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Use of solar energy in the technology of fruit drying

***Abstract**. Companies in the agri-food industry of Ukraine are trying to rationally manage all forms of energy (including solar energy) needed to implement the production process. The study investigated the process of drying plant material (fruit) based on the use of solar energy (and the intensification of this process). The present process uses a combination of an air collector and a drying chamber. The measurable effect of the performed tests is the development of diagnostic techniques for heat transfer with alternative diffusion and moisture transfer potentials (the experiment was performed at the temperature of 25-60ºC, drying time was 50-74 hours). The method is offered to calculate the diffusion and moisture transfer when drying the fruit in a solar dryer. The method enables the diagnosis of heat exchange processes and the analysis of the mathematical model of heat exchange processes [1]. The results of the research (analytical and experimental) indicate the possibility of intensifying the fruit drying process based on the solar dryer. The unit energy consumption during fruit drying in a solar dryer is reduced by 3-3.7 MJ/kg in relation to the currently used convection drying devices.*

Streszczenie.** Firmy z branży rolno-spożywczej Ukrainy starają się racjonalnie gospodarować wszystkimi formami energii (w tym energią słoneczną) potrzebną do realizacji procesu produkcyjnego. W pracy zbadano proces suszenia materiału roślinnego (owoców) w oparciu o wykorzystanie energii słonecznej (i intensyfikację tego procesu). Niniejszy proces wykorzystuje połączenie kolektora powietrznego i komory suszącej. Wymiernym efektem przeprowadzonych badań jest opracowanie technik diagnostycznych wymiany ciepła o alternatywnych potencjałach dyfuzji oraz przenoszenia wilgoci (doświadczenie przeprowadzono w temperaturze 25 ºC – 60 ºC, czas suszenia 50-74 godz.). Metoda oblicza dyfuzję i transfer wilgoci podczas suszenia owoców w suszarce słonecznej. Metoda umożliwia analizę procesów wymiany ciepła oraz modelu matematycznego procesów wymiany ciepła [1]. Wyniki badań (analitycznych i eksperymentalnych) wskazują na możliwość intensyfikacji procesu suszenia owoców w oparciu o suszarkę słoneczną. Jednostkowe zużycie energii podczas suszenia owoców w suszarni solarnej zmniejsza się o 3 MJ/kg - 3,7 MJ/kg w stosunku do obecnie stosowanych urządzeń do suszenia konwekcyjnego. **Wykorzystanie energii słonecznej w procesie suszenia owoców

Keywords: convective drying; fruit; thermal energy; solar energy; heliodilator; diffusion; moisture transfer.
Słowa kluczowe: suszenie konwekcyjne; owoc; energia cieplna; energia słoneczna; heliodylatator; dyfuzja; transfer wilgoci.

Introduction

Nowadays, there are many high temperature devices for fruit drying. The devices, intended for drying wet materials with the use of solar energy by transforming it into the thermal energy, can

be divided into two groups: installations with the concentrating devices and solar dryers of hotbed type. In the first group of installations, solar radiation comes to the dried material with different concentration multiplicity that depends on the kind of concentrating units [1,2]. Such types of installations are used for high temperature mode of drying. The drawbacks of those units include a high price of concentrators, the necessity to use tracking devices, and low efficiency. In the field of agricultural products drying, the type of solar dryers operating on the “hot box” principle is the most often used [3]. Depending on the way of heat supply to the dried material, they are divided into the solar dryers of radiation type, of convection type, and combined. In the convection solar dryers (CSD), the dried material takes the heat from the air, warmed in the air collector. Radiation solar dryers (RSD) are the aggregates, in which the dried material is placed to get the immediately effect of solar radiation. The principal portion of heat is supplied to the material by the radiation way. A combined solar dryer (CmSD) is an installation that combines two of the above described types.

The work [2] describes a solar fruit dryer of hotbed type, which consists of the bearing brick piles with girders and rafters installed behind them at the angle of inclination 20 ° to the horizon. Fruit, being pretreated, should be placed on the grid in the amount of 10 kg of fresh fruit per 1 m^2 of the surface, and covered by glass for the drying process to run. One the main drawbacks of that construction is that its assembling and exploitation is a labor consuming process.

The work [3] presents results of the research on drying fruit and grapes in the similar to the above-mentioned fruit drying installation. The comparative analysis of solar dryers of different types [4] confirms that use of them greatly cuts down the drying period as compared to the natural way of drying, whereas the quality of the final products is very high.

The work [5] describes a small, combined dryer for vegetables and fruit with an auxiliary air heater. However, the issue of an optimal mode of exploitation of the solar fruit drying installations and technological parameters are not considered in the works [3-5].

In the work [6], it is mentioned that natural climatic conditions of Greece are suitable for drying products by means of solar energy. It is commercially beneficial for the installations operating at the temperature above 60 °C. It is used for common solar dryers, similar to the installations of stationary type with glass coating. To reduce the costs for fruit drying installations, the author recommends to use the building roofs. The collected information contains the following data: the dryer type, available solar collectors, heat accumulator, systems of air recirculation, way of the drying agent circulation. In the performed review, solar dryers are grouped by the kind of dried material. Moreover, the specificity of a certain kind of product influences the solar dryer design. Therefore, all solar dryers for hay and grain, which do not operate under natural convection, belong to the chamber type, and most of them are equipped with a fuel back-up, whereas for drying vegetables and fruit all types of dryers are used. Most of such dryers have natural convection. It is explained by the fact that most dryers for fruit and vegetables are placed in warm countries, or they are intended for domestic use.

