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EXERGY ANALYSIS OF THE OPERATION OF A SOLAR DRYER

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Описано методику проведення ексергетичного аналізу роботи геліосушарки із застосовуванням теплового акумулятора та плоского дзеркального концентратора. Обґрунтовано надходження ексергії та тепловтрати у процесі сушіння фруктів в геліосушарці за рахунок використання сонячної енергії. Застосування в геліосушарці теплового акумулятора та плоского дзеркального концентратора дозволяє підвищити ексергетичну ефективність технологічного процесу сушіння на 36,8 %

Ключові слова: ексергетичний баланс, геліосушарка, сонячна енергія, тепломасоперенесення, інтенсифікація, конвективне сушіння

Описана методика выполнения эксергетического анализа работы гелиосушилки с применением теплового аккумулятора и плоского зеркального концентратора. Обоснованно поступления эксергии и тепловые потери в процессе сушки фруктов в гелиосушилке за счет использования солнечной энергии. Применение в гелиосушилке теплового аккумулятора и плоского зеркального концентратора позволяет повысить эксергетическою эффективность технологического процесса сушки на 36,8 %

Ключевые слова: эксергетический баланс, гелиосушилка, солнечная энергия, тепломассоперенос, интенсификация, конвективная сушка

1. Introduction

An important task in the creation of a new drying technology and production of modern drying equipment at present is energy saving. Therefore, we have not only to supplement drying assemblies, technological processes, and technical and energy characteristics of plants, but also to combine them into one unit.

In present processes and technologies related to the use of solar energy, the main role belongs to a direct assessment of energy perfection of a plant based on the result of thermodynamic analysis. The main method of thermodynamic analysis for a solar dryer and a power unit of a plant (a mirror concentrator, an air collector, a thermal battery accumulator) is an energy method based on the law of conservation of energy. It makes it possible to estimate full and relative losses of heat energy during drying and during a process of operation of a solar dryer. According to requirements of the indicated method, it is necessary to equate all types of energy, such as solar energy and heat energy. However, it is not entirely correct from positions of the first and the second laws of thermodynamics. In fact, any kind of energy, in particular solar energy, can completely turn into heat, and inevitable losses accompany the reverse process. Here, the main idea is to introduce an additional indicator – exergy, along with the general conception of energy. Thus, the execution of an exergy analysis of operation of a solar dryer makes it possible to investigate the use of solar energy in the process of fruit drying. In particular, it makes it possible to distinguish frequent errors that ignore a qualitative aspect of the transformations of solar energy into heat, which occur during calculations.

The peculiarity of a solar dryer is that the input and output substances, materials and parameters under investigation, are air and fruit. The input and output parameters of air such as temperature, humidity, moisture content, as well as specific enthalpy and other thermophysical parameters accept different values during operation of a solar dryer. The external environment for a solar dryer is the external air. Its parameters may vary depending on a place and time, as the main components of the environment are a dry part and water vapor contained in the air.

Resolving the issue of resource saving becomes more complicated because fruit have high variability of thermophysical, physical-mechanical, structural-mechanical and chemical properties. Therefore, substantiation of energy balances for various characteristics of a drying process in a solar dryer, taking into account exergy, is an important task, which lays the basis for improvement of the technology of fruit drying.

2. Literature review and problem statement

Underlying the exergy method of thermodynamic analysis of drying plants, which include a solar dryer, is the use of the concept of exergy. Authors in paper [1] substantiate the use of an exergy method for analysis of a process of a solar dryer operation. They consider the exergy method as a universal method for thermodynamic study of a process of plant operation, fruit drying in it and transformation of solar energy into heat. All actual processes are irreversible and irreversibility is a reason for reducing of perfection of a process in each case. This happens not due to a loss of energy, but because of a decrease in quality, as energy does not disappear in irreversible processes, but it devalues. Consequently, every irreversible phenomenon is a cause of irreversible energy devaluation. However, it was not possible to establish individual losses of exergy during the exergy analysis of the process of solar dryer operation in a work [1]. In particular, losses of exergy of a heat-transfer agent in each element of a power unit of a plant. Therefore, this does not make it possible to substantiate an increase in the efficiency of operation of each element of a unit as well as of a plant as a whole because of the lack of calculations of exergy of input and output flows of a heat-transfer agent.

In paper [2], authors developed an exergy method for analysis of a process of solar dryer operation. The basic idea of the method is to introduce an additional parameter – exergy, along with the general fundamental concept of energy. This allows them to take into account the fact that energy, depending on external conditions, can have different value for practical use. In particular, calculations of energy balances and various technical characteristics of a solar dryer, taking into account exergy, make it possible to carry out a simple calculation-quantitative experiment and to analyze operation of a plant. The developed method helps to avoid frequent mistakes that occur during calculations and relate to ignoring a qualitative aspect of transformation of solar energy into heat. However, the proposed method does not take into account component costs of exergy to overcome aerodynamic resistance in an air collector and a charge-discharge process in a thermal battery.

Paper [3] substantiates technological parameters of a tunnel type solar dryer for drying of fruits and vegetables. In particular, it proposes engineering scientific and methodical bases for substantiation of a thermal (energy) balance of a plant based on the method of calculation of infrared dryers. However, authors neglect the calculation of an exergy balance of a solar dryer for one cycle of drying. They connect it with a change in physical parameters of the environment. The proposed method cannot be used because it lacks specification (estimation) of components of an exergy balance under conditions of combined exposure of sun rays, a thermal battery, and a flat mirror concentrator.

