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RESULTS OF RESEARCH INTO KINETIC AND ENERGY PARAMETERS OF CONVECTION FRUIT DRYING IN A SOLAR DRYING PLANT

V. Boyarchuk
PhD, Professor*
E-mail: vim2@ukr.net
S. Korobka
PhD, Senior Lecturer*
E-mail: korobkasv@ukr.net
M. Babych
PhD*
E-mail: m.babych@ukr.net
R. Krygul
PhD*
E-mail: krroma@ukr.net
*Department of Energy
Lviv National Agrarian University
Volodymyra Velykoho str., 1,
Dublyany, Ukraine, 80381

Вдосконалено методику розрахунку кінетичних та енергетичних параметрів конвективного сушіння фруктів у геліосушарці, за якими можна проаналізувати підвищення ефективності технологічного процесу сушіння та зменшення затрат енергоресурсів за рахунок сонячної енергії.

Досліджено кінетику, динаміку та інтенсивність сушіння фруктів у геліосушарці, зокрема для яблук нарізаних часточками товщиною 8 мм оброблених розчином цукру, підданих бланшуванню та без обробки. Визначено кінетичні характеристики процесу: тривалість сушіння, що склала для яблук оброблених розчином цукру або підданих бланшуванню – 27 годин, без обробки – 33 годин. Інтенсивність сушіння при цьому для яблук за вологовмісту від 2,89 до 0,24 кг вол./кг сух. реч. становить 1,57÷0,18 кг/(м^2·с).

Встановлено вплив енергетичних параметрів на технологічні параметри теплоносія та ККД установки. Зокрема, за один цикл сушіння із 1,5 м^2 поверхні повітряного колектора геліосушарка використовувала енергію сонячного випромінювання в межах від 723 до 800 Вт/м^2. Встановлено, що ця енергія була перетворена в теплову (2368,2 кДж), яку поглинув теплоносій (1984,9 кДж) і затратив на нагрівання продукту (836,3 кДж) та випаровування вологи 756,7 кДж, а частину – тепловий акумулятор (356,9 кДж). Визначено ККД геліосушарки, що становив від 23 до 60 % залежно від зміни щільності надходження сонячної енергії , котра коливалася у ранковий період (з 700 до 1000 год.) від 456 до 965 Вт/м^2 та вечірній період (з 1700 до 2000 год.) – від 734 до 223 Вт/м^2.

Отримані результати можна використати під час розробки та вдосконалення технічних засобів сушіння фруктів, для підвищення технологічної та енергетичної ефективності процесу

Ключові слова: геліосушарка, конвективне сушіння, кінетика, енергія активації, інтенсивність сушіння, тепломасообмін, вологовміст

1. Introduction

The kinetics of drying is typically understood as the temporal dependence of the mean moisture content and the temperature of dried mass, based on which it is possible to calculate the amount of moisture removed and the consumption of thermal energy.

The intensity of the convection drying of fruit in a solar drying plant is characterized by the rate of a heat carrier supply, the difference of a drying agent's temperatures between surfaces of the material and the raw materials moisture release. As a result of the complex dependence of the intensity of convection drying in a solar drying plant on a large number of factors, namely the diffusion coefficient, temperature and moisture content gradients that do not make it possible to derive analytically the estimated dependence in order to calculate the intensity. Calculating the kinetic and energy parameters for the convection drying of fruit in a solar drying plant for the conditions of a particular problem is possible only through the generalization of research data based on the procedure for the calculation of the kinetic and energy parameters of convective drying [1]. However, in order to determine the energy parameters and the intensity of convection drying, it is required to know the moisture content and temperature gradients, diffusion coefficient, and heat-and-mass exchange processes near the surface and inside a material. The initial dependence to generalize experimental data on energy parameters and the intensity of convective drying is a general law of temperature distribution in the process of moisture release, which is expressed by a differential equation of convective heat exchange. In addition, it is necessary to note that the calculation of kinetic and energy parameters for convection drying of fruit in a solar drying plant employs different approaches. The first one, most common, is based on a change in the physical parameters of the environment in accordance with a change in the material's moisture content. The second approach to building the calculation implies a change in the kinetic and energy parameters of the environment depending on the duration of drying. The third approach to constructing the calculation involves a change between physical parameters of the environment, thermal-physical parameters of the dried fruit and interconnection between the energy and kinetic parameters of a dried material and the heat-and-mass exchange processes between them.

Addressing the issue of resource saving is additionally complicated by the fact that the fruits are characterized by a high variability of thermal-physical, physical-mechanical, structural-mechanical, chemical properties. Therefore, it is a relevant task to substantiate the optimal parameters for the technological process of drying in a solar drying plant as this issue is of particular importance for the intensification of drying processes.

2. Literature review and problem statement

Modern world has increasingly used alternative sources to replace scarce traditional types of energy. One such source is solar energy that can be utilized for the generation of low-potential heat in order to dry wet materials of plant origin. The authors of [2] developed a procedure for the convection fruit drying process. They investigated kinetic and energy parameters of the process in terms of the volume of energy needed to reach the target characteristics of samples. They quantified energy consumption for the implementation of drying process in a convection solar drying plant with different types of fruit raw materials, their properties, and the starting moisture content of a material. However, the paper does not highlight the issue related to the driving force behind the transfer of moisture inside a material.

In paper [3], authors proposed the design of a drying fruit chamber, which utilizes a solar collector as an additional source of thermal energy. In addition, the authors implied that this installation partially utilized the heat of the consumed heat carrier in order to heat the air supplied into a drying chamber. The authors argue that such implementation reduces the rated capacity of an electric drive of the aerodynamic recirculating heater and saves electricity. They proposed the procedure and algorithm for the execution of optimum control over the heat-and-mass exchange process in a working chamber of the proposed drying plant. However, they failed to take into consideration the diffusion coefficient and energy of the bound moisture per one kilogram of the removed moisture.

Paper [4] reports results of experimental research into the fruit drying process in a convection chamber dryer. The authors built drying curves for materials such as apples in relative and normalized coordinates, the drying rate curves, and analyzed the impact of various parameters for a heat-and-moisture mode of the drying process on fruit drying rate. The authors examined a change in the moisture content of a heat carrier in the process of drying. They plotted curves for drying and the drying rate based on the experiments that helped them more accurately evaluate the impact of temperature and moisture content of a drying agent on speed of the process of drying the raw materials. Results of experimental research into fruit drying demonstrated that the kinetic dependences of changes in the humidity and drying rate are quite similar. That has enabled the authors in the subsequent treatment of experimental material to derive the generalized dependences. Observing a change in the heat carrier's moisture content at the outlet from a drying chamber of chamber convection dryers made it possible to determine the point when it is possible to finish the process of drying the material. However, given the complexity of the structural composition of fruits as a heterogeneous anisotropic colloid capillary-porous body, it is impossible, in the process of drying fruit in a convection chamber dryer, to establish stable indicators for the intensity of drying.

In paper [5], authors analyzed quality indicators of fruit drying, namely, intensity, rate, and duration of drying. They determined an indicator for the uniformity of resulting humidity. They stablished four categories of fruit drying quality. In order to ensure the required quality of dried fruits, the authors proposed a new technique to end the technological process of drying. However, the work under consideration fails to take into consideration energy of the bound moisture and enthalpy of the dried material per 1 kg of the removed moisture.

The authors of [6] reviewed the processes of change in the temperature of air in a solar drying plant during convection fruit drying. In addition, the paper formulated boundary conditions for solving the equations of heat conductance during fruit drying. The authors presented a mathematical model of boundary conditions during convection drying of fruit in a solar drying plant. However, while substantiating the kinetic and dynamic parameters, they did not take into consideration the theoretical moisture content of the initial flow of a heat carrier, which would make it possible to describe an hourly change in the mass of fruit Δm during drying.