Today, the main problem of agricultural products drying is that it costs a lot of money. The expenses can be reduced by:

- process optimization;
- development of the most advanced methods of drying and technical means for their implementation; substitution

of the expensive sources of energy by the alternative, cheaper kinds, particularly energy of the sun;

- optimization of the design scheme of solar dryers.

Analysis of the literary sources on solar drying of agricultural products neither provides the optimal variants of solar energy use for fruit drying, nor gives clear recommendations concerning the methods and technics of solar drying of different kinds of products. Most of the active installations are experimental and have not large receiving surface. They were built on the base of singular experimental data. Unfortunately, nowadays, there is no active industrial installations, which have been tested, that is explained by the absence of standard methods of the complex analysis of solar dryers. To dry agricultural products, being submitted to complicated biochemical transformations, it is necessary to conduct supplementary studies, focused on creation of the rational design of drying installations with the characteristics meeting the production requirements, i.e. characterized by simplicity and reliability in exploitation, provide commercially reasonable indices. While choosing a type of dryers, authors of the above-mentioned researches followed only two criteria – reduction of the drying process duration and improvement of the final product quality, but organically did not associate the technological, energy and economic aspects with the kinds and amount of dried material. It has resulted in imperfection and high costs of the approved design schemes, and consequently to the relatively low efficiency of the solar technical device use. Therefore, in the future, all efforts should be focused on improvement of the process technology concerning simplification and reduction of the costs of the solar dryer design that will provide wide use of them in the agro-industrial complex. Successful solution of that very important economic and complex scientific technical problem is impossible without systematization of the great diversity of existing methods of drying and different installation constructions.

A conditional classification of solar dryers is provided in a simplified form with only mentioned direction and choice of drying method, as well as type of installation securing an effective and adequate process. While developing the classification of solar dryers, in the work [7], the authors considered three main aspects, particularly field of application, technological and constructive aspects. Depending on the field of application, the choice of a subclass of solar systems is based on one principal factor, particularly the volume of dried product. Choice of the way of heat supply to the material is based on the technology of drying of a specific kind of product that secures the required quality. Systematization and classification of installations referring to the constructive peculiarities provides the opportunity to consider their features and to continue the work on their improvement. It is caused by the diversity of fruit and vegetables, which should be dried, as well as different requirements concerning the technology of drying and requirements to the quality of obtained raw materials and final products. Moreover, it is necessary to concern the aspects of adequate technological, ergonomic, energy and technical parameters, as well as profitability of production. The solar dryers can be of direct and indirect solar energy effect [8].

In [9] it is proposed to calculate the area of the solar collector through the ratio of the daily heat productivity of the collector to the sum of the values of heat fluxes coming through the drying chamber, as well as from the insulated wall. However, the proposed technique has not taken account of the costs of heat flow to heat the drying chamber internal equipment (shelving, ducts, etc.) and charge-discharge process in the heat accumulator.

The authors in [10 - 12] developed the design of solar dryers of tunnel and chamber type. The numerical method of solving the mathematical model of stress calculation and moisture distribution in fruits during drying is substantiated and the tasks of optimization of this model are formulated. A multi-stage mode of convective drying of fruits by solving the optimization problem is proposed. However, it is impossible to develop a general technological mode of fruit drying in a solar dryer, but only to stabilize the thermal parameters of the coolant in the drying chamber during the drying process. Because during the drying of the fruit at a moisture content of W,% and weight m, kg, the thermal parameters of the coolant significantly depend on the physical parameters of the environment. In particular, the flow of solar energy, temperature and humidity, atmospheric pressure, wind speed and strength. And their coincidence and recurrence during two consecutive drying periods of 24 hours is unlikely [13-16].

In the installations of direct effect, solar energy is absorbed immediately by the product of drying and black-painted internal walls of the chamber, which contain the dried material. It has the upper light transparent film, perforated rack for placing the dried material, side walls (southern wall – made of light transparent material), heat insulation with the holes for air income. To remove the moisture from the dryer, holes are made in the upper part of the northern wall [17-20].

Drying installations of indirect effect include a solar air heater and mine or tunnel frame. In the mine solar dryer, air flows through a layer of material, placed on the grid racks, from bottom to the top, the tunnel dryer may be equipped with a conveyor belt, on which the material is transported, whereas air (the drying agent) moves countercurrent in the reverse direction. Examples of the design of chamber solar dryers can be seen below. Two sections of the air collectors of matrix type are placed in the heat-insulated case made of galvanized iron [21-24].

