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SUBSTATIATION OF THE CONSTRUCTIVE-TECHNOLOGOCAL PARAMETERS OF A SOLAR FRUIT DRYER

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Запропоновано конструкцію геліосушарки з тепловим акумулятором та плоским дзеркальним концентратором. Обґрунтовано структуру геліосушарки, що забезпечує раціональне зниження енерговитрат в процесі сушіння фруктів. Отримано аналітичні залежності для обґрунтування конструктивно-технологічних параметрів гелісушарки, а саме: площу колектора і концентратора, масу теплового акумулятора, об'єм сушильної камери

Ключові слова: сонячна енергія, геліосушарка фруктів, дзеркальний концентратор, тепловий акумулятор, сушильна камера

Предложена конструкция гелиосушилки с тепловым аккумулятором и плоским зеркальным концентратором. Обоснована структура гелиосушилки, которая обеспечивает рациональное снижение энергозатрат в процессе сушки фруктов. Получены аналитические зависимости для обоснования конструктивно-технологических параметров гелиосушилки, а именно: площадь коллектора и концентратора, массу теплового аккумулятора, объем сушильной камеры

Ключевые слова: солнечная энергия, гелиосушилка фруктов, зеркальный концентратор, тепловой аккумулятор, сушильная камера

1. Introduction

There are many high-temperature automated devices for drying fruits at present [1]. However, their application is unprofitable while processing small volumes of freshly picked fruits under conditions of personal peasant farms (PPF), which is associated with large capital investment and high energy consumption. The disadvantages of these drying installations are:

– contamination of fruits and the environment with toxic products of fuel combustion;

– uneven heating of the fruit mass and high speed of drying, which leads to overdrying, deformation and cracking of the material;

– high energy costs [2].

In this regard, in the process of fruits drying it is appropriate to apply drying plants based on solar energy. Up to now drying devices of this type have not been actively used under conditions of PPF. This predetermines the relevance of selecting optimal design of the dryer, the effective use of which under the PPF conditions is possible only if based on the substantiation of its rational design and technological parameters.

2. Literature review and problem statement

In the modern world, to replace scarce traditional types of energy (electrical or thermal), alternative sources are increasingly used. One such source is solar energy that can be used for the generation of electrical energy or low potential heat, in particular for drying wet materials of plant origin.

Paper [3] formulated an actual task of improving performance and selecting optimal drying chamber by the thermal inputs that a solar dryer receives from solar radiation and proposed a method for the calculation of design and technological parameters of air collector. The described technique is very general and does not live up to modern achievements of solar energy. In particular, heat flows through the translucent enclosure are calculated according to the building climatology recommendations [3], which contain the tables of standard average flows of energy from direct and scattered radiation in clear sky, and by following them – the mean energy illumination of the receiving surface taking into account a coefficient of cloudiness. In most applied problems such calculations can be replaced (without compromising their accuracy) with the ready results of calculations for the surfaces of typical orientation, available at the NASA website [4].

Paper [5] carried out substantiation of design and technological parameters of solar dryer of the mine type for the drying of fruits and vegetables. In particular, authors proposed an engineering scientific and methodological basis for determining the optimal area of air collector, volume of drying chamber, increasing the temperature of heat carrier in the dryer through additional radiation of drying chamber, based on the method of calculating the infrared dryers. However, they disregard the calculation of thermal (energy) budget of a solar dryer over one cycle of drying, linking to the change in physical parameters of the environment. The proposed technique cannot be used because it lacks specification (evaluation) of the components of thermal balance under conditions of combined impact of sunlight, heat accumulator and flat mirror concentrator.

Author of article [1] performs an analysis of drying plants using solar energy and substantiates their design and technological parameters. The calculations come down to the alignment and stabilization of drying regime for changing light conditions through a backup electric heater and at night – via a bulk thermal battery. Determining weight, dimensions and integral energy characteristics of dryers is also conducted. For example, the process of charging takes place only during periods when the energy illuminance is larger than the average one by 25 % while the temperature settings of input and output flows are not calculated at all.