Study [7] addressed mathematical modeling of the deformation-relaxing and heat-and-mass exchange processes in hygroscopic capillary-porous materials as the anisotropic three-phase environments, which are essential to the development and substantiation of energy-saving technologies for the hydro-thermal treatment of fruit. The authors revealed a mathematical model of the heat-and-mass transfer for the periods of constant and descending rate of drying the capillary-porous materials, and constructed a mathematical model of the rheological behavior of fruit as a three-phase environment, taking into consideration the anisotropy of thermal-mechanical characteristics. The developed object-oriented applied software for the numerical realization of mathematical models based on the adaptation of the method of finite elements. In addition, they established the regularities of influence of technological parameters of drying in a convection solar drying plant on the processes of viscoelastic deformation and heat-and-mass transfer in the solid, liquid and steam phases of the material. However, the reported procedure does not consider the rate of a dried material's moisture release in the zone of action of the heat carrier under conditions of the diffusion process of moisture transfer in the dried material.

Paper [8] reports a technique for dehydration of fruit in the greenhouse-type solar drying plant that implies a change in the temperature and moisture content of a drying agent and makes it possible to reduce drying duration and ensure energy and resource savings. In addition, the paper gives a mathematical model and a numerical method for calculating the heat-and-mass transfer dynamics, phase transformations, and shrinkage when drying colloidal capillary-porous bodies in a solar drying plant of the greenhouse type. In particular, there is the mechanism of heat-and-mass transfer based on the phenomenological understanding of the mechanics of hereditary environments and methods of the non-equilibrium thermodynamics. Due to the complexity of the structural composition of fruits as a heterogeneous anisotropic colloid capillary-porous body, the model fails to establish constant heat-and-mass exchange indicators.

The authors of work [9] report results of research into the influence of preliminary treatment of apple fruits and the temperature of a drying agent on the duration and intensity of drying process in a solar drying plant. In addition, they estimated energy efficiency of the process and the efficiency coefficient of a solar drying plant. However, the work under consideration fails to examine directions of the vectors of temperature and moisture content gradients inside the material during heating relative to the movement of moisture inside the dried material.

Choosing the rational technologies for convection drying of fruit in a solar drying plant that would ensure maximum intensity of the process and minimum energy resources is an important task. The complexity of the fruit drying process is predetermined by the course of interconnected physical phenomena related to heat-and-mass transfer and deformation under conditions of high variability in the structural and physical properties of hygroscopic bodies. A modern approach to the methodology for calculating the process of heat-and-mass transfer during convection drying of fruit in a solar drying plant should be based on the application of the theory of heat-and-mass transfer and heat-and-mass exchange. This theory makes it possible to employ the main provisions of laws and methods of classic physics, heat engineering, mathematics in order to solve differential equations of heat-and-mass transfer using the step method for calculating the fruit drying process. Particularly, in order to calculate the simplified mechanism of heat-and-mass transfer, where it is necessary to apply the methods of mathematical statistics to process experimental data.

Thus, we can sum up by arguing on the today's particular relevance of studying the influence of kinetic and energy parameters during convection drying of fruit in a solar drying plant for all kinds of raw materials, as well as methods of raw materials pre-treatment. That would enable the intensification of drying and selection of new design-driven innovation systems, resource-saving technologies, and technical means in the agricultural production and its energy supply needs, with the aim of obtaining high-quality resulting products at minimal costs and losses at the expense of solar energy.

3. The aim and objectives of the study

The aim of this study is to determine the kinetic and energy parameters for the process of convection fruit drying in a solar drying plant in order to enhance its effectiveness. This would ensure reducing the consumption of energy resources at the expense of solar energy.

To achieve the set aim, the following tasks have been solved:

– to improve the procedure for calculating the kinetic and energy parameters of the convection fruit drying in a solar drying plant;

– to examine the convection fruit drying in a solar drying plant and to determine dependences of the duration of this process in a drying plant on techniques for the treatment of raw materials and on the physical parameters of the environment;

– to assess the arrival of thermal energy and heat losses in a solar drying plant during fruit drying.

4. Materials and methods to study the kinetic and energy parameters of convection fruit drying in a solar drying plant

4. 1. Kinetics of convection fruit drying in a solar drying plant

Requirements for the technology of drying fruits are not limited only by a decrease in the moisture content to the regulatory values. It is important to preserve the nutrients, vitamins, aroma, and taste, as well as the attractiveness of a dried product. These additional requirements impose certain restrictions on the progress of heat- and mass exchange processes of drying, whose parameters are predetermined by the patterns in binding moisture to the fruits' organic material.

Free moisture at the surface of fruit as a residue after washing exists only at the stage of warming. The rest of the time the liquid phase is a multicomponent solution of organic and mineral substances, rather than free fluid characteristic of classic dispersed materials of inorganic origin. Thus, when drying fruits, it is almost impossible to distinguish between the second and third stages of drying. Therefore, results of studying the kinetics of fruit drying are formally described by the diffusion moisture transfer through structural elements – membranes and capillaries. Such a generalized approach is based on the Fick's law for a moisture flow through a membrane [10]

$$J=\frac{D\cdot K}{L}\left(\rho_o-\rho_i\right), \tag{1}$$

where J is the flow of moisture, kg/s·m^2; D is the diffusion coefficient, m^2/s; K is the distribution coefficient, which takes into consideration the ratio of the concentration of moisture inside and outside of the membrane; L is the thickness of the membrane, mm; ($\rho_o-\rho_i$) is the difference in concentrations (densities) of solution on both sides of the membrane.

In addition, at stable temperature and speed of the incoming stream of air the moisture content of thin plates of fruit (L=2...6 mm) reduces over time in line with the law that is close to exponential [10], which formally likens the kinetics of mass exchange to the diffusion process [11]. The results of examining a diffusion coefficient D are most often approximated by the following expression for the effective diffusion D_{ef} [10]

$$M\cdot R=\frac{M}{M_0}=\frac{U-U_p}{U_0-U_p}=\frac{8}{\pi^2}\exp\left(-\frac{\pi^2 D_{ef}}{4L^2}\tau\right),$$

$$U=U_p+(U_0-U_p)\frac{8}{\pi^2}\exp\left(-\frac{\pi^2 D_{ef}}{4L^2}\tau\right), \tag{2}$$

where U_0, U and U_p are the initial, current, and equilibrium moisture content, respectively; L is the thickness of the sliced plates, m.

A value for D_{ef} is taken to be equal to the angular coefficient of experimental logarithmic dependence (12) relative to time

$$k=\ln\frac{U-U_p}{U_0-U_p}=\ln\frac{8}{\pi^2}-\frac{\pi^2 D_{ef}}{4L^2}\tau. \tag{3}$$

As is known, a classic diffusion process is described by the exponential Arrhenius equation

$$D = D_0 \exp\left(-\frac{E_a}{RT}\tau\right), \tag{4}$$

where D_0 is the pre-exponential multiplier, m^2/s, numerically equal to the value of diffusion at the initial time: for water molecules in the air, $D_0=2.16\cdot10^{-}m^2/s$ under normal conditions (a temperature of 273 K and a pressure of 760 mm Hg); R=8.31 kJ/(kmol·°C) is the universal gas constant; T is the absolute temperature, °C; E_a is the activation energy, kJ/mol.