Scientists developed a design for solar dryers corresponding to the concept of an active solar power plant and proposed a method for estimation of the energy efficiency of drying units in work [4]. According to the described method, one of the most important indicators of operation efficiency of a plant is estimation of energy losses. Such an estimate makes it possible to determine heat, hydraulic and other losses, in contrast to the classical thermodynamic analysis of heat flows, which does not take into account certain types of losses. In particular, the loss of exergy associated with overcoming aerodynamic resistance in an air duct of an air collector. However, the procedure does not take into consideration the energy of bound moisture and entropy of a product in terms of 1 kg of removed moisture during the calculation of the exergy needed to heat material (exergy of a product).

Authors of work [5] developed an engineering procedure for the calculation of energy and exergy balance for a drum grain dryer. But it does not take into account enthalpies and entropies of a flow at ambient temperature during the calculation of the exergy of evaporation of moisture from dried material. This does not make it possible to calculate the amount of energy consumed and discharged by a power unit of a plant, as well as a quality of energy, that is, its ability to be transformed into useful operation.

In paper [6], author proposed to use a mine-type solar dryer with a thermal battery based on alumina, corundum and zircon and a parabolic concentrator. There is analysis of energy efficiency of a use of a solar dryer in the field of convective fruit drying in comparison with traditional schemes of the drying process realization. The paper develops scientific and methodical principles of thermal and exergy balance of a plant. It takes the energy consumption for evaporation of 1 kg of moisture as a criterion of energy efficiency and introduces an additional indicator of exergy – $E/E_{tot}\cdot 100\ \%$. However, the method does not consider velocity of a moisture content of dried material in a zone of heat-transfer agent action under conditions of the diffusion process of transfer of moisture in dried material.

In work [7], authors improved the method and procedure for the calculation of an exergy balance of a drying chamber for hybrid solar dryer. However, it does not take into account an area of a collector when calculating the exergy of the arrival of solar radiation on a receiver surface of a collector. Therefore, this does not make it possible to determine how much solar energy solar dryer took in one cycle of drying and turned into heat.

Paper [8] developed the design of a solar dryer, which corresponds to the concept of an active solar power plant and a method for evaluation of all types of heat losses during fruit drying. A solar dryer heat-transfer agent moves between the bottom of an air collector and the upper layer of a heat accumulator in the aforementioned design. Thus, the authors considered only the exergy of a heat-transfer agent flow at the outlet from a drying chamber in evaluation of all types of heat loss in a solar dryer. According to the described procedure, we should calculate the energy of a flow of a heat-transfer agent by the exergy of a direct flow at the outlet from a drying chamber only. Therefore, such an estimate will always be understated, since part of the exergy revenues is spent on heating of the upper layer of a thermal battery. Therefore, the described methodology is very general. Because energy costs of heat transfer in a solar dryer should be evaluated with a change in enthalpy and a moisture content along the flow path of a heat-transfer agent from the inlet to a collector to the outlet from a drying chamber.

Therefore, we should note that the use of generally accepted methods for evaluation of the thermodynamic efficiency of drying plants based on determination of the efficiency is not always effective. Often, in addition to the thermodynamic efficiency of a plant, it is necessary to take into account the cost of the produced thermal energy, which influences a choice of a particular power plant for a particular implementation object. The above-mentioned circumstances point to the validity of the use of solar dryers, the widespread introduction of which is due to the development of new technologies in the energy sector, as they have higher energy and economic efficiency.

Thus, the exergy method is a universal method for the thermodynamic study of various energy conversion processes in a solar dryer. As already mentioned, all real active processes are irreversible, and in each case, irreversibility is the reason for reducing the perfection of a process. This is not due to the loss of energy, but because of a decrease in quality, because energy does not disappear in irreversible processes, it devalues. Consequently, every irreversible phenomenon is a cause of irreversible energy devaluation. Performing an exergy analysis for a solar dryer makes possible to determine a loss of exergy in each element and to increase the efficiency of both – operation of each element and a plant in general. This is the main purpose of the exergy method for the analysis of a process of operation of a solar dryer.

3. The aim and objectives of the study

The aim of present study is to substantiate the exergy efficiency of a use of a solar dryer with a thermal battery and a flat mirror concentrator for individual farms, which will reduce a cost of energy due to solar energy.

It was necessary to perform the following tasks to achieve the objective:

– improvement of the method of carrying out an exergy analysis of solar dryer operation in order to perform calculation and quantitative experiments during evaluation of exergy and heat losses in the process of fruit drying;

– estimation of exergy and a heat loss in a solar dryer with a thermal battery and a flat mirror concentrator during fruit drying.

4. Materials and methods of exergy analysis of a solar dryer operation

People widely use solar dryers for fruit drying in the agro-industrial complex, in particular at private farms. For example, in western Polissya zone, it is possible to fully apply a solar dryer [9]. Specifically, at the Lviv National Agrarian University (Lviv, Ukraine), at the Department of Energy, a solar dryer was developed, which is an active system of solar energy use. The solar dryer has the construction form of an indivisible power unit, which includes an air collector, a heat accumulator, a mirror concentrator, and a drying chamber. Paper [9] gives detailed description of justification of structural and technological parameters and a structure of the solar dryer. Work [10] presents a full description of estimation of economic efficiency of the use of the proposed design of a solar dryer for individual farms and a cost of resulting products in comparison with traditional and innovative methods of fruit drying [10].

Fig. 1 shows the functional-parametric schematic of a solar dryer.

Let us consider the principle of a solar dryer operation. The air from the environment enters air collector 1 at a certain speed, it is heated between elements of bulk thermal battery 2 and enters drying chamber 3. Drying chamber 3 contains dried fruit raw material 4. The used heat-transfer agent is removed by natural convection to the environment [10]. To increase a flow of solar energy to a receiving surface of the air collector on both sides – the western (in the morning) and the eastern (in the evening) – there is a mirror concentrator. This makes it possible to increase energy performance of a solar dryer during morning and evening periods.

