period of 10–12.08. 2017

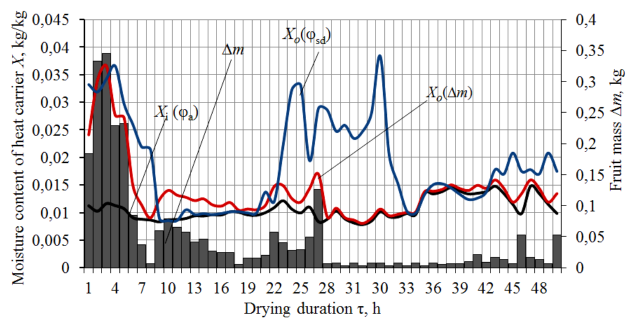

Fig. 7. Dynamics of the mass transfer processes in the solar dryer over the period of 10–12.08.2017

In the time interval from 6:00 a.m. to 03:00 p.m. the rate of moisture removal remained practically unchanged, though also higher than in the first experiment. That is why, given the large amount of the previously removed moisture, at the end of the process, in the range of 40÷50 hours, a stable post-drying occurred even at high humidity of the incoming air.

Results of the third experiment, conducted on 15–17.08.2017, indicate that, in contrast to the previous two experiments, moisture content of the incoming flow X_i remained virtually stable over the entire period. Due to this, time dependences of moisture and moisture content are much more stable and do not demonstrate significant deviations.

5. 2. 3. Operation of the solar dryer under the mode of natural cycles

The experiment on 28–31.07.2017 was conducted without interference to the natural cyclic change in the input parameters. The result is the later reduction in humidity to the normative level, at hour 74 of drying (Fig. 8–10).

At almost symmetrical, relative to the solar noon, energy illuminance of the air collector, the temperature at its output correlates with the temperature dependence of the environment, both on the first and the third day of drying.

Horizontal sections of time dependence of fruit moisture after midnight are a consequence of rapid cooling of fruit in the absence of accumulation. In these periods there occur the chaotic oscillations in the humidity curves of the outgoing flow, while its moisture content (upper chart) coincides with the incoming flow. Such a course of the specified dependences is due to the formation of moistening at the surface of fruit, which quickly disappears during morning warming. Part of the vapor from the incoming flow could condensate on internal, cooler elements of the solar dryer. Then, when blown over by the air flow, the weaker-bound moisture evaporated, and, at saturation, re-deposited on the surface of the fruit where the bond was stronger. At subsequent stirring of fruit, moisture migration processes are reactivated, which manifests itself in the form of local oscillations in curve φ_o.

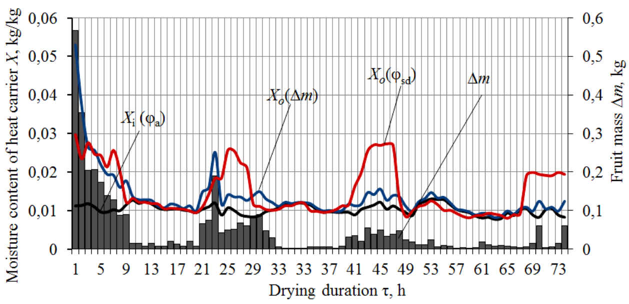

Fig. 8. Dynamics of the mass transfer processes in the solar dryer over the period of 28–31.07.2017

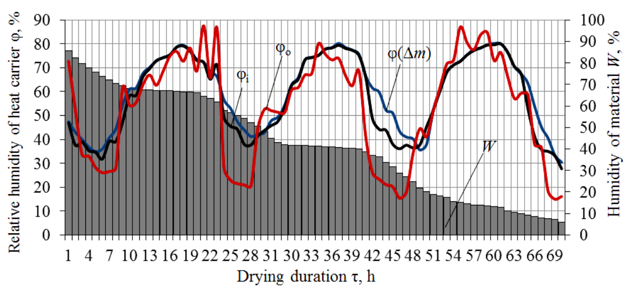

Fig. 9. Kinetic parameters of the moisture release processes in the solar dryer over the period of 28–31.07.2017