The physical meaning of activation energy is the additional energy obtained by a molecule for a spasmodic move. E_a decreases with temperature, similar to the heat of vaporization. In practice, activation energy for each temperature of drying is also determined by the angular coefficient of the temporal dependence of diffusion coefficient logarithm

$$\ln\frac{D_{ef}}{D_0} = -\frac{E_a}{R\cdot T}\tau. \tag{5}$$

Given the known values for the coefficient of diffusion and activation energy, a reduction in the moisture content over time is typically calculated from the following ratio

$$\frac{d(U-U_p)}{d\tau} = -2(U_0-U_p)\frac{D}{L^2}\exp\left(-\frac{\pi^2 D}{4L^2}\tau\right). \tag{6}$$

If we take into consideration that the drying process lasts for at least 2 days (48 hours), a reduction in the moisture content over a short period of time, such as $\Delta\tau$=1 hour, in any moment τ can be estimated using an expression for increment

$$\Delta U \simeq dU = -2(U_0-U_p)\frac{D}{L^2}\exp\left(-\frac{\pi^2 D}{4L^2}\tau\right)\Delta\tau. \tag{7}$$

Therefore, drying parameters are conveniently calculated based on the predefined coefficient of diffusion.

Diffusion processes in convection driers can be accelerated both by the growing speed of airflow and its temperature. Based on the results of experimental research into drying apples, reported in [10], the following two-parameter equation is proposed for the diffusion coefficient

$$D=(0.204\cdot T-1.48\cdot V-3.9)\cdot10^{-10}\ m^2/s. \tag{8}$$

The relative degree of influence of each parameter on the course of a diffusion process will be determined by comparing the partial differentials of the last expression

$$\partial D_T = 0{,}204\cdot10^{-10}\partial T \text{ and } \partial D_V = -1{,}48\cdot10^{-10}\partial V. \tag{9}$$

Here, both parameters are opposed to the course of diffusion processes. Instead, at small deviations of one of the parameters, the corresponding gain in another one in order to stabilize the process can be evaluated by equating a complete differential (8) to zero with the subsequent reduction of stable multipliers and by substituting partial differentials with their increments

$$0.204\cdot\Delta T-1.48\cdot\Delta V=0 \text{ or } \Delta V = \frac{0{,}204}{1{,}48}\cdot\Delta T = 0{,}14\cdot\Delta T. \tag{10}$$

Based on the close parameters of the drying fruits kinetics, it is possible to assume that ratio (10) holds for other fruits with a close structure of the pulp.

The improved mathematical model of the convection fruit drying in a solar drying plant is based on the thermal-physical system of differential equations of heat-and-mass transfer by O. V. Lykov [1], underlying which is the simplified mechanism of heat- and mass exchange that is described by the differential equations of heat-and-mass transfer:

– a heat transfer equation

$$c_f\cdot\rho_f\cdot\frac{\partial T_f(\tau)}{\partial x} = \frac{\partial}{\partial x}\left(\lambda\cdot\frac{\partial T_f(\tau)}{\partial x}\right) + \\ +\varepsilon\cdot q_b\cdot\frac{\partial}{\partial x}\left(D\cdot\rho_f\cdot\frac{\partial U}{\partial x}\right) + \varepsilon\cdot q_f\cdot\frac{\partial}{\partial x}\left(D\cdot\rho_f\cdot\delta_T\cdot\frac{\partial T_f(\tau)}{\partial x}\right), \tag{11}$$

– a moisture transfer equation

$$\frac{\partial U}{\partial\tau} = \frac{\partial}{\partial x}\left(D\cdot\frac{\partial U}{\partial x}\right) + \frac{\partial}{\partial x}\left(D\cdot\delta_T\cdot\frac{\partial T_f(\tau)}{\partial x}\right), \tag{12}$$

where $T_f(\tau, x)$ is the temperature of fruit that is a function of drying duration τ; $U(x)$ is the change in a field of moisture content of the dried material along the x coordinate; c_f is the specific heat capacity of fruits, kJ/(kg·°C); λ is a thermal conductivity coefficient, W/(m^2·°C); $\rho_f=(\rho_o-\rho_i)$ is fruit density, kg/m^3; q_b is the energy of moisture bound in fruits, kJ/kg; U is the fruit moisture content, kg moisture/kg of dried matter; ε is a phase transition criteria, equal to the ratio of the volume of evaporated moisture to moisture content in a certain volume (at ε =1, water moves in the form of steam; when ε=0, in the form of a liquid); D is a diffusion coefficient, m^2/s; x is a spatial coordinate, mm; δ_T is a thermal-gradient coefficient, 1/°C; $\frac{\partial U}{\partial x}$ and $\frac{\partial T_f(\tau)}{\partial x}$ are, respectively, the gradients of moisture content and temperature of the material.

Initial conditions for the mathematical model will be accepted in the following form

$$T_f(\tau, x; 0)=T_{fi}(\tau, x);\ U(x; 0)=U_i(x),$$

where $T_{fi}(x)$, $U_i(x)$ are the temperature and moisture content of fruit at the initial time of drying.

The boundary conditions can be written in the following form:

– in the center of a dried material (conditions for symmetry)

$$\frac{\partial T_f(\tau)}{\partial x_{x=0}} = 0;\ \frac{\partial U}{\partial x_{x=0}} = 0, \tag{13}$$

– at the surface of a dried material (condition of the third kind)

$$\alpha\cdot\left[T_{dc}(\tau)-T_f(\tau)_R\right] = \lambda\cdot\frac{\partial T_f(\tau)}{\partial x_{x=R}} - \\ -\left|\rho_f\cdot(1-\varepsilon)\cdot q_b\cdot\beta\cdot\left(U_{x=R}-U_p\right)\right|, \tag{14}$$

$$\alpha\cdot\left(U_{x=R}-U_p\right) = D\cdot\frac{\partial U}{\partial x_{x=R}} + \left|D\cdot\delta_T\cdot\frac{\partial T_f(\tau)}{\partial x_{x=R}}\right|, \tag{15}$$

where α is a heat exchange coefficient, W/(m^2·°C); β is a mass exchange coefficient, m/s; U_p is an equilibrium moisture content, kg moisture/kg of dry matter; R is the thickness of fruit slices, mm.

A mass release coefficient β is calculated from, m/s

$$\beta=\frac{\Delta m}{S_a\cdot\left(a_\omega\cdot(P_{hc}-P_f)\right)},\qquad(16)$$

where Δm is the mass of a fruit material in the process of drying, kg; a_ω is the water activity coefficient; S_f is the heating area of the fruit raw materials surface, m^2; P_f is the pressure of water vapor over a product, Pa; P_{hc} is the water vapor pressure in a heat carrier, Pa.

The activity coefficient of water is determined from

$$a_\omega=\exp\left[-\frac{\Delta p\cdot m_m}{\rho\cdot R\cdot\left(T_f(\tau)+273\right)}\right],$$

where m_m is the molecular weight of water, g/mol; ρ is the density of water (or a solvent), kg/m^3; R is the universal gas constant (R=8.314·10^3), J/(mol·k); Δp is the pressure drop, equal to the difference between pressure in the zone of a liquid and the saturated vapor pressure of a heat carrier under a given temperature od air, Pa.

The external and internal transfer of heat and moisture in a raw material is affected by the material's shape. Coefficients of mass exchange at the same state of air will accept different values depending on the shape of the material. Therefore, when employing the specified coefficients in order to calculate a drying process, it is necessary to take into consideration the area of the heating surface of a fruit raw material.