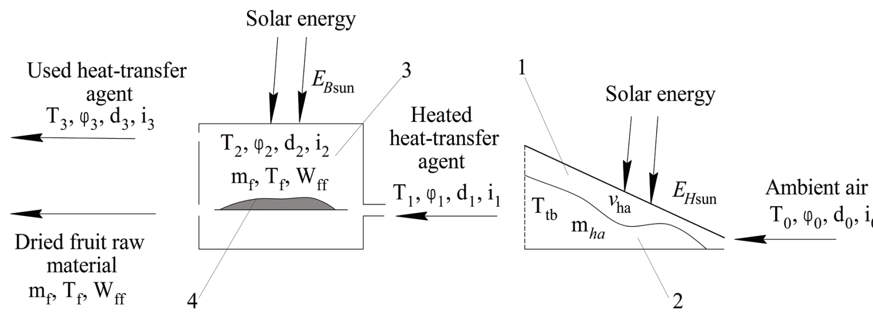

Fig. 1. Functional-parametric scheme of a solar dryer: 1 – air collector; 2 – thermal battery; 3 – drying chamber; 4 – fruit raw material; $T_{0...n}$ – temperature of a heat-transfer agent, K; $\varphi_{0...n}$ – relative humidity of a heat-transfer agent, %; $d_{0...n}$ – moisture content of a heat-transfer agent, kg/kg; $i_{0...n}$ – enthalpy of a heat-transfer agent, kJ/kg·moist.; v_{ha} – velocity of a heat-transfer agent, m/s; E_{Bsun}, E_{Hsun} – energy illumination, W/m^2; m_{ha} – mass of heat-accumulating material, kg; m_f – weight of fruit, kg; W_{ff} – a final moisture content of fruit, kg; T_{tb} – temperature of a thermal battery, K; T_f – temperature of fruit, K

The developed design of a solar dryer is consistent with the concept of an active solar power plant. At the same time, a mirror concentrator, an air collector, and a thermal battery combined in one energy unit do not correspond to the classical models of solar thermal plants constructively. There is no theoretically established correlation between energy parameters for the developed plant. For example, it is impossible to test an air collector and a mirror concentrator according to the standard method independently or to calculate energy parameters of a bulk thermal battery or to investigate operation of a plant. Therefore, we establish parameters for evaluation of efficiency of solutions during calculation-quantitative experiments based on the exergy analysis of a solar dryer operation [11]. In particular, we estimate rational methods of the use and storage of thermal energy on the basis of an exergy balance of a solar dryer [12].

The equation of the exergy balance of a solar dryer is as follows:

1) for daytime operating conditions (solar illumination is active):

$$E_{ha}^{/} + E_{sun} = E_{pr}^{/} + E_{pr}^{//} + E_{ha}^{//} + E_{moist.} + \Delta E_{ard} + \Delta E_{envir.} + \Delta E_{leak.} + \Delta E_{mix} - E_{tb} + \Delta E_{ext.} + \Delta E_{ins.}, \quad (1)$$

2) for operating conditions at night (no sunlight):

$$E_{ha}^{/} + E_{tb} = E_{pr}^{/} + E_{pr}^{//} + E_{ha}^{//} + E_{moist.} + \Delta E_{ard} + \Delta E_{envir.} + \Delta E_{leak.} + \Delta E_{mix} + \Delta E_{ext.} + \Delta E_{ins.}, \quad (2)$$

where $E_{ha}^{/}$, $E_{ha}^{//}$ are the exergies of a heat-transfer agent at the inlet and outlet from a solar dryer, respectively, kJ; E_{sun} is the exergy of solar radiation, kJ; $E_{pr}^{/}$, $E_{pr}^{//}$ are the exergies of a product at the inlet and outlet of sieves, kJ; E_{tb} is the exergy of a thermal battery, kJ; $E_{moist.}$ is the exergy of removed moisture from a drying chamber, kJ; ΔE_{ard} is the loss of exergy to overcome aerodynamic resistance in an air collector, kJ; $\Delta E_{envir.}$ is the loss of exergy into the environment through walls of a solar dryer, kJ; $\Delta E_{leak.}$ is the loss of exergy due to leakage of a heat-transfer agent, kJ; ΔE_{mix} is the loss of exergy due to irreversibility of processes of mixing evaporating moisture with a heat-transfer agent, kJ; $\Delta E_{ext.}$ is the loss of exergy due to irreversible external heat transfer, kJ; $\Delta E_{ins.}$ is the loss of exergy due to irreversibility of heat and mass transfer within a product, kJ.

We accept the equilibrium moisture content of a product at the temperature T_{envir} and relative humidity φ_{envir} of the ambient air as a reference point for calculation in accordance with the content of the exergy function. Therefore, when calculating the exergy of a moist product, it is expedient to use isotherms of sorption for a number of fixed environmental parameters.

We note that further we will consider enthalpy, entropy, and exergy as specific functions attributed to one kilogram of dry matter.

Fig. 2 shows the thermodynamic system of a solar dryer.