Paper [6] proposed to calculate the area of solar collector through the ratio of daily thermal output of collector to the sum of values of the heat flows that arrive through the enclosures of drying chamber, as well as from the thermally insulated wall. However, the proposed method did not consider constituents of the heat flows consumption for heating the inner equipment of a drying chamber (racks, air ducts, etc.) and charging-discharging process in the thermal battery.

Authors of paper [7] devised an engineering method for the calculation of required area of solar collector for a drum grain dryer. But while calculating the area of solar collector, efficiency of the collector is not taken into account. This does not allow calculating transitional modes of the collector, instantaneous and daily performance efficiency.

In article [8], author suggested using a solar dryer of the mine type, which houses a parabola-cylindrical concentrator. However, when calculating the air collector's thermal output, the gain factor in solar energy flow is not accounted for that allows describing a change in the maximum energy illuminance of horizontal surface of air collector relative to a daily one.

Along with it, there is a still insufficiently explored question of the accumulation during daytime of the excess heat and acceleration of slant flows of morning and evening solar radiation on the receiving surface of air collector. Given this, it is appropriate to use heat accumulator and flat mirror concentrator as part of a solar dryer. This solution is effective enough and provides for the possibility to increase heat productivity of the collector, thermal power and efficiency of solar dryer, to improve technological and energy efficiency of the process and reduce the consumption of energy resources, but it requires additional research into the substantiation of its technological parameters.

Thus, a crucial aspect for making a decision when using solar dryer with a thermal battery and flat mirror concentrator for drying fruits under the PPF conditions is the substantiation of its technological and structural parameters, which implies determining: area, the heat productivity of collector and the angle of its inclination to the horizon, the volume of heat accumulator, inner width and depth of the drying chamber, thermal power of the solar dryer, opening angle of the concentrator.

3. The aim and tasks of the study

The purpose of present research is to improve the efficiency of technological process of drying fruits based on designing the structure and the substantiation of technological and structural parameters of solar dryer, which will make it possible to reduce the consumption of energy under the PPF conditions.

To achieve the set aim, the following tasks were to be solved:

– to design a structure of solar dryer with a thermal battery and a flat mirror concentrator and to substantiate its technological and structural scheme;

– to devise a method for the substantiation of rational design and technological parameters of a solar dryer;

– to substantiate the parametric series of solar dryers for the PPF conditions.

4. Materials and methods for the substantiation of design and technological parameters of a solar dryer

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

A basic requirement when operating the solar power plants is the maximum use of the potential of solar energy. With regard to solar dryers, this means that the decisive ones are the technical solutions, aimed at the provision of maximum current energy illuminance of the receiving surface and of the work of air collector under the mode of maximum thermal output. These measures include additional radiation exposure of the drying chamber.

For the rational use of energy generated during a minimum 48-hour drying cycle, there should be means for the alignment of daily irregularities of solar energy input. These primarily include sun-tracking devices or the option alternative to them – a flat mirror concentrator to enhance energy illuminance of the stationary air collector during mornings and evenings. To ensure the continuity of the process of drying at night or in the case of prolonged cloudiness, it is necessary to predict an intermediate reservation of excess thermal power.

Traditional air collectors, designed for heat supply, are divided into flat or tubular, which differ in the structural implementation of receiving surface and the configuration of heat exchanger. However, only for some of the simplest designs there is a possibility to obtain analytical dependences for the calculation of heat productivity or efficiency. In addition, these collectors are mainly used as heating elements of tunnel dryers, which have not been widely used at the farms because of cumbersome design and the need for mechanisms to move the fruits in a flow of air.

Household solar dryers with a small volume of drying chamber, where the sieves with the dried material are placed on the racks only in several tiers, are distinguished by a low gradient of temperature and humidity along the flow. Due to this, the drying of fruits happens practically simultaneously, and regular maintenance comes down to episodic rearrangement of sieves only. Such solar dryer usually operates under a cyclic mode, which during cloudless weather usually does not exceed two days. In addition, the rack design of block structure is much more compact, it is easy to transport and to prevent natural fluctuations in the flow of solar energy by using a flat mirror concentrator and a thermal battery. With small dimensions of the drying chamber and, accordingly, lesser heat capacity of structural elements, as well as a short path of heat carrier, side heat losses are significantly reduced, including through the enclosures at night. The compactness of solar dryer set-up components in turn reduces materials consumption.