Solar energy is absorbed by the matrix which consists of two layer of black-painted metal grids and filled with metal particles (chips) between them. It may also have several layers of black grid. The hot air enters the conic dryer chamber, which has several layers of grid, where the material for drying is placed. A specific partition of vertical type is placed to supply air under each layer of dried material. Use of solar dryers for drying agricultural products set some requirements. They are derived from the tasks, which should be primarily performed to dry the material, namely cleanliness; preserving nutritive and taste qualities of the final product; equal drying through the whole volume of material; efficient use of the obtained energy. To fulfil those tasks, the solar dryer should be characterized both by the appropriate technological and constructive parameters, and heat insulation indices to secure the saving use of solar energy, accumulated by the solar collector [25-28]. Therefore, materials of the elements of the solar dryer construction should possess the adequate thermophysical properties. However, except of the thermophysical characteristics of the material, much attention is paid to their price at the market for the producer, who aims to build and use the solar dryer can afford buying those materials. Weight characteristics of the materials used for the solar dryer construction are also of some concern, especially if the solar dryer is either portable or mobile, i.e. makes sun tracking rotational move, e.g. azimuthal tracking of the sun. High efficiency of a solar dryer is usually achieved by the increase of the area of the solar energy capturing, or by larger sizes of the dryer. It makes the construction heavier and thus, causes displacement of the above-mentioned bearers. Therefore, the design elements of the solar dryer should be made of the material characterized by the least possible density, however not deteriorating their thermophysical characteristics and not increasing the costs. Thus, development of a drying device for thermal treatment of vegetable material, which considers the above-mentioned drawbacks, is made of available modern materials, which secure sufficient carrying capacity of solar energy and efficient use of the received energy, needs further scientific investigation and researches of the process theory to implement them in practice. Analysis of the works on design of the currently existing devices of drying to produce dried vegetable products confirms that its main indices are influenced by the method of heat supply and the mode of drying. In some works, intensity of the drying process is achieved by reducing the size of the material particles. It is known that in that case, the area of the radiation surface is larger. Considering everything above mentioned, it is proposed to use the solar dryer of mine type with a heat accumulator and mirror concentrator to reduce the passive zones in the drying chamber, as well as to avoid the overheat of the dried products [29-32].

2. Materials and Methods for the substantiation of design and technological parameters of a solar dryer

2.1. Substantiation of design-technological scheme and structure of a solar dryer

The design-technological scheme of a heliodryer for fruits with a heat accumulator and a flat mirror concentrator, shown in Fig. 1, 2 [3,5,6,13].

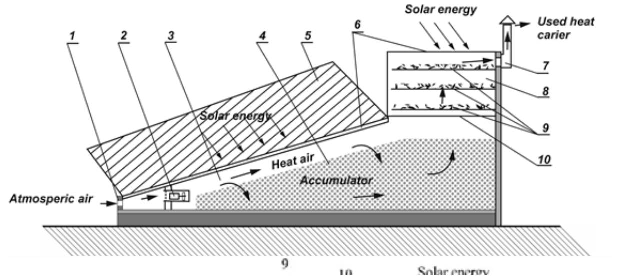

Fig. 1. Structural-technological schematic of solar dryer with thermal battery and flat mirror concentrator: 1 – input channel; 2 – fan; 3 – air duct; 4 – air collector; 5 – heat accumulating material (pebble–based); 6 – drying chamber; 7 – exhaust channel; 8 – sieves with fruit; 9 – flat mirror concentrator; 10 – valve.

To study the process of fruit drying in the solar dryer, the unit has been equipped with measuring devices and feeders, demonstrated at the Figure 2.

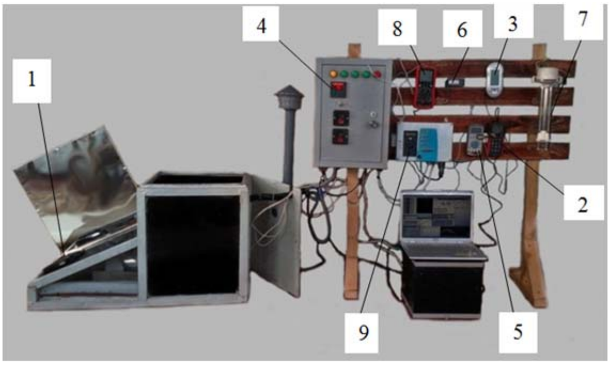

Fig. 2. General plan of the experimental solar dryer, equipped with measuring devices and feeders: 1 – pyranometer PELENG SF-06; 2 and 3 - hot-wire anemometers UT 362 and Testo 425; 4 – temperature measuring regulator PT – 0102-8 with thermal supports Pt 100; 5 – digital hygrometer WCM-1 with a water feeder EE HC 200; 6 – digital thermohygrometer PT – 0102 with thermal supports Pt 1000; 7 – Assman psychrometer; 8 – digital multimeter UT - 70B; 9 – humidity meter of the dried material BFS-1A.

A solar dryer consists of a wooden frame with an income channel and air duct with a blower on its front side. In the upper part of the frame, there is an air collector with the flat mirror concentrator, and in the lower part there is heat-accumulating material (pebble stones). The drying chamber is placed in the back space of the wooden frame with a chimney, sieve and shutter installed on it.

A parametric series of five solar dryer is proposed, their design parameters are substantiated: air collector area; area of flat mirror concentrator; mass of thermal battery; inside volume of drying chamber.