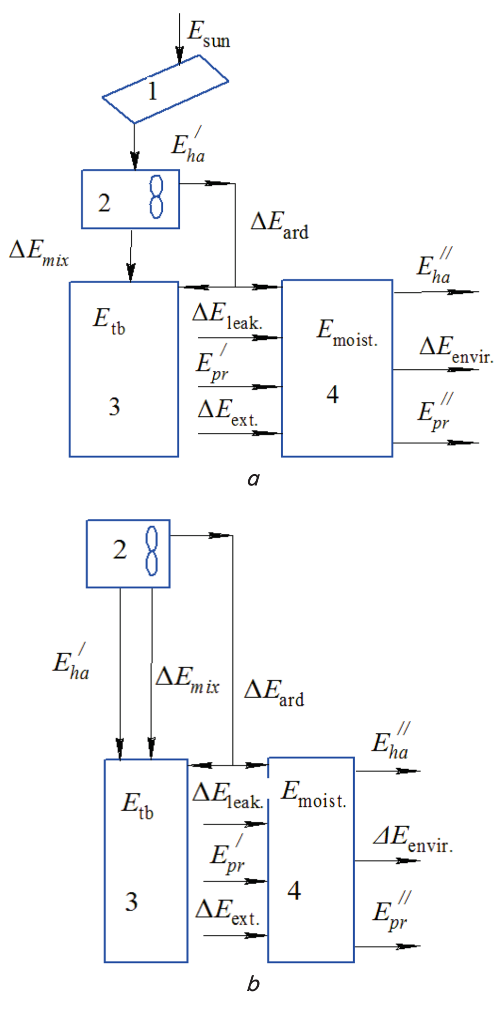

Fig. 2. Thermodynamic system of a solar dryer:
1 — an air collector with a mirror concentrator; 2 — an air duct with fan; 3 — a thermal battery; 4 — a drying chamber with exhaust duct; *a* — daytime; *b* — night time

Product exergy at the sieve inlet:

$$E_{pr}^{/} = G_1 \cdot \tau \cdot \left[i_{pr}^{/} - i_{pr}^{//} - T_{envir} \cdot \left(S_{pr}^{/} - S_{pr}^{//} \right) \right], \tag{2}$$

where G_1 is the productivity of a solar dryer for moist material, kg/s; $i_{pr}^{/}$, $i_{pr}^{//}$ are the enthalpies of a dry and a wet product, respectively, in a state of equilibrium with the environment, kJ/kg· moist.; S_{pr} is the entropy of dried material for 1 kilogram of dry matter, kJ/(kg·K); T_{envir} is ambient temperature, K; τ is the drying time, s.

We can give enthalpy and entropy of moist material classified as one kilogram of dry matter as follows:

$$i_{pr} = i_{dr.mat.} + i_{moist.} + r, \tag{3}$$

hence

$$i_{dr.mat.} = c_{dr.mat.} \cdot (T_{f2} - T_{f1}), \tag{4}$$

$$i_{moist.} = c_{moist.} \cdot U \cdot (T_{f2} - T_{f1}), \tag{5}$$

where $i_{pr.}$ is the enthalpy of a dry product in a state of equilibrium with a heat-transfer agent, kJ/kg·moist.; $i_{dr.mat.}$, $i_{moist.}$ are the enthalpies of a dry and a wet product in a state of equilibrium with the environment, respectively, kJ/kg moist.; r is the specific heat of steam evaporation of moisture, kJ/kg moist.; $c_{dr.mat.}$ is the specific heat of a dry product, kJ/(kg·K); $c_{moist.}$ is the specific heat capacity of a wet product, kJ/(kg·K); T_{f1}, T_{f2} are temperatures of fruit, K; U is the moisture content of material to be dried, kg moist./kg of dry matter.

$$S_{pr} = S_{dt.mat.} + U \cdot S_{moist.}; \tag{6}$$

$$S_{eq.} = S_{dt.mat.} + U_{eq.} \cdot S_{moist.}, \tag{7}$$

where S_{pr} is the entropy of dried material per kilogram of dry matter, kJ/(kg·K); $S_{dr.mat.}$, $S_{moist.}$ are the entropies of a dry and a wet product, respectively, kJ/(kg·K); $U_{eq.}$ is the equilibrium moisture content of material to be dried, kg moist./kg of dry matter.

Using dependences (1)–(7), we write the equation that determines heat exergy usefully used to reduce a moisture content of fruit from U to $U_{eq.}$ (exergy of a product at the outlet from a sieve):

$$E_{pr}^{//} = G_2 \cdot \tau \cdot \begin{bmatrix} \left(i_{dr.mat.} + i_{moist.} + q_{bound} \right) - \\ - \left(i_{dr.mat.eq.} + i_{moist.} + q_{bound} \right) - \\ - T_{envir} \begin{bmatrix} \left(S_{dr.mat.} + U \cdot S_{moist.} \right) - \\ - \left(S_{dr.mat.} + U_{eq.} \cdot S_{moist.} \right) \end{bmatrix} \end{bmatrix}, \tag{8}$$

where G_2 is the productivity of a solar dryer with a drying material, kg/s; q_{bound} is the energy of bound moisture in fruit, kJ/kg; U, $U_{eq.}$ is the moisture content and an equilibrium moisture content of dried material, kg moist./kg dr. mat.; $S_{dr.mat.}$, $S_{moist.}$ are the entropies of a dry and a wet product, respectively, kJ/(kg·K).

The energy of bound moisture in fruit

$$q_{bound} = 4200 \cdot \frac{U_{st} - U_{fin}}{2} + c_{ha} \cdot T_{ha2} +$$

$$+ \left(c_v \cdot T_{ha2} + r \right) \cdot d_2 + \left(T_f(\tau) \cdot S_{pr.} \right) \text{ kJ/kg},$$

where U_{st}, U_{fin} are the initial and a final moisture content of fruit, kg moist./kg dr. mat.); c_v, c_{ha} are specific heat of water vapor and a heat-transfer agent, respectively, kJ/(kg·K); r is the specific heat of steam evaporation of moisture, kJ/kg; T_{ha2} is the heat-transfer agent temperature, K; d_2 is the moisture content of a heat-transfer agent over dried material, g/kg; $S_{pr.}$ is the entropy of dried material per one kilogram of removed moisture, kJ/(kg·K).