We propose a design of the solar dryer that includes air collector with a flat mirror concentrator, vertical drying chamber and a bulk thermal battery for leveling the temperature mode of drying, developed at the Department of Energy of Lviv National Agrarian University (Ukraine) [9]. A design-technological schematic of the solar dryer is shown in Fig. 1.

Air collector the size of 1×1.5 m is installed at the angle of inclination to the horizon optimal for the season and is permanently oriented in the southern direction. The flat mirror concentrator rotates around the axis parallel to the long side of the air collector. By manually adjusting the angle of inclination in the range from 0 to 120°, reflected rays additionally illuminate the receiving surface of the air collector from morning until noon. After midday, the device of turning is reinstalled on the opposite side of the edge of collector.

The air collector is manufactured by the classic slit variant and consists of a wooden frame with the cross-section of beams 50×50 mm, a single-layer transparent cover and an adsorber – a copper sheet, coated with selective paint of thickness 4.5 μm. Air is blown through the slit between the back part of the copper lining of air collector and iron bottom made of roof profile, which is simultaneously a top cover of the thermal battery. The ledges of the profile are located across the air flow for the purpose of its turbulence with the aim of improving the efficiency of heat emission of the adsorber. There are slits cut on the slopes of the ledges to release a part of the heated air in the direction of rock filling of the thermal battery.

Air enters the drying chamber in two flows – a high-temperature one, directly from the opposite end of the air collector, and the low-temperature one – through the openings in the bottom and the thermal battery. An interrelation between direct and branched-off flows, and hence the temperature of heat carrier at the input of the drying chamber is regulated by the valve.

The drying chamber is in the form of a vertical shaft of square cross section with inner dimension of 1×1 m with grooves for the installation of three square sieves filled with fruits. The front wall and roof are made light-transparent for possible intensification of the process by radiation exposure. The side and rear walls of the drying chamber are thermally-insulated, and their inner surface is covered with aluminum light-reflecting foil. At night and during bad weather, to reduce the heat losses, translucent surfaces are covered by thermally-insulating plates made of plastic foam.

In the dark period of the day, the main source of thermal energy is the bulk thermal battery filled with natural river pebbles of average size 20 cm. The charging takes place during day, by the flow of heated air branched off from the primary one. The rate of charge and end temperature inside the thermal battery can be adjusted by changing the shut-off of main stream at the outlet of the air collector. With a fully closed valve, the supply of heat carrier to the drying chamber occurs only through a layer of heat accumulating material. The drive of the fan is powered by direct current of voltage 12 V, thus under the real conditions of fruit drying season a solar dryer can work in autonomous mode with power supplied by a solar cell.

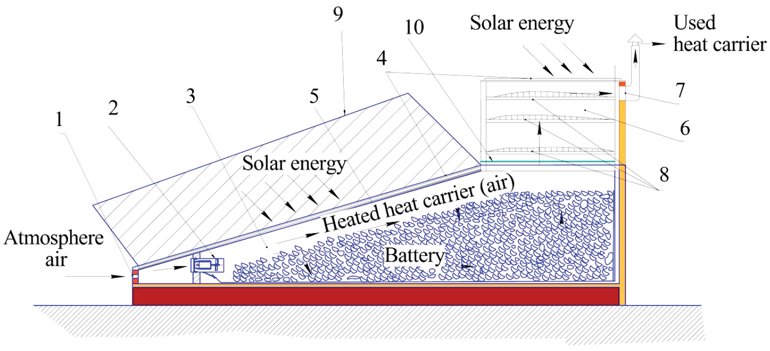

Fig. 1. Structural-technological schematic of solar dryer with thermal battery and flat mirror concentrator: 1 — input channel; 2 — fan; 3 — air duct; 4 — air collector; 5 —heat accumulating material (pebble-based); 6 — drying chamber; 7 — exhaust channel; 8 — sieves; 9 — flat mirror concentrator; 10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

4. 2. Calculation of the design and technological parameters of solar dryer

The main directions of improving technological and energy efficiency of drying process based on solar radiation, as well as the absence of such types of drying plants in the marketplace, necessitate designing a solar dryer with optimal parameters:

– of the area of receiving surface of the air collector and a flat mirror concentrator;

– of the mass of heat accumulating substance for the thermal battery;

– of the internal volume of the drying chamber.