Table 1. Parametric series of solar dryers

Parameter	Index				
Mass of dried material, kg	5.5	6.3	8	10	12.5
Air collector area, m^2	1.5	1.7	2.2	2.8	3.2
Area of flat mirror concentrator, m^2	1.5	1.7	2.2	2.8	3.2
Mass of thermal battery, kg	50	69	86	118	140
Inside volume of drying chamber, m^3	0.5	0.6	0.9	1.4	1.9

3. Investigation of the technological process of fruit drying in a solar dryer

3.1. Results and Discussion

Investigation of the technological process of drying in a solar dryer was conducted in the period of ripening of the most kinds of fruit, i.e. July and August 2019, when the weather was mostly sunny. Dried material included apples of Semyrichka variety, pears of Stolovka, Kiure varieties with the primary moisture content W_n = 70.3-85.2 %, sliced or cut into 6 mm thick pieces, and one time loaded in the solar dryer m_f = 5.5 kg.

In the period of full-scale testing of the solar dryer from 15 July 2019 to 17 July 2019 in Korets town of Rivne region (Ukraine), the weather was sunny and dry. The degree of atmospheric transmittance variated from 0.72 to 0.86. The flow of air (wind) variated from 1.3 m/s to 2.8 m/s. Drying in the solar dryer was done at the temperature t = 52 °C under unequal temperatures of the air flow and dried sample in the regime of continuous control for the process and hourly registration of the checked values [3,5,6,13]. Results of the measuring are demonstrated in the Table 1 and corresponding graphical materials in the form of time dependences. Hourly weighting of the raw material supplied information on the time dependence of the speed of drying, and represented the proportional value of the weight loss dm/dt:

$$(1) \qquad \frac{dU}{d\tau} = \frac{d\tau}{d\tau}\left(\frac{m}{m_c}\right) = \frac{1}{m_c}\frac{dm}{d\tau}$$

In case of hourly registration d$\tau \rightarrow \Delta\tau$ = 1 hour = 3600 s

$$(2) \qquad \frac{dU}{d\tau} \approx \frac{\Delta U}{\Delta\tau} = \frac{1}{m_c}\frac{\Delta m}{\Delta\tau} = \frac{1}{m_c}\frac{\Delta m}{3600} \sim const \cdot \Delta m \sim m$$

To demonstrate the speed of drying, it is better to represent it by a column diagram Δ*m* that reveals both a general tendency and peculiarities of moisture separation in the form of periodical mass expulsion. The last does not correlate with the corresponding time dependences of the temperature of coolant flow or its humidity. Probably, the processes of self-organization happen inside the dryer. The processes are caused by accumulation of steam in half-closed capillaries and its jump-type breakthrough out under critical overpressure. A similar physical mechanism describes the pulsating emission of chlorine under radiolysis of alkali-halide crystals. In the thin slices of raw material with insignificant flow of steam to the surface, that phenomenon is better manifested than in massive materials (for example, thicker pieces of raw material), where rapid breakthrough of steam is repressed by the system of subdivided intermediary capillaries. Gradual increase of the interval between the following peaks of moisture exudation

– from 4-6 hours at the start of drying to 8 hours at approaching the balance can be explained by intensification of the double-phase zone of evaporation. In particular, minimum of the integral index of moisture content $\Sigma\Delta m$ reduction at the 38th hour of drying (Figure 4) is a result of impact of two unfavorable factors, i.e. lower night temperature of the coolant and increase of its humidity (Figure 4 of the corresponding time dependences), which depress the processes of steam production and reduce the probability of outcropping. Therefore, the moment of discharge of the excessive pressure is shifted by the phase and dragged out for almost 6 hours – from 39 to 45 hours. The next peak of moisture exudation was marked with a longer delay even in case of an increased daily temperature and sun warming. Such extension of inter-peak interval can be probably explained by increase of the efficient area of evaporation during fragmentation of the complete double-phase zone of capillary-porous medium.

Table 2. Consolidated conditions and results of the tested drying of apples and pears in the solar dryer by the change of raw fruit weight ln(MR) – [1) U_{eq} = 0.12; $U_0 - U_{eq}$ = 0.6328; 2) m_{eq} = 4.9 kg; $M_0 - m_{eq}$ = 2.83 kg]