Exergy of evaporation of moisture, which is associated with heating of atmospheric air to the temperature of a heat-transfer agent located in an air duct and a drying chamber:

$$E_{moist.} = \Delta m \cdot \tau \cdot \begin{bmatrix} (i_{ha1} - i_{ha2} - i_{ha3} - i_{envir}) - \\ - T_{envir} \cdot (S_{ha_1} + S_{ha_2} + S_{ha_3}) - S_{envir}) \end{bmatrix}, \quad (9)$$

where Δm is the amount of removed moisture, kg/s; i_{ha} and S_{ha} are the enthalpy and entropy of a heat-transfer agent flow with its actual parameters, respectively, kJ/kg and kJ/(kg·K); i_{envir} and S_{envir} are the enthalpy and entropy of a flow at ambient temperature, respectively, kJ/kg and kJ/(kg·K).

Heat-transfer agent exergy:

$$E_{ha}^{/} = L \cdot \tau \cdot \begin{bmatrix} c_{dr.ha.} \cdot \left(T_{ha2} - T_{ha1} - T_{ha1} \cdot \ln \frac{T_{ha2}}{T_{ha1}} \right) + \\ + T_{envir} \cdot \left((R + d_0 \cdot R_v) \cdot \ln \frac{P_2 - \varphi_2 \cdot P_{sat} \cdot T_{ha2}}{P_1 - \varphi_1 \cdot P_{sat} \cdot T_{ha1}} + d_1 \cdot R_v \cdot \ln \frac{d}{d_0} \right) + \\ + d_2 \cdot \left[i_{P_2} - i_{P_1} - T_{ha1} \cdot (S_{P_2} - S_{P_1}) \right] \end{bmatrix}, \quad (10)$$

$$E_{ha}^{//} = L \cdot \tau \cdot \begin{bmatrix} c_{dr.ha.} \cdot \left(T_{ha3} - T_{ha2} - T_{ha2} \cdot \ln \frac{T_{ha3}}{T_{ha2}} \right) + \\ + T_{envir} \cdot \left((R + d_1 \cdot R_v) \cdot \ln \frac{P_3 - \varphi_3 \cdot P_{sat} \cdot T_{ha3}}{P_2 - \varphi_2 \cdot P_{sat} \cdot T_{ha2}} + d_2 \cdot R_v \cdot \ln \frac{d}{d_0} \right) + \\ + d_3 \cdot \left[i_{P_3} - i_{P_2} - T_{ha2} \cdot (S_{P_3} - S_{P_2}) \right] \end{bmatrix}, \quad (11)$$

where L is the mass consumption of a heat-transfer agent, kg/s; $c_{dr.ha}$ is the specific heat capacity of a heat-transfer agent, kJ/(kg·K); T_{ha1}, T_{ha2}, T_{ha3} are the temperatures of a circulating heat-transfer agent, K; P is the heat-transfer agent pressure, kPa; P_{sat} (T_{ha1}), P_{sat} (T_{ha2}), P_{sat} (T_{ha3}) are the pressures of saturated water vapor at T_{ha1}, T_{ha2}, T_{ha3} temperatures, kPa; d_0 is the moisture content of external air, g dr.air/kg moist.; $d_{1...3}$ is the moisture content of a heat-transfer agent, g/kg; i_{P1}, i_{P2}, i_{P3} are the enthalpies of water vapor for pressures P_1, P_2, P_3, kJ/kg; S_{P1}, S_{P2}, S_{P3} are the entropies of water vapor for pressures P_1, P_2, P_3, kJ/(kg·K); R=8.31 J/(mol·K) and R_v=0.462 J/(mol·K) are the universal gas constants of dry air and water vapor, respectively.

Exergy of solar energy referenced per square meter of a solar dryer (taking into account absorption and throughput capacity of a plant)

$$E_{sun} = K_{pol} \cdot K_{refl.} \cdot A_{absor.} \cdot k \cdot E \cdot S_{absor.sur.} \cdot \tau, \quad (12)$$

where K_{pol} is the coefficient of pollution of a body of an air collector, K_{pol}=0.95; $K_{refl.}$ is the coefficient of repeated reflection of solar radiation from an absorber to light penetrating material of an air collector, $K_{refl.}$=0.23; $A_{absor.}$ is the average absorption capacity of an absorber; E is the energy illumination, W/m^2, k is the coefficient of amplification of a solar energy flow by a mirror concentrator, $S_{irrad.sur.}$ is the irradiated surface, m^2; τ is the drying time, s.

Exergy of a thermal battery:

$$E_{tb} = \pm V_{tb} \cdot \rho_{tb} \cdot c_{tb} \cdot (T_{tb2} - T_{tb1}), \quad (13)$$

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

Losses of exergy associated with overcoming of aerodynamic resistance in an air duct of an air collector:

$$\Delta E_{ard} = L \cdot T_{ha} \cdot R \frac{\Delta p_{full}}{P} \cdot \tau, \quad (14)$$

where L is the air consumption, kg/s; Δp_{full} is the total resistance of a solar dryer, Pa; P is the absolute air pressure at the inlet to an air collector, Pa.

Losses of exergy associated with irreversibility of heat and mass transfer processes within a moist product:

$$\Delta E_{ins.} = \Delta m \cdot S_{pr} \cdot \Delta T_f, \quad (15)$$

where Δm is the weight of fruit during drying, kg; $S_{pr.}$ is the entropy of dried material per kilogram of dry matter, kJ/(kg·K); ΔT_f is the temperature difference at a surface and inside material, K.

Loss of exergy due to mixing of evaporated moisture with a heat-transfer agent:

$$\Delta E_{mix} = T_{ha3} \cdot \Delta S_{mix} \cdot L \cdot (1 + d_3) \cdot \tau, \quad (16)$$

where d_3 is the moisture content of air at the outlet of a solar dryer, kg moist./kg dr. air; $\Delta S_{mix.}$ is the entropy increase due to mixing of ideal gases per kilogram of mixture, kJ/kg·K.