When calculating a new standard size for a solar drying device, let us formulate the input data that include:

1. The type and productivity of solar dryer, which are predetermined by the volume of processing the products (fruits).
2. The starting and resulting moisture content of the fruits exposed to drying.
3. Characteristics of the sources of energy flows.
4. Thermal and technical parameters of drying agent and the environment.
5. The modes of drying.
6. Thermal and physical properties, heat and mass exchange characteristics of the dried material that is exposed to drying.
7. Characteristics of the sources of energy flows.
8. The speed of circulation of heat carrier.

The basis for the calculation of a solar dryer is the thermal (energy) budget – a comparison of purposefully used and consumed thermal energy in the process of drying.

The thermal (energy) balance of a solar dryer in one cycle of drying, kJ:

– during daytime

$$dQ_a+dQ_h=dQ_{hs}+dQ_p+dQ_e+dQ_{ac}+dQ_{chc}+\sum dQ_l; \qquad (1)$$

– at night

$$dQ_{tb}+dQ_h=dQ_{hs}+dQ_p+dQ_e+dQ_{chc}+\sum dQ_1, \qquad (2)$$

where dQ_a is the energy of solar radiation that is absorbed by the absorber, kJ; dQ_h is the energy, which a heated heat carrier gives to the drying chamber, kJ; dQ_{hs} is the energy spent on heating the sieves, kJ; dQ_p is the energy used for heating a product, kJ; dQ_e is the energy spent on the evaporation of moisture, kJ; dQ_{ac} is the amount of thermal energy that accumulates in one day in the thermal battery, kJ; dQ_{tb} is the energy removed from the thermal battery, kJ; dQ_{chc} is the energy of consumed heat carrier, released into the environment, kJ; $\sum dQ_l$ is the heat losses through the casing of a solar dryer, kJ.

The energy of solar radiation that is absorbed by the absorber is determined by formula

$$dQ_a = K_c \cdot K_{ref} \cdot A_a \cdot E \cdot S_a \cdot d\tau, \text{ kJ}, \qquad (3)$$

where K_c is the coefficient of contamination of the casing of air collector, $K_c=0.95$; K_{ref} is the coefficient of multiple reflection of solar radiation from absorber to light-penetrable material of air collector, $K_{ref}=0.23$; A_a is the mean absorbing capacity of absorber; E is the energy illuminance, W/m^2, S_a is the irradiated surface, m^2; $d\tau$ is the duration of drying, s.

The energy that a heated heat carrier gives to the drying chamber, over time $d\tau$, is determined by formula

$$dQ_h = S_{dc} \cdot v_{hc} \cdot \rho_{hc} \cdot c_{hc} \cdot \left(T_{hc2} - T_{hc1}\right) \cdot d\tau, \text{ kJ}, \quad (4)$$

where S_{dc} is the area of drying chamber, m^2; v_{hc} is the heat carrier velocity, m/s; ρ_{hc} is the heat carrier density, kg/m^3; c_{hc} is the specific heat capacity of heat carrier, kJ/(kg·°C); T_{hc1}, T_{hc2} are the heat carrier temperature, °C.

The energy used on heating the sieves is determined by formula

$$dQ_{hs} = h_l \cdot \rho_p \cdot \left(\sum S_s\right) \cdot c_p \cdot \left(T_{hc3} - T_{hc2}\right) \cdot d\tau, \text{ kJ}, \quad (5)$$

where h_l is the height of a layer of fruits in the sieves, mm; ρ_p is the product density, kg/m^3; S_s is the sieves area, m^2; c_p is the specific heat capacity of product, kJ/(kg·°C); T_{hc2}, T_{hc3} is the heat carrier temperature, °C.

The energy spent on heating a product is calculated as

$$dQ_p = \Delta m \cdot c_p \cdot \left(T_{f2} - T_{f1}\right) \cdot d\tau, \text{ kJ}, \quad (6)$$

where Δm is the mass of fruits during drying, kg; T_{f1}, T_{f2} is the fruit temperature, °C.