Duration of drying		Sample №1: M_0 = 7.73 kg; m_p = 4.90 kg; m_{c0} = 4.41 kg; $m_{\text{в}0}$ = 3.32 kg; U_{eq} = 12.0									
№	Hour	m, kg	Δm	$\Sigma(\Delta m)$	m_c	U, %	U_{eq},%	ln$(MR)_m$	ln(U)	$\frac{U - U_{eq}}{U_0 - U_{eq}}$	ln$(MR)_U$
5	0	7.73	0	0	2.83	75.3	75.28	0	–0.2836	1	0
6	1	7.59	0.14	0.14	2.69	72.1	72.10	–0.0507	–0.3271	0.9497	–0.0516
7	2	7.48	0.11	0.25	2.58	69.6	69.60	–0.0925	–0.3624	0.9102	–0.0940
8	3	7.31	0.17	0.42	2.41	65.8	65.76	–0.1606	–0.4192	0.8496	–0.1630
9	4	7.16	0.15	0.57	2.26	62.4	62.36	–0.2249	–0.4722	0.7958	–0.2284
10	5	6.99	0.17	0.74	2.09	58.4	58.50	–0.3031	–0.5361	0.7348	–0.3081
11	6	6.88	0.11	0.85	1.98	56.0	56.01	–0.3572	–0.5796	0.6954	–0.3632
12	7	6.77	0.11	0.96	1.87	53.5	53.51	–0.4143	–0.6253	0.6560	–0.4216
13	8	6.69	0.08	1.04	1.79	51.7	51.70	–0.4686	–0.6597	0.6273	–0.4662
14	9	6.57	0.12	1.16	1.67	49.0	48.98	–0.5274	–0.7138	0.5844	–0.5372
15	10	6.45	0.12	1.28	1.55	46.3	46.26	–0.6020	–0.7709	0.5414	–0.6136
16	11	6.37	0.08	1.36	1.47	44.4	44.44	–0.6550	–0.8110	0.5126	–0.6682
17	12	6.28	0.09	1.45	1.38	42.4	42.40	–0.7182	–0.8627	0.4804	–0.7331
18	13	6.18	0.10	1.55	1.28	40.1	40.14	–0.7934	–0.9128	0.4447	–0.8104
19	14	6.11	0.07	1.62	1.21	39.6	38.55	–0.8496	–0.9532	0.4196	–0.8685
20	15	6.04	0.07	1.69	1.14	37.0	36.96	–0.9092	–0.9953	0.3944	–0.9303
21	16	5.98	0.06	1.75	1.08	35.6	35.60	–0.9633	–1.0328	0.3729	–0.9863
22	17	5.94	0.04	1.79	1.04	34.7	34.69	–1.0011	–1.0587	0.3586	–1.0256
23	18	5.86	0.08	1.87	0.96	32.9	32.88	–1.0811	–1.1123	0.3300	–1.1086
24	19	5.78	0.08	1.95	0.88	31.1	31.07	–1.1681	–1.1689	0.3014	–1.1994
25	20	5.72	0.06	2.01	0.82	29.7	29.71	–1.2387	–1.2137	0.2799	–1.2733
26	21	5.69	0.03	2.04	0.79	29.0	29.02	–1.2760	–1.2372	0.2690	–1.3130
27	22	5.66	0.03	2.07	0.76	28.3	28.34	–1.3147	–1.2609	0.2582	–1.3540
28	23	5.59	0.07	2.14	0.69	26.8	26.76	–1.4113	–1.3183	0.2255	–1.4841
29	24	5.53	0.06	2.20	0.63	25.4	25.40	–1.5023	–1.3704	0.2118	–1.5523
30	25	5.51	0.02	2.22	0.61	26.9	24.94	–1.5346	–1.3887	0.2045	–1.5872
31	26	5.49	0.02	2.24	0.59	24.5	24.48	–1.5679	–1.4073	0.1972	–1.6234
32	27	5.46	0.03	2.27	0.56	23.8	23.81	–1.6201	–1.4351	0.1866	–1.6786
33	28	5.44	0.02	2.29	0.54	23.4	23.36	–1.6565	–1.4541	0.1795	–1.7175
34	29	5.40	0.04	2.33	0.50	22.5	22.45	–1.7334	–1.4939	0.1651	–1.8010
35	30	5.34	0.06	2.39	0.44	21.1	21.09	–1.8613	–1.5564	0.1436	–1.9404
36	31	5.32	0.02	2.41	0.42	20.4	20.63	–1.9078	–1.5784	0.1364	–1.9923
37	32	5.31	0.01	2.42	0.41	20.0	20.41	–1.9319	–1.5891	0.1329	–2.0181
38	33	5.29	0.02	2.44	0.39	19.7	19.95	–1.9819	–1.6119	0.1256	–2.0744
39	34	5.28	0.01	2.45	0.38	19.3	19.72	–2.0079	–1.6235	0.1220	–2.1038
40	35	5.26	0.02	2.47	0.36	19.1	19.27	–2.0619	–1.6466	0.1149	–2.1638
41	36	5.25	0.01	2.48	0.35	18.6	19.05	–2.0901	–1.6581	0.1114	–2.1945
42	37	5.23	0.02	2.50	0.33	17.0	18.59	–2.1489	–1.6825	0.1041	–2.2620
43	38	5.16	0.07	2.57	0.26	16.1	17.01	–2.3874	–1.7737	0.0792	–2.5361
44	39	5.12	0.04	2.61	0.22	15.9	16.10	–2.5544	–1.8264	0.0648	–2.7366
45	40	5.11	0.01	2.62	0.21	15.4	15.87	–2.6009	–1.8407	0.0611	–2.7943
46	41	5.09	0.02	2.64	0.19	14.5	15.42	–2.7010	–1.8695	0.0540	–2.9179
47	42	5.05	0.04	2.68	0.15	14.1	14.51	–2.9374	–1.9303	0.0397	–3.2273
48	43	5.03	0.02	2.70	0.13	13.2	14.06	–3.0805	–1.9618	0.0326	–3.4249
49	44	4.99	0.04	2.74	0.09	12.9	13.15	–3.4482	–2.0287	0.0182	–4.0078
50	45	4.98	0.01	2.75	0.08	12.7	12.93	–3.5660	–2.0456	0.0147	–4.2201
51	46	4.97	0.01	2.76	0.07	12.5	12.70	–3.6995	–2.0636	0.0111	–4.5042
52	47	4.96	0.01	2.77	0.06	12.2	12.47	–3.8537	–2.0818	0.0074	–4.9026
53	48	4.95	0.01	2.78	0.05	12.0	12.24	4.0360	–2.1005	0.0038	–5.5747
54	49	4.94	0.01	2.79	0.04	11.8	12.02	4.2591	–2.1371	0.0003	–8.0596
55	50	4.93	0.01	2.80	0.03	11.6	11.79	4.5468	–2.15741	x	x
56	51	4.92	0.01	2.81	0.02	11.1	11.56	4.9523	–2.1982	x	x
57	52	4.90	0.02	2.83	0	11.1	11.11	∞	–2.1982	x	x