The result of external heat-and-mass exchange is the broken equilibrium inside a material, where there occur the gradients of moisture content ∇U and temperature ∇T, specifically:

– directions of vectors of temperature and moisture content gradients inside a material during heating are opposite to the moisture transfer inside the dried material, under the following conditions

$$J_m=-D\cdot\rho_f\cdot\left(\Delta U-\delta_T\cdot\Delta T(\tau)\right),\ \text{kg/(m}^2\text{·s)}.\qquad(17)$$

– when cooling, the temperature and moisture transfer gradients decrease under the following conditions

$$J_m=-D\cdot\rho_f\cdot\left(\Delta U+\delta_T\cdot\Delta T(\tau)\right),\ \text{kg/(m}^2\text{·s)}.\qquad(18)$$

The overall duration of fruit drying τ depends on the structural-technological parameters of a solar drying plant, as well as the physical parameters of the environment, and is determined from

$$\tau=\frac{W_i-W_r}{N}+\frac{1}{K_c}\cdot\ln\left[\frac{W_r-W_e}{W_r-W_e}\right]+$$
$$+\frac{\Delta m\cdot c_f\cdot\left(T_{f2}-T_{f1}\right)+h_l\cdot\rho_f\cdot\left(\sum S_s\right)\cdot c_f\cdot\left(T_{hc3}-T_{hc2}\right)}{S_{dc}\cdot\upsilon_{hc}\cdot\rho_{hc}\cdot c_{hc}\cdot\left(T_{hc2}-T_{hc1}\right)/\tau_h-(S_c\cdot E)-S_{sd}\cdot P_{ht}\cdot\left(T_{dc}-T_a\right)-V_{ha}\cdot\rho_{ha}\cdot c_{ha}\cdot\left(T_{ha2}-T_{ha1}\right)/\tau_d},\ \text{s.}\qquad(19)$$

where τ is the duration of fruit drying, s; W_i is the initial moisture content of fruit, which is determined experimentally, %; N is the drying rate, which is determined from experiments, %, s; K_c is a drying coefficient, which is determined experimentally, s; W_r is the resulting moisture content of fruit, which is determined experimentally, %; W_c is the critical moisture content of fruit at a critical point of the drying process, which is determined experimentally, %; W_e is the equilibrium moisture content of fruit for the predefined mode of drying, %; E is the energy illumination, W/m^2; S_{dc} is the area of a drying chamber, m^2; τ_h is the duration of heating a drying chamber, s; υ_{hc} is a heat carrier velocity, m/s; ρ_f, ρ_{hc}, ρ_{ha} is the density of fruit, heat carrier, and heat-accumulating material, respectively, kg/m^3; c_{hc}, c_f, c_{ha} is the specific heat capacity of heat carrier, fruit, and heat-accumulating material, J/(kg·°C); h_l is the height of the layer of a fruit material on sieves, mm; T_{tb1}, T_{tb2} is the temperature at the inlet of a thermal battery and at its outlet, °C; S_s is the area of sieves, m^2; S_{sd} is the solar drying plant area, m^2; T_a is the ambient temperature, °C; P_{ht} is the coefficient of heat transfer through a solar drying plant's casing, W/(m^2·°C); τ_d is the duration of discharge of a thermal battery, s.

The equilibrium moisture content of fruit for the predefined mode of drying is determined from

$$W_e=K_1(T)+K_2(T)\left[\lg\left(\frac{1}{1-\varphi_{0\ldots n}}\right)\right]^{1/2},$$

where W_p is the equilibrium moisture content of fruit during desorption process, %; $\varphi_{0\ldots n}$ is the relative humidity of air, $\varphi_{0\ldots n}=\frac{P_p}{P_{vp}}$; P_{vp} is the partial pressure of saturated vapor pressure, kPa; P_p is the steam partial pressure, kPa.

Therefore, a knowledge of the mechanisms for the transfer of heat- and mass exchange processes is the basis for substantiation of the optimum modes of drying and parameters for a drying agent in the chamber. A description of the character of influence of the heat-and-technical parameters of the environment on energy indicators of the process is necessary in order to substantiate the kinetics of convection drying of fruit in a solar drying plant.

4. 2. Energetics of the convective fruit drying in a solar drying plant

Over time, in the isolated system water-air there occurs a dynamic equilibrium between the opposing flows of molecules from the free surface into the air and vice versa. In such a system, the temperature of both environments is the same, while air has a maximum humidity, which is called saturated. In its place, in the open system, water temperature θ is always lower than the ambient temperature t due to the independent process of transition of activated molecules into the atmosphere. The difference in temperatures is regulated by the rate of diffusion processes and the compensating thermal flow from the ambient air to the water surface. The concentration of vapor gradually decreases from that close to saturation in the near- surface layer to the level of the current air humidity. Under non-moving air, a transition of molecules from the near-surface layer into the volume occurs owing to the mechanism of stationary diffusion agitation [1, 11].

Under real conditions of natural drying in the open air the wet surface is always blown by the air flow, which intensively diffuses the molecules of saturated vapor of the near-surface layer of air. In this case, temperature of the water surface further decreases, while moisture release accelerates. Consequently, a low-temperature drying occurs even when the temperature of the air flow is equal to the temperature of the environment. Convection solar drying plants that utilize ambient air as a drying agent, regardless of its temperature, are referred to as atmospheric.

When approximating a theoretical convective dryer, there occurs an isobaric-adiabatic (no access of outside heat) heat-and-mass transfer during which a wet material is blown by air with a constant temperature t. In such a process, a change in the thermal energy dQ of an air stream is equal to a gain in its internal energy du and to the work of vapor expansion $d(pV)$

$$dQ=d(u+pV)=dI, \quad (20)$$

where $I=u+pV$ is the enthalpy of wet air, whose value is calculated relative to the freezing point 0 ºC as a sum of enthalpies of vapor I_v and dry gas I_g (air)

$$I=I_g+I_v X \quad (21)$$

or

$$I=c_a t+(r_o+c_v t)X, \quad (22)$$

where c_a=1.004 and c_v=1.842 kJ/(kg·ºC) is the specific heat capacity of air and vapor, respectively; r_o=2,500 kJ/kg is the hidden heat of water vaporization; X is the air moisture content, kg/kg. Since enthalpy in its physical sense is the energy, attributed to the unit of mass, then during energy calculations a moisture content is numerically equal to the mass of water in 1 kg of wet air.

In a solar drying plant, an increase in the enthalpy of airflow dI occurs at the expense of reducing the heat of a wet mass ($-c_w\cdot\theta\cdot dm_w$), where c_w is the specific heat capacity of water; θ is the equilibrium temperature of a wet mass; $dm_w=dX$ is the mass lost by a body, equal to the moisture content acquired by the flow dX

$$dQ=d(u+pV)-I_w dW=dI-c_w\,\theta\, dX=0. \quad (23)$$

Hence the specific enthalpy of wet air per unit mass of the released moisture in a theoretical solar drying plant is

$$dI/dX=c_w\,\theta. \quad (24)$$

Upon integrating (31) within the range from state 1 to state 2, we obtain an expression that is characteristic of the equation for a straight line

$$\frac{I_2-I_1}{X_2-X_1}=\frac{\Delta I}{\Delta X}=c_w\cdot\theta. \quad (25)$$

In a solar drying plant enthalpy of the outlet flow is maximum (it is called equilibrium and denoted I_p) since relative humidity is close to saturation. Specific heat capacity of moisture in the process of drying is considered to be a constant quantity and is equal to such at a temperature of the wet thermometer, which is why the enthalpy of water $I_w=c_w\cdot\theta=c_w\cdot t_{wt}$=const [12].

Thus, in a solar drying plant the process occurs at a constant overall enthalpy, because the removed vapor introduces to the air exactly as much heat as was taken from the wet mass prior to evaporation. In a solar drying plant, a drying process can be implemented at any temperature provided a condition for the constancy of the flow enthalpy is satisfied

$$I_1=I_2=I=\text{const}. \quad (26)$$

Hence, enthalpy of a wet air at an arbitrary point along the line of adiabatic saturation relative to the fixed state I_1 and X_1 can be calculated from

$$I_2=I_1-c_w\cdot\theta\cdot(X_1-X_2). \quad (27)$$

In this process, the amount of heat consumed to remove moisture is proportional to the air temperature, which is called the equilibrium temperature or a line of a steady temperature of the wet thermometer.