Loss of exergy to the environment through walls of a solar dryer:

$$\Delta E_{envir.} = S_{sd} \cdot K \cdot (T_{cham} - T_{envir.}) \cdot \tau, \quad (17)$$

where S_{sd} is the area of a solar dryer, m^2; K is the coefficient of heat transfer through a body of a solar dryer, W/(m^2·K); T_{cham} is the temperature of a heat-transfer agent in a drying chamber during drying, K; $T_{envir.}$ is the ambient temperature, K.

We determine the loss of exergy due to irreversibility of external heat transfer and air leakage as a difference between exergy at the inlet to a solar dryer and a sum of all exergy losses:

$$\Delta E_{ext.} + \Delta E_{leak.} = = E_{moist.} + E_{ha}^{/} - \begin{pmatrix} E_{ha}^{//} + \Delta E_{mix} + \Delta E_{envir.} + \\ + \Delta E_{ins.} + E_{tb} + \sum E^{//} \end{pmatrix}. \quad (19)$$

Exergy efficiency of a solar dryer without a use of a thermal battery:

$$\eta_{w.tb.} = \frac{E_{moist.} + E_{ha}^{//}}{E_{ha}^{/} + E_{sun}} \cdot 100\,\%, \qquad (20)$$

using a thermal battery:

$$\eta_{tb} = \frac{E_{moist.} + E_{ha}^{//} + E_{tb}}{E_{ha}^{/} + E_{sun}} \cdot 100\,\%. \qquad (21)$$

Thus, the resulting exergy balance of a solar dryer makes it possible to calculate rational ways to use and maintain thermal energy that is consumed in a drying process.

5. Results of the exergy analysis of solar dryer operation

Field tests of a solar dryer with a thermal battery and a flat mirror concentrator took place at the farm «Zorya» located in the city of Kortsi, Rivne oblast (Ukraine) in the summer-autumn period from July 16 to October 9, 2017.

Work [13] presents a detailed description of the results of the study of a technological process of fruit drying in a solar dryer and the analysis of the influence of regime parameters on the energy efficiency of a plant with different configuration and duration of a drying process. Specifically, authors of the work investigated a process of operation of an energy unit of a solar dryer with different configurations, namely in the complete set with a mirror concentrator and a thermal battery and without their use, and in the mode of natural cyclicity. Table 1 shows the summary on production tests of a solar dryer.

The daily average physical parameters of the environment were as follows in the period of tests of solar dryer from 15.07.2017 to 17.07.2017:

1. Air temperature T_{envir} – 16...30 °C.
2. Relative humidity of the air φ_{envir} – 26...86.8 %.
3. Energy illumination E – 100...800 W/m^2 for the area of the absorbing surface $S_{absor.surf.}$=1.5 m^2.
4. Heat technical parameters of a heat-transfer agent (air) entering the drying chamber were: at daytime temperature (from 8:00 to 21:00) T_{ha} – 20...60 °C, at night (from 22:00 to 7:00) T_{ha} – 30...20 °C.
5. Velocity of circulation of a heat-transfer agent (air) v_{ha} – 1...3 m/s.
6. Relative humidity of a heat-transfer agent (air) φ_{ha} – 9.8...86 %.
7. Temperature of the battery T_{tb} at daylight hours (from 8:00 to 14:00) was 30.5...45.6 °C, at night (from 22:00 to 7:00) – 45.6...20.9 °C.

We measured temperature in degrees Celsius (°C) in experimental studies. We converted them it into units of thermodynamic temperature (K) during calculations.

We established numerical values of the exergy balance of a solar dryer during calculation-quantitative experiments in relation to the analysis of operation of a power unit of a plant. Table 2, 3 show the results obtained.

Table 2

Arrival of exergy (heat energy) to a solar dryer

Arrival of exergy	Value of components of the balance, kJ		Ratio $E/E_{tot}\cdot 100$ %	
	day time	night time	day time	night time
Exergy of solar radiation energy	578.2	–	24.5	–
Exergy of a heat-transfer agent at the inlet to a drying chamber	27,856	1,319.8	29.3	38.5
Exergy for evaporation of moisture	23,987	698.38	17.7	19.1
Exergy of a thermal battery	614.9	614.9	28.5	42.4
Total	53,036	2,633.1	100	100

Table 3

Losses of exergy (heat energy (heat loss)) in a solar dryer

Exergy losses	Value of components of the balance, кJ		Ratio $E/E_{tot}\cdot 100$ %	
	day time	night time	day time	night time
Losses of exergy associated with overcoming of aerodynamic resistance	2,036.4	256.24	31.1	33.3
Loss of exergy due to mixing of evaporated moisture with a heat-transfer agent	158.4	17.12	15.2	10.5
Loss of exergy to the environment	456.2	41.23	12.4	12.4
Exergy of a used heat-transfer agent removed to the environment	1,355.6	24.93	41.3	43.8
Total	4,006.6	339.52	100	100

Table 1

Consolidated results of the study of a technological process of fruit drying in a solar dryer in the period from 15.07 to 09.09.2017

No.	Duration of drying, h	Duration of drying interval τ_{days}, h (day)	Plant configuration		Investigated raw material	$E_{sun.}$, MJ	E_{pr}, MJ/kg
			TB*	FMC**			
1	50	15–17.07	+	+	Apple	108.5	47.6
2	119	15–21.07	–	–	Pear	–	0
3	74	28–31.07	–	–	Apple	123.1	44.1
4	77	7–10.08	–	–	Apple	110.5	39.6
5	50	10–12.08	+	+	Pear	74.8	26.8
6	50	15–17.08	+	+	Plum	81.3	29.1
7	98	31–3.09	–	–	Plum	95.8	35.7

*Notes: * – thermal battery; ** – flat mirror concentrator*

Thus, the structure of distribution of solar energy entering an air collector indicates that a solar dryer used solar energy in the range of 100 to 800 W/m^2 during one drying cycle. This makes it possible to obtain thermal energy within the limits of 55,669.1 kJ, which absorbed 27,856 kJ of heat-transfer agent and consumed 23,987 kJ for heating and evaporation of moisture from a product. Excess of heat energy accumulated in a battery is within 2,633.1 kJ.