x – no data

Time dependences of the moisture content $U(\tau)$ are developed by the results of immediate measuring of moisture and calculated with the use of current values of weight loss by the dried material. The first approach may include a significant deviation because of instable conditions of interaction of the sensitive element (sensor) with the dried material. In contrast, accuracy of calculations by the second method depends on the methodology of determination of the share of dry mass. The absolute method of determination of the dry mass mc requires a long process of moisture exudation in dry air that is technologically irrational. However, it is more reasonable to calculate it by the results of measuring the weight and moisture content of the material, e.g. in the balance with the surrounding air – after its some-hour stabilization. Thus, according to determination of the moisture content

$$U = \frac{m}{m_c} = \frac{M - m_c}{m_c} \tag{3}$$

where *M* is the current weight of raw fruit material, kg.
Thus

$$m_c = \frac{M}{U + 1} \tag{4}$$

The value of moisture content, calculated by using such methodology, is an integral characteristic, independent on the temperature or local moisture content of the material of the measuring sensor zone. The state of balance with the external environment secures reduction of the deviation of moisture content measuring by means of multiple repetition and averaging. Therefore, weight and moisture content of the examined raw material, compiled into one thin plate (0.6 mm) of the total thickness *L*=0.0042 m and being pre-stabilized at room temperature, made *m* = 4.9 kg and *U* = 11.1 % respectively:

$$m_c = \frac{4.90}{0.111+1} = 4.41 \text{ kg}$$

The graph of the current moisture content, built according to the calculation of weight loss, resembles an exponent, whereas its corresponding logarithmic dependence ln*U(t)* is close to a linear one at some stages of the process (Figure 3). The last can be a feature of the change of kinetics of the moisture transfer process. It is known fact that drying is considered a typical process of relaxation under which the over-watered system tends to balanced conditions, when the diffusion flows inside and outside are in counter poise. Its intensity is normally characterized by the factor of effective diffusion, which, in case of raw fruit material, is related with the excessive moisture content U-U_{eq} by the equation (4). The value of balanced moisture content U_{eq} = 0.12 kg/kg is marked at the 53rd hour from the start of drying – one hour after its compliance that is necessary for balancing moisture content in the volume of material. To reduce the amount of calculations, the correlation of excessive moisture contents can be substituted by the ratio of the corresponding excessive mass of moisture in the material that is derived from the following correlations:

$$\ln\frac{U - U_{eq}}{U_0 - U_{eq}} = \ln\frac{\dfrac{M}{m_c} - \dfrac{m_{eq}}{m_c}}{\dfrac{M_0}{m_c} - \dfrac{m_{eq}}{m_c}} = \ln\frac{M - m_{eq}}{M_0 - m_{eq}} = \ln MR \tag{5}$$

The figures of that value, calculated according to the measured moisture content ln$(MR)_U$ and separately by the change of the pack ln$(MR)_m$ weight, demonstrated in two columns of the Table 2, are very close. However, in the further calculations, the preference is given to more reliable data, based on the weight loss.

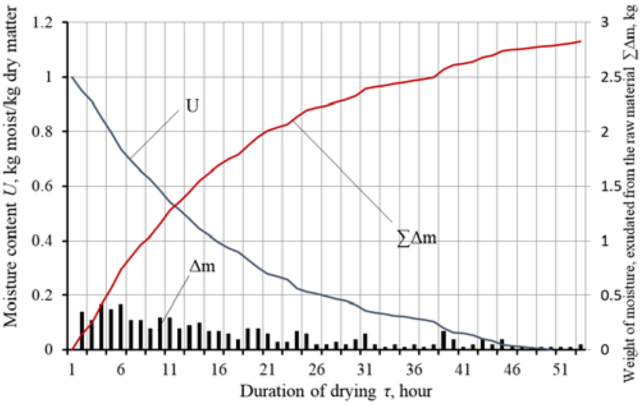

Fig. 3. Input characteristics of fruit drying

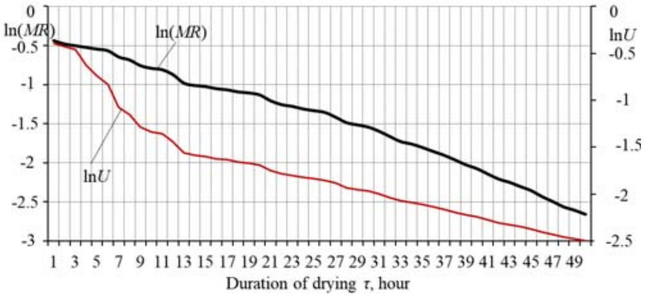

Fig. 4. Logarithmic time dependences of moisture content and relative (ln*U*) excessive humidity ln(*MR*)