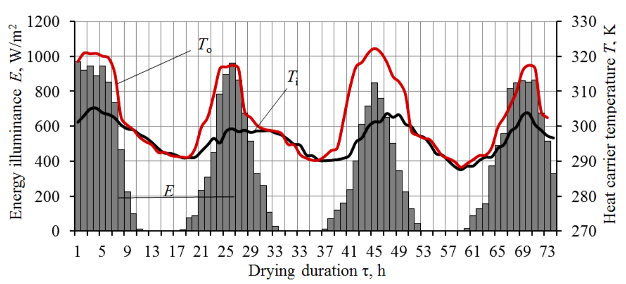

Fig. 10. Energy parameters of the solar dryer operation over the period of 28–31.07.2017 without a dryer

The third day saw the higher day temperature of the environment and the flow, heated by the air collector, and, as a consequence, a continuation, well into midnight, of the process of active drying due to the increased reserve of heat. After midnight, as a result of a deeper fall in the ambient air temperature, there was also partial sorption of moisture by the surface of fruit, but we did not visually detect the condensate formation. The following night, humidity of the outgoing flow only for a short period exceeded the humidity of the incoming flow, and it was lower for the rest of the night. This means that part of the moisture of cold flow, close to the state of saturation, was adsorbed by the dried surface of the fruit. In this case, the condensate did not form, otherwise it would be found in the form of a convergence between curves φ_i and φ_o the following morning.

The repeated experiment of the solar dryer operation under the mode of natural cycles was held a week later, on August 7–10, 2017, under almost identical weather conditions. As one would expect, time dependences of the controlled parameters did not differ significantly; the explanation of separate details does not require the construction of other models for the course of drying processes. However, the duration of complete drying in both studies increased to 74÷80 h instead of 50 h under conditions of complete configuration of the solar dryer.

5. 3. Results of the technological process of fruit drying in the solar dryer

Depending on the technological techniques for treating raw materials before drying, we observed significant differences for the duration of drying and the quality of the finished product. The apple, treated with a sugar solution, started to get dark at the very beginning of drying. The first to end was the drying of apple that was blanched, it lasted for 27 hours, for pear – 27÷51 hours. The drying duration of the untreated apple was 33 hours, pear – 53 hours (Fig. 11). The dried apples varied in the physical appearance and quality. The apple, treated with a sugar solution, had slightly dark coloring, but a good aroma and sweet, pleasant taste. The apple, treated with a salt solution, had a bright color, sweet and pure taste, but a faint aroma. The untreated apple went dark after drying in some places, anyway, had a good physical appearance, aroma and taste.

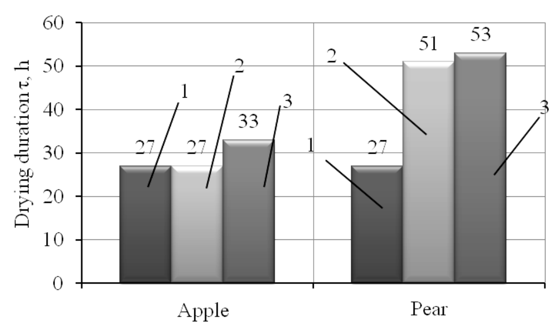

Fig. 11. Duration of fruit drying depending on a blanching technique: 1 – in a sugar solution; 2 – in a salt solution; 3 – without treatment

Treatment of pear did not influence quality of the finished product, but made it possible to speed up the uniform moisture release throughout the thickness of the fruit and prevented the formation of a crust that allows the shortening of drying duration. Excessive reduction of the thickness of apple sliced to 5 mm resulted in that the dried products broke and crumbled. Physical appearance of the dried apples, sliced by different techniques and to different thickness, is shown in Fig. 12.

The apple, sliced to a thickness of 8 mm, was dried in the solar dryer and at atmospheric drying. In the solar dryer, the intervals were 27÷33 hours; at atmospheric drying – 87 hours.

a *b* *c*

Fig. 12. Physical appearance of dried apples, depending on a blanching technique: *a* – in a sugar solution; *b* – in a salt solution; *c* – without treatment

Physical appearance of the finished product retained its original color, and had a pleasant aroma. Finished products were selected and chemically analyzed: results are given in Table 2.