In a solar drying plant, the intensity of drying is typically accelerated by rising the temperature of an incoming air stream. This means that the right-hand part of expression (25) must be supplemented with a term for the related heat losses. Specifically: q_a – additional heating of moisture to the current temperature; q_m – heating the material and the internal equipment q_e, and q_{hl} – compensation of heat losses with the flow of dry air as a vapor carrier [11]

$$\Delta I/\Delta X=(c_w\,\theta+q_a)-(q_m+q_e+q_{hl})=\Delta. \quad (28)$$

Depending on the ratio between the flow of incoming and consumed heat, a drying process can occur with an increase in the specific enthalpy $\Delta I/\Delta X=\Delta>0$ or a decrease in it $\Delta I/\Delta X=\Delta<0$. Therefore, during the first period of the constant drying rate, under condition for the existence of the free water surface, the heat consumption required to desorb 1 kg of moisture is equal to the hidden heat of vaporization r_θ at a temperature θ of the process. A value for r_θ can be calculated from

$$r_\theta=r_0+c_a\cdot\theta-c_w\cdot\theta. \quad (29)$$

In its place, over the second period of the drying rate descent, the process of vaporization begins inside the structural elements in the zone of the so-called bound moisture, while the surface of a material hosts, instead of free moisture, the adsorbed molecules of vapor. That is why the heat of desorption over the period of descending rate is taken to be equal to the sum of hidden heat of vaporization and energy of the bind between moisture and a material q_b

$$q_d=r_\theta+q_b. \quad (30)$$

Thus, it is necessary to introduce another term to the right-hand part of equation (25)

$$\Delta I_p/\Delta X=c_w\,\theta-q_b. \quad (31)$$

The ratio given describes the balance of energies in the case of an equilibrium process that is implemented at a low flow rate of a drying agent. All the supplied heat is then transferred to the dried mass, temperatures of the outgoing flow and moisture are equal, and its state is close to saturation.

That is why the process of fruit drying occurs at incomplete saturation of the outgoing flow, and, accordingly, the incomplete utilization of the supplied heat. Here a gain in enthalpy is lower than the equilibrium by the magnitude of the excess heat flow [12]

$$dI = dI_p - dQ_e/L,$$

and

$$dQ_e = (A_{dm} + A_w \cdot U)\cdot m_{dm} \cdot d\theta \pm \sum q \cdot dU,$$

where I_p is the enthalpy of flow during an equilibrium process; L is the air mass flow rate, kg/s; c_{dm} and c_w are the specific heat capacity of dry mass m_{dm} and water, respectively, kJ/kg·°C; Σq is the sum of additional arrival (–) or loss (+) of heat. Therefore, an hourly energy balance of a convection solar drying plant can be represented by the following expression

$$\Delta I = \left[c_w + E_b(U)\right]\cdot \Delta X -$$
$$-\frac{1}{L}\left[\left(c_{dm} + c_w \cdot U\right)\cdot m_{dm} \cdot d\theta \pm \sum q_b \cdot dU\right].$$

The result of integration is the derived balance expression throughout the entire cycle of fruit drying in a convection solar drying plant

$$\frac{I_f - I_i}{X_f - X_i} = \frac{\Delta I}{\Delta X} = c_w \cdot \theta_0 - q_m - \frac{1}{\Delta X}\int_{X_i}^{X_f} q_b \cdot dX \pm \sum q$$

or

$$I_f - I_i = A_w \cdot \theta_i \cdot \Delta X - \frac{1}{\sigma}\left(c_{dm} + c_w \cdot U_f\right)\cdot\left(\theta_f - \theta_i\right) -$$
$$-\int_{\%_i}^{\%_w} q_b \cdot dX \pm \sum q \cdot \Delta X,$$

where I_i, I_f is the initial and final enthalpy of wet air, kJ/kg; θ_i and θ_f are the initial and final temperatures of a dried material; U_r is the resulting moisture content, kg/kg; q_m are the specific heat costs to heat a material to the temperature of adiabatic evaporation; q_b is the specific heat of bond between moisture and the material; c_w and c_{dm} is the specific heat capacity of water and a dry material; Σq is additional heat: (+) of arrival, (–) of loss; $\sigma = L/m_{dm}$ is the specific consumption of thermal energy for desorption calculated per 1 kg of dry weight, which can be represented using the following equation [10]

$$\sigma = \frac{G}{m_{dm}} = \frac{(c_{dm} + c_w)\cdot \Delta\theta + \left(I_{ve} - A_w \cdot t + \bar{q}_b \pm \sum \bar{q}\right)\cdot \Delta U}{I_i - c \cdot t_f - I_{ve} \cdot \%_f}, \quad (32)$$

where L is the air mass flow rate, kg/s; m_{dm} is the mass of a dry material, kg; $\Delta\theta$ is a change in the temperature of a material from the beginning to the end of the process; I_{ve} is the enthalpy of vapor at the end of the process; $\bar{q}_b$ is the average heat of bond between moisture and a material, kJ/kg; q_m is additional heat equal to the sum of energies of evaporation and vapor expansion; $\sum \bar{q}$ is the balance of additional arrival (+) or loss (–) of heat; the two last quantities are accepted or calculated as the mean magnitudes of the entire process, kJ/kg. $\Delta U = U_i - U_f$ is the difference between the starting U_0 and final U_f moisture content of a material, kg/kg; ΔX is the difference between the starting X_i and final X_f moisture content of air, kg/kg.

The last balance equations make it possible, at known temperature and air flow rate, to estimate performance of a solar drying plant and vice versa under a stationary mode. However, both parameters are interdependent and their theoretical calculation is possible only for certain perfect conditions. Therefore, the balance equations are only used in order to analyze effectiveness of a solar drying plant. Solar drying plants mainly operate under a circular mode with a daily period and a random component of change in the flow of air. Therefore, the given equations should be used only to assess the work of a solar drying plant over small (hourly) intervals when the flow of solar energy can be considered stable. In the case of changing cloudiness, significant portion of the drying cycle in a solar drying plant belongs to transitional processes, and during prolonged cloudiness and at night it enters the mode of an atmospheric dryer.

In capillary-porous materials the bulk of moisture is in the bound state, which is why specific energy of desorption exceeds the hidden heat of vaporization. Moisture binding energy q_b, when drying a material, grows in line with a complex nonlinear dependence whose mean integral value is calculated from

$$\overline{q_b} = \frac{1}{U_f - U_i}\int_{U_i}^{U_f} q_b(U)dU. \quad (33)$$

During calculation, one uses an approximate average integral value for desorption energy, which is estimated based on the area under a respective approximation straight line. For most organic materials, angular coefficient of the approximation straight line is the same and equals 4,200 kJ/kg [11]. Therefore, the average binding energy in the process with known values for the starting U_i and final U_f moisture content is calculated from the following ratio [11]

$$\overline{q_b} \simeq 4200\frac{U_i - U_f}{2}. \quad (34)$$

The total value of the mean binding energy and the hidden heat of vaporization is employed as an input parameter in order to substantiate the daily heat capacity of an air collector.

Thermodynamic or energy efficiency of a solar drying plant as a thermal machine is typically assessed through the ratio of the useful energy to the consumed energy. Useful energy is understood as the evaporation energy of free and bound moisture; consumed energy is the energy of heating a heat carrier. Under a stationary operation mode, ratios of energies can be replaced with a ratio of the corresponding heat flows.

$$\eta_E = \frac{q_u}{q_{co}}. \quad (35)$$

In the approximation of the isobaric process in a solar drying plant the values for the consumed heat flow are equal to the difference in enthalpies of the flow of air at the inlet and outlet of the collector, and for the consumed – to the difference in enthalpies between the inlet and outlet of a drying chamber. In fact, a drying process is not completely reversible, which is why energy efficiency of the dryer is estimated based on the mass efficiency of a solar drying plant.