Figure 4 presents a time dependence ln*MR*, approximate linear dependence in the interval from the start of the process to the break at the 37th hour. The dependences ΣΔ*m* and moisture content $U(\tau)$, particular for that moment, are characterized only by the deviation from the fine dependence and almost invisible tendency to a change of the process run. The factor of effective diffusion is proportional to the slope ratio ln*MR* and therefore, the break means the same rapid reduction of the factor of effective diffusion because of redistribution of the contributions of driving forces of the diffusion process. At that moment, in most capillaries, the free moisture has been left only in the conical endings, as well as in the form of adsorbed films on their internal surface and other hollows. Thus, the desorption process is slowed down, because the energy of activation of the bound molecules is much higher. Starting from that moment, it is reasonable to rise the coolant temperature to intensify the process without the risk of material cracking. As the amount of evaporated moisture is reduced, it is expedient to reduce the speed of the coolant flow 3 m/s to 2 m/s, to the level, sufficient for the excessive steam absorption that is at the speed of the coolant flow less than 1 m/s.

Values of the effective diffusion are determined by the slope ratio, using the correlation, which is derived from the equation (2):

$$D_f = \frac{4L^2}{\pi^2}\,\text{tg}\alpha \tag{6}$$

Visually, the value of tgα equal is evaluated by the correlation of the difference of y- and x-coordinates of the beginning and end of the linear dependence:

$$tg\alpha = \frac{\Delta(\ln R)}{\Delta\tau} = \frac{2.20}{34.5 \cdot 3600} = 1.77 \cdot 10^{-5}$$

Thus, in that time interval, the value of the effective diffusion is equal to:

$D_f = \frac{4 \cdot 0.0042^2}{\pi^2} \cdot 1.77 \cdot 10^{-5} = 7.15 \cdot 10^{-6} \cdot 1.77 \cdot 10^{-5} = 1.2655 \cdot 10^{-10}$m^2/s.

The correspondence of the supplied value of the effective diffusion of veneer drying process can be evaluated by the immediate calculation of moisture content, e.g. at the 30th hour of drying, using the formula, derived from the (3):

(7) $$U = U_{eq} + \left[\left(U_0 - U_{eq}\right)\frac{8}{\pi^2} exp\left(-\frac{\pi^2 D_f}{4L^2}\tau\right)\right]$$

(8) $$U_{30} = 0{,}12 + \left[(0{,}7528 - 0{,}12)\frac{8}{\pi^2} exp\left(-\frac{\pi^2 \cdot 1{,}2655 \cdot 10^{-10}}{4 \cdot (0{,}0042)^2} \cdot 30 \cdot 3600\right)\right] = 0{,}12 + [0{,}6328 \cdot exp(-1{,}9117)] = 0{,}2135$$

Thus, the measured U_{30} = 0.211, that is by 1.2 % less, and is within the deviation of measuring. Assuming that the temperature dependence of the effective diffusion is described by the known Arrhenius equation:

(9) $$D_{fa} = D_0 \exp\left(-\frac{E_a}{RT}\right)$$

its pre-exponential multiplier D_0 should be evaluated for the case of the average temperature of the process (see Table 2) T = 307.8 K:

$D_0 = D_{fa}\, exp\left(\frac{E_a}{RT}\right) = 1.2655 \cdot 10^{-10}\, exp\left(\frac{28956.2}{8.31 \cdot 307.8}\right) = 1.04 \cdot 10^{-5}$m^2/s.

However, the recommendations on use of that formula for forecasting the moment of balance achievement should be proceeded by its experimental testing on absence of redistribution of the contributions of driving forces of different constituents of the process kinetic and dynamic parameters. Therefore, it is necessary to make field testing of the solar dryer and determine operation characteristics (energy characteristics of the designed drying machine, heat and mass exchange characteristics of the process of fruit drying) of the solar dryer under standard regimes of solar insolation and typical (seasonal) meteorological conditions. In the period of the study, the daily average physical parameters of environment were the following:

1. Air temperature t_a – 12-32 °C.
2. Relative air humidity ϕ_a – 12-84.5 %.
3. Solar insolation E − 100-988 Watt/m^2 for the area of absorbing surface S_a = 1.5 m^2.
4. Thermal engineering parameters of the coolant (air), entering the solar dryer, included: temperature in daylight hours (from 8 a.m. to 9 p.m.) t_{dc} – 15-71 °C, at night time (from 10 p.m. to 7 a.m.) t_{dc} – 50-14 °C.
5. Speed of the coolant (air) circulation v_{dc} – 1-3 m/s.
6. Relative humidity of the coolant (air) φ_{dc} – 10.8-82.3 %.