The energy used on the evaporation of moisture from the fruit material is calculated according to expression

$$dQ_e = J_t \cdot \left(\left(i_{ac} - i_{dr} - i_a\right) + q_{bm}\right) \cdot S_{dc} \cdot d\tau, \text{ kJ}, \quad (7)$$

where J_t is the density of moisture flow, kg/(m^2·s); i_a, i_{ac}, i_{dr} are, respectively, enthalpies of the flow of heat carrier along the path from the inlet to air collector to the outlet from drying chamber, kJ/kg; q_{bm} is the desorption of bound moisture in fruits, kJ/kg.

The energy that is removed from the thermal battery is determined as

$$dQ_{tb} = \pm V_{tb} \cdot \rho_{tb} \cdot c_{tb} \cdot \left(T_{tb2} - T_{tb1}\right) \cdot d\tau, \text{ kJ}, \quad (8)$$

where V_{tb} is the volume of thermal battery of solar dryer, m^3; ρ_{tb} is the heat accumulating material density, kg/m^3; c_{tb} is the specific heat capacity of heat accumulating material, kJ/(kg·°C); T_{tb1}, T_{tb2} is the temperature at the inlet to thermal battery and the outlet from it, °C.

The energy of used heat carrier, released into the environment, is calculated as

$$dQ_{chc} = \left(1 - K_{cir}\right) \cdot \rho_{hc} \cdot c_{hc} \cdot v_{hc} \cdot S_{dc} \cdot \left(T_{hc3} - T_a\right) \cdot d\tau, \text{ kJ}, \quad (9)$$

where K_{cir} is the coefficient of air circulation; v_{hc} is the heat carrier velocity, m/s; ρ_{hc} is the heat carrier density, kg/m^3; c_{hc} is the specific heat capacity of heat carrier, kJ/(kg·°C); S_{dc} is the area of drying chamber, m^2; T_{hc3} is the heat carrier temperature, °C; T_a is the ambient temperature, °C.

The heat losses through the casing of solar dryer are determined by formula

$$dQ_1 = S_{sd} \cdot K \cdot \left(T_{dc} - T_a\right) \cdot d\tau, \text{ kJ}, \quad (10)$$

where S_{sd} is the solar dryer area, m^2; K is the coefficient of heat transfer through the casing of solar dryer, W/(m^2·°C); T_a is the ambient temperature, °C; T_{dc} is the heat carrier temperature in drying chamber over a period of drying, °C.

The basic structural parameters of solar dryer that define the technological parameters (heat productivity of air collector Q, thermal power of solar dryer N_{sd}, and opening angle of flat mirror concentrator (dihedral solar concentrator), α), are:

- the area of receiving surface of the air collector S_a;
- the angle of inclination of air collector to the horizon β;
- the volume of thermal battery V_{tb};
- inner width W_{dc} and depth D_{dc} of the drying chamber.

The area of receiving surface of the air collector S_a is determined

$$S_a \geq \frac{Q_{dr} / 2}{3600 \cdot \eta \cdot H_\beta}, \text{ m}^2, \quad (11)$$

where Q_{dr} is the daily need in thermal energy for drying the fruits, kJ; H_β is the incoming solar energy, kW·h/m^2; η is the efficiency of collector.

Heat productivity of the air collector Q is calculated by formula

$$Q = S_a \cdot F_R \times$$
$$\times \left[\left(k(\tau) \cdot R_\beta \cdot E^{max} \cos \pi \frac{\tau}{\tau_c}\right) \cdot (\alpha \cdot \tau) - U_L \cdot \left(T_{a1} - T_a\right)\right], \text{ W}, \quad (12)$$

where F_R is the coefficient of heat radiation from the air collector; k is the gain factor of the solar energy flow; R_β is the coefficient of average monthly incoming solar energy; E^{max} is the maximum energy illuminance of horizontal surface of air collector, W/m^2; τ_c is the duration of incoming solar energy, s; τ is the duration of 24 hours, s; α, τ are the coefficients of absorption and transmittance of solar radiation; U_L is the coefficient of thermal losses of the air collector, W/(m^2·°C); T_a, T_{a1} is the air temperature at the inlet to the collector and the outlet from it, °C.