In practice, it is more important to assess effectiveness of a solar drying plant based on the specific mass of removed moisture Δm per unit of the supplied heat ΔQ – the mass efficiency of a solar drying plant. We propose to determine the current mass release of a convection solar drying plant based on the ratio of an hourly change in the mass of moisture

Δm_i of the consumed thermal energy, represented via the difference in enthalpies of the flow of air between the inlet and outlet of an air collector

$$\eta_m = \frac{\Delta m}{(I_{SC} - I_a)\cdot G\cdot \Delta\tau} = \frac{m_c \cdot \Delta U}{(I_{SC} - I_a)\cdot G\cdot \Delta\tau}, \qquad (36)$$

where m_{dw} is the dry weight, kg; G is the drying agent mass flow rate, kg/s; ΔU is a change in the moisture content, kg of dry matter/kg of wet matter; $\Delta\tau$=1 hour is the time interval between two measurements of mass.

Energy costs for moisture transfer in a convection dryer are typically estimated based on a change in enthalpy and moisture content of the flow of a heat carrier along the path from the inlet to a solar collector to a drying chamber's outlet. Enthalpy of the incoming flow is equal to the ambient air enthalpy, which is calculated from

$$I_a = c_a t_a + (c_v t_a + r_0)\cdot X_a,$$

where c_a=1.004 kJ/kg·K is the specific heat capacity of air; c_v=1.842 kJ/kg·K is the specific heat capacity of water vapor; r_0=2,500 kJ/kg is the hidden heat of water vaporization at 0 °C; t is the temperature in °C: X is the moisture content of external air.

At the SC's outlet the air moisture content is equal to that at the inlet, which is why an increase in enthalpy at SC is defined only by the higher temperature of the outgoing flow t_{SC}

$$I_{SC} = c_p t_{SC} + (c_{aa} t_{SC} + r_0)\cdot X_a.$$

At the outlet from a drying chamber temperature T_{CK} does not exceed the temperature of t_{SC}, while moisture content X_{SC} is larger at the expense of moisture Δm_m lost by fruit. Therefore, enthalpy of the outgoing flow is determined through its relative humidity and temperature t_{SC}

$$I_{CK} = c_p t_{SC} + (c_{aa} t_{SC} + r_0)\cdot X_{SC}.$$

The current energy efficiency of a solar drying plant, equal to the ratio of an hourly consumption of heat for desorption to the hourly heat capacity of a solar collector

$$\eta_V = \frac{(r_\theta + q_b)\cdot \Delta\%}{A_{aa}\cdot (t_{SC} - t_a)}$$

cannot be calculated because of the lack of objective data about the current values of the moisture binding energy in fruit q_b based on ratio $\Delta I/\Delta X$. Instead, it is possible to evaluate the current energy efficiency of drying by heated air based on the ratio of an hourly moisture loss Δm_l to a change in the enthalpy of the entire mass of air $I_{DC} - I_{SC}$

$$\eta_{ks} = \frac{\Delta m_f}{(I_{DC} - I_{SC})\cdot G_m \cdot \Delta\tau} = \frac{N}{(I_{DC} - I_{SC})\cdot G_m},$$

where G_m is the heat carrier mass flow rate; $\Delta\tau$ is the time interval between two measurements, s; N is the rate of drying. If we consider performance efficiency of the entire solar drying plant, it is more appropriate to relate the rate of moisture removal to heat productivity of a solar collector or to the density of solar energy arrival

$$\eta_S = \frac{\Delta m_l}{c_{aa}\cdot (t_{SC} - t_a)\cdot G_m \cdot \Delta\tau} = \frac{N}{c_{aa}\cdot (t_{SC} - t_a)\cdot G_m}.$$

The total energy efficiency of a dryer is proposed to evaluate based on the ratio of the current drying rate to the density of arrival of solar energy E onto a solar collector

$$\eta = \frac{\Delta m_f}{E\cdot \Delta\tau} = \frac{N}{E}, \qquad (37)$$

where c_{aa} is the specific heat capacity of an incoming heat carrier; $t_{SC} - t_a$ is the temperature difference at the inlet and outlet of the collector.

Given such a representation, the side heat losses are not considered, which is convenient to compare the energy efficiency of wet removal by solar drying plants with different techniques for the generation and supply of energy. Specifically, a convection solar drying plant, which works during operation under a mode close to the theoretical, consumes and loses for drying only the energy of the environment. Since the operation of an actual solar drying plant always includes a theoretical component, the energy costs for drying could be smaller than the work for desorption. Therefore, energy-saving technologies of drying must necessarily take into consideration this energy component of moisture removal when substantiating the kinetics and energetics of convective drying of fruit in a solar drying plant.

5. Results of substantiation of the kinetic and energy parameters of convection drying of fruit in a solar drying plant

5. 1. Results of studying the convection drying process of fruit in a solar drying plant

We performed convection drying of fruit in a solar drying plant at the privately-owned farm FG "Zorya", located in the town of Kortsy, Rivne oblast, Ukraine, in the summer-autumn period from 16 July to 29 September, 2018.

Detailed description of the results of research into the technological process of drying fruits in a solar drying plant, as well as analysis of influence of operational parameters on energy efficiency of the installation with different configuration and on duration of the drying process, is given in paper [13]. Specifically, we investigated the work of the energy unit of a solar drying plant with different configuration, namely, in a combination with a mirror concentrator and a thermal battery and without applying them, as well as under the mode of natural periodicity.

Depending on the technological techniques for treating the raw materials prior to drying, the fruits under consideration demonstrated significant differences in terms of drying duration. For example, the apples cut in slices with a thickness of 8 mm, and treated with a sugar solution, were dried in a solar drying plant for 27 hours (Fig. 1), while those without treatment – for 33 hours.

The optimal apples in terms of drying duration are those apples that were cut in slices with a thickness of 8 mm and were treated with a sugar solution (Fig. 1).

Thus, based on analysis of the convection fruit drying process, depending on the treatment technique, the best results in terms of drying duration in a solar drying plant and quality of the finished product were demonstrated by apples cut in slices with a thickness of 8 mm, which were treated with a sugar solution.

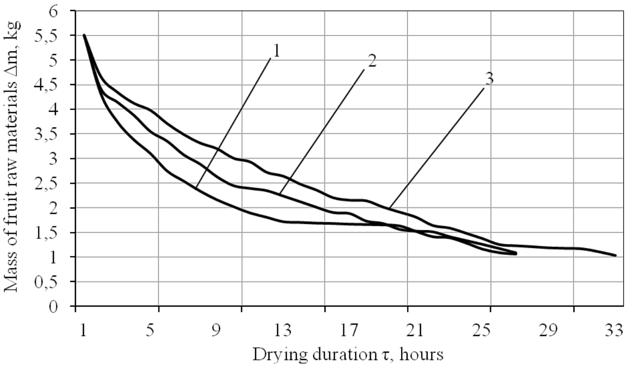

Fig. 1. Dynamics of apple drying: 1 – circles of 8 mm treated with a sugar solution; 2 – circles of 8 mm exposed to blanching; 3 – circles of 8 mm without treatment

5. 2. Results of studying the kinetics of fruit drying in the process of operation of a solar drying plant

When studying the kinetics of drying, we used as a raw material for drying the apple fruits cut in slices with a thickness of 8 mm treated with a sugar solution, exposed to blanching, and without treatment, in the amount of 5.5 kg (Fig. 2) over different periods.