Table 2

Results of chemical analysis of the fruit raw materials before and after drying

Fruit	Vitamin C, mg/%		Sugar content, %		Acidity, %		Dry substances, %		Nitrates, mg/100 g	
	Before	After	Before	After	Before	After	Before	After	Before	After
Pear	10.2	5.2	17.24	59.36	0.53	0.29	14.50	87.5	13.98	83.6
Apple	9.6	4.3	16.9	57.8	0.56	0.46	13.23	85.9	14.29	85.7

Thus, the proposed design of the solar dryer has demonstrated its efficiency, reliability, and the possibility of obtaining a quality product.

6. Discussion of results of the substantiation of operation modes of the solar fruit dryer

This work investigates the intensification of the drying process of fruit raw materials in a stationary layer in order to substantiate effective operation modes of the solar dryer. We describe field tests of the energy unit of the solar dryer (mirror concentrator – air collector – heat accumulator – drying chamber – the object of drying) in various configurations. We examined the technological process of fruit drying at small volumes of processing the freshly-gathered fruits under conditions of private peasant farms.

The study of the technological process of drying used apple of the variety Semyrichka and pears of the varieties Cure and Stolovka – at initial humidity W_i=70.3÷85.2 %. This makes it possible to extend the assortment of dried fruits by using “local” raw materials, to improve quality of dried products, and reduce the cost of domestic production.

The processes of convective, radiation and thermal drying simultaneously proceed in the designed solar dryer. It is clear that during day time, at low humidity of the incoming air and large intensity of solar radiation, it is advisable to reduce the temperature of a drying agent, and to store excessive heat of the collector. For this purpose, the receiving surface of the collector is made from heat-accumulating elements while the heated flow is controlled by a valve. However, at a large heat-accumulating mass, a collector almost constantly operates under transition modes of heat exchange. Therefore, its calculation comes down to determining energy efficiency under assumption of a quasi-stationary regime. Given such a design, the primary condition for the high heat output of the collector is met, that is a low temperature of the heat carrier at its outlet, which never exceeds the value of T=289.15...328.15 K.

In the process of drying, a solar dryer should work under a low-temperature mode. This makes it possible to reduce nonproductive heat losses through the casing of a drying device and to efficiently utilize the potential of solar energy over 24 hours. The reduction of heat losses is also contributed to by the configuration that combines a collector, a heat accumulator, and a drying chamber. A transparent front wall of the drying chamber makes it possible to intensify the process through additional radiation heating of the fruit mass.

The studies on fruit drying traditionally focus on the effect of temperature and air speed on the kinetics of moisture removal. Thereby, in the dryers with traditional power supply, high relative humidity of the incoming air is reduced by increasing its temperature. Instead, in solar dryers, it is more appropriate in terms of energy efficiency to slightly heat the drying chamber by the heat accumulated at night when humidity approaches the dew point. In this case, drying chamber operates under a mode of the atmospheric dryer. The positive results of such an effect on the humidity of the incoming flow are visually confirmed by the presented graphical dependences, built based on the results of measuring humidity, as well as the results of simulation of the kinetics of mass exchange processes.

We determined static characteristics of the dried products: equilibrium moisture content as a function of temperature and relative air humidity, chemical potential, and specific thermal moisture capacity.

The effect of operational parameters on a change in chemical and biochemical indicators was established. A significant reduction in the duration of drying makes it possible to improve the organoleptic and biochemical indicators of the dried product at a decrease in the consumption of heat for the process of drying.

Thus, the series of analytical and experimental studies that we conducted has confirmed the possibility to intensify the process of drying of raw materials in the dryer.

The work, however, does not give the regression equation for natural values in order to determine kinetic and dynamic parameters. It could contribute to formulating a unified procedure for investigating the technological process of fruit drying in the solar dryer.

Thus, the application of solar dryers with a heat accumulator and a flat mirror concentrator for fruit drying is feasible and efficient under conditions of private peasant farms. This would make it possible to increase the volume of high-quality dried products at minimal energy expenditure. In addition, the results obtained would be useful for improving the technology and equipment for fruit drying.