The volume of thermal battery of solar dryer V_{tb} is determined by formula

$$V_{tb} = \frac{Q_a \cdot K_a}{c_{Vtb} \cdot \Delta T_{tb}}, \text{ m}^3, \quad (13)$$

where Q_{ac} is the amount of thermal energy that accumulates in one day in the battery, W·s; K_a is the coefficient of mean daily accumulation of thermal energy in the battery; c_{Vtb} is the volumetric heat capacity of the battery, W·s/(m^3·°C); ΔT_{tb} is the change in temperature of solid particles (pebble) during the supply and removal of heat $\Delta T_{tb}=(T_{tb2}-T_{tb1})$, °C.

Internal width W_{dc} of the drying chamber is determined by formula

$$W_{dc} = n_r \cdot b_s + \left(n_r + 1\right) \cdot \left(b_r + b_{fr}\right) + b_{bk}, \text{ m}, \quad (14)$$

where b_r is the width of racks, m; b_{fr} is the width of frames of the sieves, m; b_{bk} is the width of heat accumulating material, m; n_r is the number of rows by the drying chamber width, pcs.; b_s is the side of the sieve, m. The sieves are selected of standard size 785×785×23 mm and the distance from the upper sieve to the ceiling is equal to the thickness of the layer of insulation.

Inner depth D_{dc} of the drying chamber is determined by formula

$$D_{dc}=n_{rd}\cdot b_p+\left(n_{rd}+1\right)\cdot\left(b_r+b_{fr}\right)+b_{bk},\ \text{m}, \tag{15}$$

where n_{rd} is the number of rows into the depth of the drying chamber, pcs. Thermal power of the solar dryer N_{sd} is determined by formula

$$N_{sd}=E^{max}\cdot S_{sd}\cdot k\cdot k_{ac},\ \text{W}, \tag{16}$$

where S_{sd} is the solar dryer area, m^2; k is the coefficient of clarity of the atmosphere; k_{ac} is the coefficient that takes into account the losses caused by heat exchange of the air collector.

The angle of inclination of the air collector to horizon β is selected by the mean annual angle of incoming solar energy on a slanting surface for the conditions of the city of Lviv (Ukraine) – $\beta=40.4^{\circ}$.

The flat mirror concentrator is set near the receiving surface of air collector at angle α to the horizon (Fig. 2) that changes relative to the incoming solar rays.

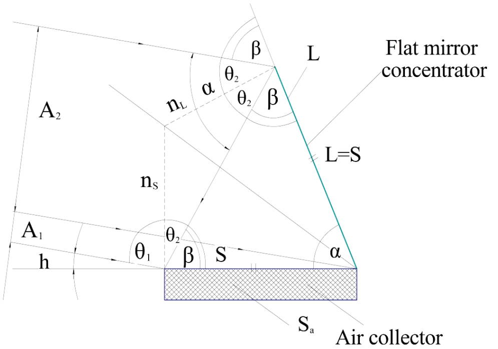

Fig. 2. Passage of rays in the mirror concentrator: L and S – width of the mirror and the collector, respectively; α – opening angle of the concentrator; A_1 and A_2 – cross section of the input direct and reflected flows; n_s and n_L – normals to planes S and L; θ_1 and θ_2 – angles of falling rays on the collector and the mirror; h and β – ray sliding and ray reflection angles

Area of the mirror concentrator L is accepted equal to the area of receiving surface of air collector S_a. Planes L and S_a form between them a dihedral solar concentrator.

Solar energy reaches the solar dryer with different intensity. The temperature of heat carrier and fruits in a solar dryer changes within 24 hours depending on the intensity of incoming solar radiation and meteorological conditions. In this regard, those patterns that describe the drying process must reproduce this periodicity in a mathematical model for the technological process of drying fruits in a solar dryer.

For selecting the type of fan, of key importance is the capacity of fan N, which is calculated by formula

$$N=\frac{k\cdot U\cdot\Delta m\cdot\Delta p_i}{3600\cdot 102\cdot\gamma\cdot\eta_d\cdot\eta_f},\ \text{kW}, \tag{17}$$

where U is the air consumption per 1 kg of evaporated moisture, m^3/kg; Δm is the amount of removed moisture, kg/s; k is the reserve ratio: for the fan connected to the electric motor by a rigid coupling – 1.2; Δp_i is the impedance of solar dryer, Pa; γ is the specific weight of displaced air, kg/m^3; η_d, η_f is the efficiency of the drive and the fan.