Exergy efficiency of a solar dryer without the use of a thermal battery $\eta_{w.tb.}$=87.6 %; with it – η_{withtb}=89.8 %. When using a thermal battery, the exergy efficiency of a solar dryer increases by 1.02 times.

Unspecified loss of exergy, for example due to irreversibility of heat and mass transfer inside a product, are small in their specification and do not affect the general analysis of the exergy balance of a solar dryer. Therefore, we included all unexplained losses of exergy to the loss of exergy from mixing of evaporated moisture with a heat-transfer agent.

The fact that the configuration of a solar dryer is a kind of indivisible energy unit with combination of a collector, a battery and a drying chamber explains reduction of exergy losses to the environment by 12.4 %. The low-temperature mode of operation of a solar dryer with natural convection contributes to reduction of heat loss also. This makes it possible to reduce unproductive heat losses through the body of a solar dryer and to convert solar energy into heat effectively and to use it over the course of a day.

Traditional and innovative methods for fruit drying analyze influence of a moisture content, temperature, and velocity of air in a drying chamber in relation to reduction of heat loss and increase of exergy of a heat-transfer agent mainly. In addition, we control a moisture content of the incoming air by an increase in temperature and a decrease in velocity of a heat-transfer agent by an electric heater in drying plants with traditional power supply. Instead, in a solar dryer, it is exergetically advisable to provide only a slight heating of a heat-transfer agent at the inlet to a drying chamber by accumulated heat at night when relative humidity of the air approaches the dew point, as a solar dryer operates in the mode of convective air drying with natural convection at the night period. Calculation-quantitative experiments with regard to the exergy analysis of an energy unit of a solar dryer confirm positive results of such influence on a moisture content of the inlet and outlet flow (exergy of a heat-transfer agent). According to data from analysis (Table 2, 3), the exergy of the heat-transfer agent at the inlet to the drying chamber during day is 29.3 %, and at night period it is 38.5 % relative to the overall ratio $E/E_{tot}\cdot 100$ %. The exergy of the used heat-transfer agent removed to the environment in the daytime is 41.3 %, and at the night period – 43.8 %. The exergy analysis performed here makes it possible to estimate numerical values of the exergy balance of a solar dryer and to explain how it is possible to increase an amount of exergy and to reduce heat loss during a drying process by using a mirror concentrator and a thermal battery. The use of a mirror concentrator enables an increase in the flow of solar energy to a receiving surface of an air collector and an increase in the exergy of solar energy E_{sun} at daytime by 24.5 %. Accumulation of excess heat in a heat accumulator makes it possible to maintain optimal energy parameters during the period of cloudiness by 28.5 %, and at night – 42.4 %. This makes it possible to maintain stable fruit drying during entire 24 hours and to increase the exergy efficiency of a drying process by 36.8 %, in relation to the overall ratio $E/E_{tot}\cdot 100$ %.

Consequently, the analysis of the data obtained by the exergy balance of a solar dryer helped to detect and reduce loss of leakage of a heat-transfer agent to overcome aerodynamic resistance in an air collector and to reduce loss of heat into the environment through walls of a plant. This made possible to increase the energy efficiency of a solar dryer and to substantiate the efficiency of the use of an air collector, a mirror concentrator, and a thermal battery.

In conclusion, we emphasize that the exergy balance of a solar dryer should be considered as a method that shows ways of receipt and losses of thermal energy, taking into account the exergy for different thermophysical parameters of the environment. It makes it possible to simultaneously investigate operation of an energy unit of a solar dryer in detail and to describe ways to increase the energy efficiency of a plant and to evaluate a drying process in it due to solar energy.

6. Discussion of results of the exergy analysis of a solar dryer operation

We considered the process of operation of a solar dryer, which has an energy unit consisting of a mirror concentrator, an air collector, and a thermal battery in its structure. A solar dryer of such design belongs to energy saving equipment and has a high coefficient of use in individual farms due to solar energy. Since the average annual solar power in the city of Kortsi, Rivne oblast, during the summer–autumn period from July 16 to October 9, 2017, is 3.41 kWh/m^2 per day, it is possible to obtain from 74.8 to 123.1 MJ of thermal energy per day from 1 m^2 of an air collector area. But we should note also that the recent rate of growth of tariffs for traditional energy sources dictates conditions and norms of the cost of energy resources. Here we mean the expediency of introduction of energy-saving technologies of fruit drying for small amounts of fruit processing at individual farms, since an important condition for the successful development of technical progress at private farms is the use and introduction of energy saving equipment.

In order to choose which energy-saving equipment is needed for fruit drying for small amounts of processing at an individual farm specifically, we need to evaluate the energy efficiency of equipment. For example, we can estimate an energy unit of a solar dryer using the general thermodynamic method of analysis – the exergy balance of a plant. The exergy balance of a solar dryer makes it possible not only to take into account an amount of energy consumed by a drying process and deduced from a power unit, but also the quality of energy that is usefully spent on the operation of a plant.

We improved one of the methods of thermodynamic analysis of a solar dryer operation to do this. The method is necessary to obtain complete information on the process of operation of a solar dryer and an amount of energy received, a quality of the energy and its ability to be transformed into useful work. The result of the analysis is finding the exergy efficiency factor (efficiency) of a plant in the whole process of operation, income, and loss of exergy in individual elements of an energy unit and a process of fruit drying.