The step iteration of calculations of the results of intensity measuring during 50 hours of drying 15÷17.07.2019 has determined that for three days, 25.2 × 1.5 = 37.8 kWh or 136.8 MJ of thermal energy came to the surface of the air collector. Under evaporation of 2.792 kg of water, energy intensity of the process made 10.7 kWh/kg or 38.8 MJ/kg.

The results of the first test allowed us to identify and explain problematic issues and make recommendations for their prevention. Thus, during the second test on August 10-13, a water absorber was additionally added to the drying chamber in the evening in a similar configuration. In combination with lower humidity, no condensate was detected. Instead, with the increased intensity of solar radiation in the first hours of drying there was an increased moisture release, which gradually stabilized in the afternoon. As a result of the subsequent alignment of diffusion processes on the surface and inside the fruit, the diagram of changes in their humidity at night is aligned. The increased moisture content of the original in the period from 23 to 35 hours of drying is due to the drying of the moisture accumulated at night in the near-surface layers of the fruit.

In the third experiment (15.08-16.08), due to the lower intensity of solar radiation, the drying rate decreased smoothly in the afternoon and stopped at night. The high humidity of the inlet air was partially compensated by the water absorber. The period of high humidity of the source stream at 23-33 hours of drying is also the result of intensive drying the next day.

The study on July 28-30 and 7-10 under almost identical weather conditions was conducted without heat accumulator, mirror concentrator and night drying of the input flow, ie without interfering with the mode of natural cyclic change of input parameters. With a lower level of solar radiation, the process of moisture removal was less intense, but in accordance with the daily cycle. But the duration of drying to the standard level lasted for a day. Intensification of the process with the help of a mirror concentrator requires control of additional factors, in particular relative humidity.

The research is focused on the application of solar energy for fruits drying which is acceptable for the latitude of Rivne region dislocation characterized by 3.41 kW·h/m^2 average annual solar radiation power for a light day. This allows to achieve 1.5-2.3 kW·h power from 1 m^2 per 1 day.

Discussion of results of the substantiation of design and technological parameters of solar dryer

The work supplies fundamentals of the diagnostics and forecast of the heat and mass exchange processes with the variable heat and mass transfer potentials. The applied methods of the research of heat and mass exchange characteristics of the processes of fruit drying in the solar dryer are developed based on the synthesis of the main laws of irreversible processes.

The authors of the research present an improved model of the convection drying of fruit in the solar dryer, which is based on a simplified mechanism of the diffusion factor calculation. The work also supplies a consolidated criterial method to measure the time of fruit drying in the solar dryer. Basing on the results of conducted researches, the authors propose engineering methods for the main elements design and present the developed constructions of solar drying chambers to fulfil the task of using non-traditional ecologically clean sources of energy for fruit drying. The research describes the created methodology for calculation of the kinetic parameters of heat and mass exchange, temperature of the material surface, and the diffusion factor in the process of combined drying, as well as developed and scientifically substantiated recommendations on forecasting the heat and mass exchange processes, improvement of the technologies and equipment for fruit drying.

5. Summary

A principially new solar drying installation with a heat accumulator and flat mirror concentrator is proposed. Design parameters of the proposed drying installation is substantiated by solving the equations (1, 2, 3, 4) with the corresponding boundary conditions of the chamber dryer. Computer modeling was used to make the mathematical model of the convection drying of fruit in the solar dryer that was based on the simplified mechanism of the diffusion factor calculation. The obtained models provided optimal values of the phases of the least and the best heat and mass exchange.

Basing on the theoretical and experimental researches it is determined that transfer of the moisture inside the dried material into the drying chamber with the mass of m = 4.9 kg is determined not only by the value of the temperature gradients Δt_{tn} from 20 to 60° and moisture content $U(t)$ = 4.202/3.528 = 1.191 kg dry matter/kg wet matter, but also by the diffusion factor D, which depends on the temperature and speed of the coolant in the drying chamber and varies within 0.17...4.2·10-10 m^2/s. In case the coolant temperature increases in the drying chamber Δt_{tn} from 20 to 60 °C, the diffusion factor D also increases, whereas raise of the coolant speed v_{tn} from 1 to 2.8 m/s causes its nonlinear reduction during the drying process of 58 hours.

Solution of the internal (heat and mass transfer inside the fruit) and external (transfer of heat and mass at the edge of the environments – solid body) tasks with consideration of the regularities of external heat and moisture exchange has been used for substantiation of the methods of research and determination of the factors of diffusion and moisture exchange, moisture content and moisture conductivity potential in the process of fruit drying in a solar dryer. Mathematic models for the factors measuring are obtained. Those models extend the theoretical fundamentals of the heat and mass transfer in the process of fruit drying in the solar dryer.

We proposed a parametric series of five mini-solar dryers for the conditions of PPF and substantiated their design parameters (Table 1), in particular: area of air collector and mirror concentrator, mass of thermal battery, inside volume of drying chamber.

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