Material balance of a solar dryer for one cycle of drying is determined by

$$G_2=G_1\cdot\frac{100-W_1}{100-W_2}, \tag{19}$$

where G_1, G_2 are the productivity of the dryer by humid and dried material, respectively, kg/s; W_1, W_2 is the humidity of material at the inlet to the drying chamber and the outlet from it, %.

One-time download of fruit raw material into the drying chamber G_d is determined by formula

$$G_d=G_1\cdot\tau_d,\ \text{kg}, \tag{20}$$

where τ_d is the duration of drying, s.

Energy efficiency of a solar dryer is based on determining the energy efficiency of the solar dryer – it is the ratio of the amount of heat, purposefully used for the evaporation of moisture from fruits, to the amount of heat that is removed from the thermal battery, and the amount of used energy from solar radiation

$$\eta_{sd}=\frac{Q_e+Q_{chc}}{Q_h+Q_a}, \tag{21}$$

where Q_e is the heat spent for the evaporation of moisture, kJ; Q_{chc} is the heat that is removed with the used heat carrier from the drying chamber, kJ; Q_h is the energy (heat) that a heated heat carrier gives to the drying chamber, kJ; Q_a is the energy of solar radiation that is absorbed by the absorber, kJ.

The analytic equations obtained allow us to calculate the design and technological parameters of solar dryer.

4. 3. A method for the substantiation of parametric series of solar dryers

In the course of substantiation of structural parameters of the solar dryer that uses a flat mirror concentrator and a thermal battery, the input technical specifications include:

1) mass of dried material in the drying chamber;
2) surface area of the air collector;
3) area of the flat mirror concentrator;
4) mass of the thermal battery;
5) inside volume of the drying chamber of a solar dryer.

The selection of numerical values of the mass of material that is exposed to drying in the chamber is conducted in accordance with the established series of prevailing numbers that are accepted by the results of calculation of geometric progression [10].

A geometric progression is the consecutive series of numbers, which is determined by formula [10]

$$U_n=a\cdot Q^{n-1}, \tag{22}$$

where a is the first member of the series; Q is the denominator of progression; n is the number of member of the progression, n=1, 2, 3, 4, 5.

It is necessary to select from a set of geometric series those that will prevail when selecting the numerical values of the mass of material that is exposed to drying in the drying chamber. The numerical values of the mass of dried material will enable us to calculate the design parameters of solar dryers. These series include a geometric progression with the denominator that is determined by formula

$$Q=\sqrt[R]{10}, \tag{23}$$

where R is the conditional designation of series, by using DSTU 8032 [10] we establish a basic parametric range: R=10, which satisfies the requirements when choosing a range of numeric values for the mass of dried material in the drying chamber; Q is the denominator of the progression,

$$Q = \sqrt[10]{10} = 1{,}25.$$

The denominator of progression Q=1.25, the first member of the series after rounding a=1. We obtain a range of numerical values for the mass of material that is exposed to drying in the drying chamber: 5.5; 6.3; 8; 10; 12.5.

5. Results of the substantiation of design and technological parameters of solar dryer

Based on the devised method for the calculation, given in chapter 4.2, we determined numerical values for the main parameters of a solar dryer:

- air collector area;
- mass of the thermal battery;
- inside volume of the drying chamber, flat mirror concentrator area.

The results obtained are summarized in Table 1.

Table 1

Parametric series of solar dryers

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

The research results allowed us to obtain optimal parametric series of five mini-solar dryers, which enables us to evaluate and substantiate the design and technological parameters: mass of thermal battery, area of receiving surface of air collector, inside volume of drying chamber for the PPF conditions.

In the process of drying physical parameters of the environment changed in the range: air temperature T_a – 16...30 °C; air relative humidity ϕ_a – 26...86.8 %; energy illuminance E – 100...800 W/m^2; angle of incidence of direct solar radiation θ_1 and θ_2 – from 20° to 60°. Thermal and technical parameters of the heat carrier (air), supplied to the drying chamber, were as follows: temperature in the daytime (from 8^{00} to 21^{00}) T_{hc} – 20...60 °C, at night (from 22^{00} to 7^{00}) T_{hc} – 30...20 °C; rate of circulation v_{hc} – 1...3 m/s; relative humidity ϕ_{hc} – 9.8...86 %. Heat capacity of the air collector Q was from 117 to 480 W for the area of absorbing surface S_a=1.5 m^2. Temperature of the battery T_b in the daytime (from 8^{00} to 21^{00}) was 30.5...45.6 °C, at night (from 22^{00} to 7^{00}) – 45.6...20.9 °C [2].