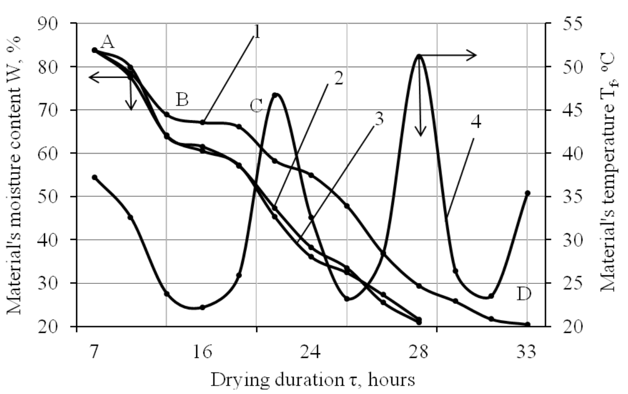

Fig. 2. Kinetics of apple drying: 1 – a batch laid on 16.07.2018, at 12:00, circles of 8 mm treated with a sugar solution; 2 – a batch laid on 10.08.2018, at 12:00, circles of 8 mm exposed to blanching; 3 – a batch laid on 15.08.2018, at 12:00, circles of 8 mm without treatment; 4 – temperature of the dried material

Based on analysis of the kinetics of fruit drying (Fig. 2), it was established that at the beginning of drying the evaporation of moisture occurs slowly (line AB), because the dried material starts to rapidly heat up. If one increases temperature of the dried material the evaporation of moisture intensifies and the process of evaporation occurs along a straight line BC. Point C characterizes the moment when the process of evaporation of moisture starts slowing down. Moisture content at point C is called the first critical humidity. The CD straight line characterizes a slowdown of moisture evaporation. At point D, material's humidity is approaching the equilibrium humidity where drying is terminated.

Thus, despite the diversity of modes and weather conditions during fruit drying, the drying curves demonstrate the same character that makes it possible to establish the respective functional dependences $W=f(\tau)$ and $T_f=f(\tau)$.

5. 3. Results of research into technological operational modes of a solar drying plant

During drying, the important technological parameters of the process are:

1) the rate of a heat carrier flow in a solar drying plant, which ranged v_{hc} – 1÷3 m/s;

2) the temperature of a heat carrier in a drying chamber T_{hc} – 20÷60 °C;

3) the moisture content of a heat carrier $d_{0...n}$.

At the time of research, the average moisture content of outside air during tests was 13.2 g/kg. The difference between moisture content of the consumed drying agent d_3 and moisture content of the heat carrier at the inlet to a drying chamber d_2 defines the amount of moisture removal from a single kilogram of a drying agent, which ranged from 3 to 14 g/kg dry air.

Our research was carried out at a temperature of the heat carrier T_{hc}=30÷60 °C that reaches a drying chamber in the day time, in the evening time T_{hc}=30÷20 °C, the speed of a heat carrier v_{hc}=1÷2.5 m/s, and moisture content d=10÷14 g/kg of dry air. The curves of drying intensity (Fig. 3) allow us to analyze the effect of a drying mode on the kinetics of the process. All curves of drying intensity are shifted along the abscissa axis at a magnitude of the equilibrium moisture content of a dried material, and the countdown of moisture content is performed from equilibrium.

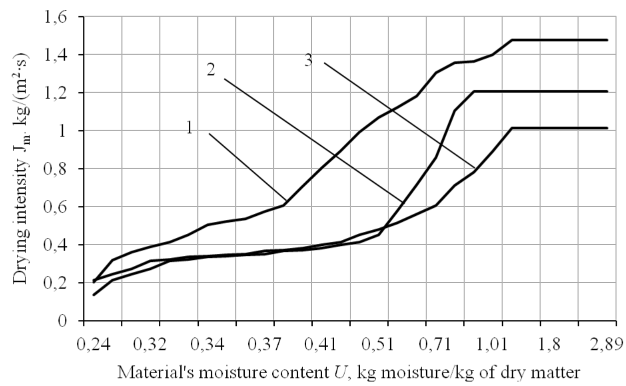

Fig. 3. Intensity curves of apple drying: 1 – circles of 8 mm treated with a sugar solution; 2 – circles of 8 mm exposed to blanching; 3 – circles of 8 mm without treatment

An analysis of the obtained results (Fig. 3) revealed that the curves of drying intensity over different periods of 16.07–29.08.2018 (curves 1, 2, 3) of operation of a solar drying plant, despite the diversity of modes of drying, physical parameters of the environment and weather conditions, have the same character. That made it possible to establish the intensity of drying J_m, which for apples at moisture content U from 2.89 to 0.24 kg moisture/kg of dry matter is 1.57÷0.18 kg/(m²·s).

When conducting the estimation quantitative experiments regarding the operation of the power unit of the installation, we established numerical values for the energetics of convection fruit drying in a solar drying plant. The results obtained are summarized in Tables 1, 2.

In accordance with the structure of the distribution of density of the solar energy that reaches an air collector with an area of 1.5 m^2 within 24 hours on 16.07.2018, we obtain that the solar drying plant consumed, over one hour, energy of solar radiation in the range from 723 to 800 W/m^2. Thereby converting it into heat (2,368.2 kJ), consumed by the heat carrier (1,984.9 kJ) and spent to heat the product (836.3 kJ) and evaporation of moisture 756.7 kJ, and part – by the heat accumulator (356.9 kJ).

Table 1

Arrival of energy for convection drying of fruit in a solar drying plant over one hour

Arrival of heat	Values for balance components, kJ		Ratio q_u/q_{co} ×100 %	
	day time	night time	Day time	night time
Density of solar radiation absorbed by the absorber	723	–	24.5	–
Energy generated by the absorber	2,368.2	–	29.3	38.5
Energy that enters a drying chamber from the heat carrier heated in an air collector and by a thermal battery	1,984.9	1,236.5	17.7	19.1
Energy of a thermal battery	356.9	286.7	28.5	42.4
Total	4,710	1,523.2	100	100

Table 2

Losses of energy during convection drying of fruit in a solar drying plant over one hour

Heat loss	Values for balance components, kJ		Ratio q_u/q_{co} ×100 %	
	day time	night time	Day time	night time
Heat consumed to heat the sieves	1,828.3	1,234.7	21.4	31.2
Heat consumed to heat the product	836.3	502.7	23.2	18.9
Heat consumed to moisture evaporation	756.7	507.2	32.4	18.8
Heat removed by the consumed heat carrier	179.3	132.9	12.9	18.7
Heat losses into the environment	41.26	24.5	10.1	12.4
Total	3,641.9	1,167.3	100	100

Thus, the analysis of energy parameters reveals that the greatest energy losses occur in the drying section of the installation – 83.2 %. Observing the energy for convection fruit drying in a solar drying plant over one hour, one can see that thermal energy q_u/q_{co}·100 % is generally (97.2 %) consumed with a mixture of the used heat carrier for the evaporation of moisture from a material.

When performing the estimation-quantitative experiments regarding an analysis of energy efficiency of a solar drying plant over one cycle of drying, we built a bar chart (Fig. 4). The chart demonstrates the complete hourly energy efficiency of a solar drying plant estimated based on the ratio of the current drying rate to the density of arrival of solar energy E onto a solar collector.

Therefore, efficiency of the solar drying plant (Fig. 4) is significantly affected by the density of arrival of solar energy E, which ranges in the morning period (from 7:00 to 10:00) from 456 to 965 W/m^2 and in the evening period (from 17:00 to 20:00) – from 734 to 223 W/m^2, which makes it possible to obtain η from 23 to 60 %.