The improved technique of the exergy analysis of an operation process of a solar dryer makes it possible to perform calculational-quantitative experiments during substantiation of the exergy balance of a plant. This allows us to reengineer a process of operation of a solar dryer and to solve the problem of increasing the efficiency of a power unit.

We established the influence of thermophysical parameters of the environment on energy characteristics and the exergy efficiency of a solar dryer and receipt and loss of exergy in the fruit drying process. We determined that the loss of exergy on irreversible heat and mass transfer inside a product is small and does not affect a general picture of solar dryer operation. Therefore, it is necessary to examine all receipts and losses of exergy in order to find out what relationship between them should be and whether their choice may or may not be arbitrary during the exergy analysis of operation of a solar dryer.

The study substantiated due to which reasons there is an increase in the energy efficiency of a solar dryer with the use of a thermal battery. This made it possible to obtain a relatively high exergy efficiency of a solar dryer in the range of 89.8 %.

Consequently, the complex of analytical and calculation-quantitative studies confirmed the possibility of intensification of a drying process of raw materials in a solar dryer.

Thus, the use of solar dryers with a thermal battery and a flat mirror concentrator for fruit drying is appropriate and effective for personal farming. It will help to increase production of high-quality dried products at minimum energy consumption. In addition, the results will be useful for improvement of the technology and equipment for fruit drying.

7. Conclusions

1. The study substantiates the approach to determining exergy costs for moisture removal inside dried material, which is evaluated by a change of enthalpy, entropy, and moisture content of raw materials. We established that it is also necessary to determine energy of bound moisture in fruits per 1 kilogram of dry matter when calculating the exergy of a product at the outlet from sieves. The use of an advanced method for calculation of an exergy balance of a solar dryer makes it possible to distinguish frequent errors related to ignoring the qualitative aspect of transformation of solar energy into heat, which occur during calculations, and confirm reliability of results of the study.

2. We investigated energy parameters in the study. In particular: physical parameters of the environment that changed in the range: air temperature T_{envir} is 289.15...303.15 K; relative humidity of the air $\varphi_{envir.}$ is 26...86.8 %; energy illumination E is 100...800 W/m^2. Thermal-technical parameters of a heat-transfer agent entering a drying chamber were: temperature T_{ha} – from 293.15 to 333.15 K; circulation velocity v_{ha} – from 1 to 3 m/s; relative humidity φ_{ha} varied from 9.8 to 86 %. During one drying cycle a solar dryer absorbed solar energy in the range from 100 to 800 W/m^2, converted it to thermal energy (55,669.1 kJ), which was absorbed as heat-transfer agent (27,856 kJ) and consumed to heat a product and evaporate moisture from it (23,987 kJ), and part of it – a thermal battery (2,633.1 kJ). The performed analysis of energy parameters shows that the greatest losses of exergy occur in the drying section of a plant – 58.3 %. We can see from the exergy balance that thermal energy $E/E_{tot}\cdot 100$ % in total (97.2 %) is spent with a mixture of the used heat-transfer agent to evaporate moisture from material. At the same time, the exergy balance established that the energy value of a mixture of the used heat-transfer agent is 41.3 %.

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. URL: https://www.ijser.org/researchpaper/Experimental-performance-and-modeling-of-a-greenhouse-solar-dryer.pdf
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. IV, Issue II. URL: http://www.technicaljournalsonline.com/ijeat/VOL%20IV/IJAET%20VOL%20IV%20ISSUE%20II%20APRIL%20JUNE%202013/Vol%20IV%20Issue%20II%20Article%207.pdf
5. Kaveh M., Amiri Chayjan R., Esna-Ashari M. Thermal and physical properties modelling of terebinth fruit (Pistacia atlantica L.) under solar drying // Research in Agricultural Engineering. 2016. Vol. 61, Issue 4. P. 150–161. doi: 10.17221/45/2013-rae
6. Azimi A., Tavakoli T., Khademhosseini H. Experimental Study on Eggplant Drying by an Indirect Solar Dryer and Open Sun Drying // Iranica Journal of Energy & Environment. 2012. Vol. 3, Issue 4. P. 347–353. doi: 10.5829/idosi.ijee.2012.03.04.09
7. Review on the Application of a Tray Dryer System for Agricultural Products / Misha S., Mat S., Ruslan M. H., Sopian K., Salleh E. // World Applied Sciences Journal. 2013. Vol. 22, Issue 3. P. 424–433.
8. Mohanraj M., Chandrasekar P. Performance of a forced convection solar drier integrated with gravel as heat storage for chili drying // Journal of Engineering Science and Technology. 2009. Vol. 4, Issue 3. P. 305–314. URL: https://www.researchgate.net/publication/49593948_Performance_of_a_forced_convection_solar_drier_integrated_with_gravel_as_heat_storage_material
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. Substantiation of economic efficiency of using a solar dryer under conditions of personal peasant farms / Babych M., Korobka S., Skrynkovskyy R., Korobka S., Krygul R. // Eastern-European Journal of Enterprise Technologies. 2016. Vol. 6, Issue 8 (84). P. 41–47. doi: 10.15587/1729-4061.2016.83756
11. Shargut Ya. V., Petela R. I. Eksergiya: ucheb. pos. Moscow: Energiya, 1968. 280 p.
12. Sazhin B. N. Osnovy tekhniki sushki: ucheb. pos. Moscow: Himiya, 1984. 320 p.
13. Results of research into technological process of fruit drying in the solar / Korobka S., Babych M., Krygul R., Zdobytskyj A. // Eastern-European Journal of Enterprise Technologies. 2018. Vol. 1, Issue 8 (91). P. 64–73. doi: 10.15587/1729-4061.2018.122816