7. Conclusions

1. It was established that the use of an accumulator and a concentrator in the solar dryer decreases the duration of drying by 23 hours. This makes it possible to speed up the

intensity of the process by 1.5 times. Over the period of work of the solar dryer, the area of 1.5 m^2 of the air collector surface received 30.2 kW·h, or 108.5 MJ, of thermal energy at moisture evaporation of 2.8 kg. Energy efficiency of the process amounted to 10.7 kW·h/kg, or 38.8 MJ/kg.

2. We analyzed energy parameters, kinetic processes of moisture release, dynamic processes of mass exchange, and temperature-humidity fields in the processes of convective fruit drying.

3. We studied the energy parameters that changed in the following range: the physical parameters of the environment – air temperature T_a – 289.15…303.15 K; relative air humidity φ_a – 26…86.8 %; energy illuminance E – 100…800 W/m^2. Thermal-technical parameters of the heat carrier fed to the drying chamber were as follows: temperature T_{hc} – from 293.15 to 333.15 K; speed of circulation υ_{hc} – from 1 to 3 m/s; relative humidity φ_{hc} changed from 9.8 to 86 %.

References

1. Modeling of the motion of free convective drying agent in plastic helio dryer / Khazimov Z. M., Bora G. C., Khazimov K. M., Khazimov M. Z. // Journal of Engineering Thermophysics. 2014. Vol. 23, Issue 4. P. 306–315. doi: 10.1134/s1810232814040080
2. Thin layer drying model for simulating the drying of Tilapia fish (Oreochromis niloticus) in a solar tunnel dryer / Kituu G. M., Shitanda D., Kanali C. L., Mailutha J. T., Njoroge C. K., Wainaina J. K., Silayo V. K. // Journal of Food Engineering. 2010. Vol. 98, Issue 3. P. 325–331. doi: 10.1016/j.jfoodeng.2010.01.009
3. Experimental performance and modeling of a greenhouse solar dryer for drying macadamia nuts / Janjai S., Phusampao C., Nilnont W., Pankaew P. // International Journal of Scientific & Engineering Research. 2014. Vol. 5, Issue 6. P. 1155–1161.
4. Manoj M., Manivaimair A. Simulation of solar dryer utilizing green house effect for cocoa bean drying // International Journal of Advanced Engineering Technology. 2013. Vol. 4, Issue 2. P. 24–27.
5. Holmanskiy A. S., Tilov A. Z., Tyuhov I. I. Issledovanie kinetiki sushki rastitel'nyh pishchevyh produktov // Vestnik Rossiyskoy akademii sel'skohozyaystvennyh nauk. 2012. Issue 2. P. 15–17.
6. Mathematical modelling of thin layer drying kinetics of plum in a tunnel dryer / Goyal R. K., Kingsly A. R. P., Manikantan M. R., Ilyas S. M. // Journal of Food Engineering. 2007. Vol. 79, Issue 1. P. 176–180. doi: 10.1016/j.jfoodeng.2006.01.041
7. Experimental Study on Eggplant Drying by an Indirect Solar Dryer and Open Sun Drying / Azimi A., Tavakoli T., Beheshti H. K., Rahimi A. // Iranica Journal of Energy & Environment. 2012. Vol. 3, Issue 4. P. 347–353. doi: 10.5829/idosi.ijee.2012.03.04.14
8. Korobka S. V. Heliosusharka z teplovym akumuliatorom: Pat. No. 97139U UA. MPK A23L3/00 / zaiavnyk ta patentovlasnyk Korobka S. V. No. UA 97139U; declareted: 26.12.2014; published: 25.02.2016, Bul. No. 4. 3 p.
9. Korobka S., Babych M. Substatiation of the constructive-technologocal parameters of a solar fruit dryer // Eastern-European Journal of Enterprise Technologies. 2017. Vol. 1, Issue 8 (85). P. 13–19. doi: 10.15587/1729-4061.2017.90299
10. Research into technological process of convective fruit drying in a solar dryer / Korobka S., Babych M., Krygul R., Tolstushko N., Tolstushko M. // Eastern-European Journal of Enterprise Technologies. 2017. Vol. 3, Issue 8 (87). P. 55–63. doi: 10.15587/1729-4061.2017.103846
11. NASA Surface meteorology and Solar Energy. URL: https://eosweb.larc.nasa.gov/