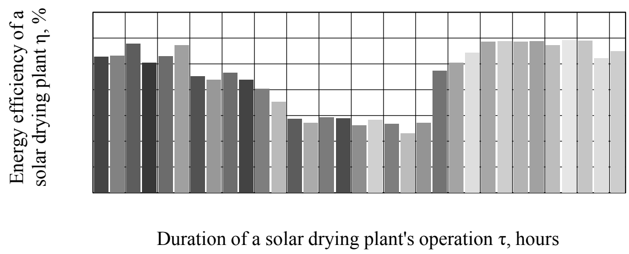

Fig. 4. Energy efficiency of solar drying plant over 24 hours on 16–17.08.2018

6. Discussion of results of substantiating the kinetic and energy parameters of convection drying of fruit in a solar drying plant

We have considered main regularities in the process of convection fruit drying in a solar drying plant under the non-stationary operating modes of the installation. We provide a detailed analysis of research methods into critical moisture content and techniques to determine the intensity, duration of fruit drying, and energy efficiency of the installation. It has been shown that the intensification of the drying process should be based on the study of thermal-physical, physical-chemical, and other properties of fruits as the object of drying. Therefore, construction of a unified generalized theoretical base of convection fruit drying required a comprehensive combination of thermal-physical and physical-chemical properties of fruits and the kinematic heat-and-mass exchange characteristics and thermo-technical parameters of the installation.

While improving the procedure for calculating the kinetic and energy parameters for convection drying of fruit in a solar drying plant, we employed as a thermal-physical basis a system of differential equations of heat-and-mass transfer by O. V. Lykov. The improved calculation procedure makes it possible to analyze an increase in the efficiency of the technological process of drying and to reduce energy consumption at the expense of solar energy. Specifically, the kinetics, dynamics, duration, and intensity of fruit drying, consumption of thermal power for initial heat-and-moisture treatment and drying process; the losses of thermal energy through the enclosure and with the consumed drying agent, efficiency of the installation. These calculations are based on the results of studies into convection drying of fruit in a solar drying plant depending on the technological techniques for treating raw materials.

In a solar drying plant, there could simultaneously occur the processes of convection, radiation, and thermal drying, whose separate contribution to the result is difficult to assess. It is absolutely clear that in the day time, at low humidity of incoming air and the large intensity of solar radiation, it is advisable to reduce the temperature of a drying agent, and to accumulate the excessive heat. However, a solar drying plant most of the time operates under transitional modes of heat exchange.

That is why it is possible to calculate only the energy characteristics of a drying process based on the derived theoretical relations, obtained under the assumption of a quasi-stationary regime. Under such operating conditions, the basic condition is satisfied, which is obtaining a high-quality dried material during a low-temperature drying mode in a solar drying plant.

The publications that address fruit drying mainly consider the effect of temperature and air velocity on the kinetics of moisture removal. Thus, in the dryers with traditional power supply the high relative humidity of incoming air is reduced by increasing its temperature. Instead, in a solar drying plant it will suffice, in terms of energy, to slightly heat a drying chamber with a backup source of heat over night periods when humidity approaches the dew point temperature. In this case, a drying chamber works under the mode of an atmospheric dryer. The positive results of such an influence on humidity of the incoming flow are visually confirmed by the given graphical dependences of the kinetics and dynamics of apple drying, built based on the results of measuring humidity. In addition, according to the results obtained during modelling the intensity of apple drying by different treatment techniques, namely, 1 – circles of 8 mm treated with a sugar solution, 2 – circles of 8 mm exposed to blanching; 3 – circles of 8 mm without treatment.

We have examined the kinetics, dynamics, and intensity of fruit drying in a solar drying plant depending on the technological techniques for treating raw materials. That has made it possible to establish the kinetic characteristics of the process – the duration of drying, which, for the apples treated with a sugar solution, or exposed to blanching, is 27 hours, without treatment – 33 hours. In terms of drying duration in a solar drying plant, as well as quality of the finished product, the best results were shown by apples cut in slices with a thickness of 8 mm, which were treated with a sugar solution. The intensity of drying J_m in a solar drying plant of apples at moisture content U from 2.89 to 0.24 kg moisture/kg of dry matter is 1.57÷0.18 kg/(m^2·s).

We have established the effect of thermal-physical parameters of the environment on the energy characteristics and efficiency of a solar drying plant and the arrival and loss of thermal energy in the process of fruit drying. We have defined the thermal-technical parameters of the heat carrier that reaches the solar drying plant, namely the air temperature in the daytime, T_{hc}=30÷60 °C, in the evening time T_{hc}=30÷20 °C, the velocity of a heat carrier v_{hc}=1÷2.5 m/s, and moisture content d=10÷14 g/kg of dry air. It was found that the solar drying plant utilized energy of solar radiation in the range from 723 to 800 W/m^2, thereby converting it into heat (2,368.2 kJ), consumed by the heat carrier (1,984.9 kJ) to heat the product (836.3 kJ) and to evaporate moisture, 756.7 kJ, part – a thermal accumulator (356.9 kJ). It was determined that the efficiency of a solar drying plant, which totaled from 23 to 60 %, is affected by a change in the density of arrival of solar energy E, which ranged in the morning period (7:00 to 10:00) from 456 to 965 W/m^2 and in the evening period (from 17:00 to 20:00) from 734 to 223 W/m^2.

Thus, the set of analytical and calculation-quantitative studies has confirmed the possibility to intensify the process of convective drying of fruit in a solar drying plant. Therefore, the use of a solar drying plant during convection fruit drying is appropriate and effective.

The research reported in this work is the final stage of a comprehensive study into improvement of the efficiency of the technological process of fruit drying based on the development of design and substantiation of operating modes of a solar drying plant, which would decrease the consumption of energy resources at the expense of solar energy. The results obtained could be useful for improving the technology and equipment for fruit drying.

7. Conclusions

1. We have improved the procedure for calculating the kinetic and energy parameters of the convection drying of fruit in a solar drying plant, based on which it is possible to analyze improvement in the efficiency of the technological process of drying and to reduce energy costs at the expense of solar energy. Specifically, the kinetics, dynamics, duration, and intensity of fruit drying, consumption of thermal power for initial heat-and-moisture treatment and drying process; losses of heat energy through the enclosure and with the used drying agent, efficiency of the installation. These calculations are based on the results of study conducted into convection drying of fruit in a solar drying plant depending on the technological techniques for treating raw materials.

2. We have examined the kinetics, dynamics, and intensity of fruit drying in a solar drying plant depending on the technological techniques for treating raw materials. Specifically, for apples cut in slices with a thickness of 8 mm, treated with a sugar solution, exposed to blanching, and without treatment. That makes it possible to specify the following kinetic characteristics of the process: the duration of drying, which, for the apples treated with a sugar solution, or exposed to blanching, is 27 hours, without treatment – 33 hours. The intensity of drying J_m in a solar drying plant of apples at moisture content U from 2.89 to 0.24 kg moisture/kg of dry matter is 1.57÷0.18 kg/(m^2·s).

3. We have established the impact of energy parameters on the technological parameters of a heat carrier and efficiency of the installation. In particular, over a single cycle of drying, namely, in one hour, from 1.5 m^2 of the air collector's surface, a solar drying plant used energy of solar radiation in the range from 723 to 800 W/m^2, thereby converting it into heat (2,368.2 kJ), consumed by the heat carrier (1,984.9 kJ) and spent to heat the product (836.3 kJ) and to evaporate moisture 756.7 kJ, part – a thermal accumulator (356.9 kJ). Efficiency η of the solar drying plant was established that equaled 23 to 60 % depending on a change in the density of arrival of solar energy E, which ranged in the morning period (7:00 to 10:00) from 456 to 965 W/m^2 and in the evening period (from 17:00 to 20:00) from 734 to 223 W/m^2.

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