Energy efficiency of the solar dryer reached η_{sd}=53 %, and current thermal power of the solar dryer N_{sd} was 117...1429.3 W.

Thus, based on the theoretical and experimental research, we substantiated optimal parameters of solar dryer and proposed a parametric series of five mini-solar dryers for the PPF conditions.

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

Based on the analysis of existing technical means of fruit drying, in particular household fruits and vegetables dryers of periodic action, it was established that their application is unprofitable when processing small volumes of freshly picked fruits under conditions of PPF [11]. This is primarily due to large capital investment and high energy consumption. That is why the drying of small amounts of fruits is expedient to carry out using the solar dryer that provides energy-efficient mode of drying.

Based on the performed research, we proposed engineering methods for calculating the basic elements and devised a design of the solar dryer, which is protected by the copyright patent [9]. We selected a thermal battery based on pebble for the accumulation of excess heat during night time and a flat mirror concentrator to enhance the slanting flows of morning and evening solar radiation that makes it possible to increase heat productivity of the collector by 2 times in order to solve the problem of using non-conventional thermal energy sources for drying the fruits.

We developed and scientifically substantiated methodological recommendations concerning the construction and prediction of parametric series of solar dryers by the numerical values of mass of the dried material. Authors obtained a parametric series of five mini-solar dryers and substantiated their optimal design parameters: area of air collector and mirror concentrator; mass of thermal battery; inside volume of the drying chamber.

The research conducted in the present work requires further studies to improve effectiveness of the technological process of fruit drying based on the substantiation of operating modes and energy analysis of the effectiveness of solar dryer, which provides for a reduction in energy costs due to solar energy.

According to the results obtained in the present work, it was revealed that in order to ensure the productivity of solar dryer at 1.085...1.87 kg of dry product per hour, its parameters should be as follows:

- area of the receiving surface of air collector S_a=1,5 m^2;
- mass of the thermal battery m_{tb}=50 kg;
- area of the flat mirror concentrator L=1.5 m^2;
- inside volume of the drying chamber V_{dc}=0,5 m^3.

Thus, the solar dryer proposed is not inferior by technical characteristics to existing solar dryers and traditional technical means of drying [2, 11].

However, this article does not describe a method for calculating the mass of thermal battery and inside volume of drying chamber, which would be very relevant for the formulation of uniform methodology for the substantiation of design and technological parameters of solar dryer.

Thus, the use of solar dryers with thermal battery and flat mirror concentrator for drying the fruits is appropriate and effective under the PPF conditions, which will increase the volume of high-quality dried products at minimal energy consumption due to solar energy.

7. Conclusions

1. A solar dryer design with a thermal battery and a flat mirror concentrator is developed and its technological and structural scheme is substantiated. It was established

that the heat productivity of air collector Q=117...480 W is significantly affected by energy illuminance E^{max}, enhanced by a mirror concentrator, which in the morning period (from 7^{00} to 10^{00}) is from 456 to 965 W/m^2 and in the evening period (from 17^{00} to 20^{00}) is from 734 to 223 W/m^2, and the application of thermal battery makes it possible to increase the energy efficiency of solar dryer (η_{sd}=53 %) that allows obtaining maximum current thermal power of the solar dryer (N_{sd}=117...1429.3 W).

2. Analytical equations were obtained that allowed us to substantiate the design and technological parameters of a solar dryer. In particular, it was determined that to ensure the solar dryer productivity of 1.085...1.87 kg/h of dry products, its parameters should be as follows: area of the receiving surface of air collector S_a=1.5 m^2, mass of the thermal battery m_{tb}=50 kg, area of the flat mirror concentrator L=1.5 m^2, inside volume of the drying chamber V_{dc}=0,5 m^3.

3. 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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