*Розроблено і обґрунтовано наукові положення щодо діагностики тепломасообмінних процесів при конвективному сушінні фруктів. Виконано аналіз і синтез математичної моделі технологічного процесу конвективного сушіння фруктів у геліосушарці. Проведено моделювання стану тепло-, волого-, масоперенесення в середині висушуваного матеріалу на основі системи диференціальних рівнянь, в яких використано ступінчастий метод розрахунку процесу сушіння фруктів*

*Ключові слова: сонячна енергія, геліосушарка фруктів, дифузія, вологовміст, тепломасоперенесення, інтенсифікація, конвективне сушіння*

*Разработаны и обоснованы научные положения относительно диагностики тепломассообменных процессов при конвективной сушке фруктов. Выполнен анализ и синтез математической модели технологического процесса конвективной сушки фруктов в гелиосушилке. Проведено моделирование состояния тепло-, влаго-, массопереноса в середине высушиваемого материала на основе системы дифференциальных уравнений, в которых использован ступенчатый метод расчета процесса сушки фруктов*

*Ключевые слова: солнечная энергия, гелиосушилка фруктов, диффузия, влагосодержание, тепломассоперенос, интенсификация, конвективная сушка*

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# RESEARCH INTO TECHNOLOGICAL PROCESS OF CONVECTIVE FRUIT DRYING IN A SOLAR DRYER

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## 1. Introduction

Convective fruit drying is a complicated heat and mass exchange process. To examine it, it is necessary to determine thermal, physical-mechanical, chemical and other properties of fruit as an object of drying. In addition, it is necessary to choose and substantiate the modes of the process with subsequent creation of rational designs of energy-saving drying plants [1]. Development of the new and improvement of the existing technologies and techniques of drying are determined not only by intensities of heat and moisture exchange between the source (generator) of heat and an object of drying, but also by the intensities of heat and moisture transfer inside the material. Therefore, a focused search for ways to intensify the process of convective drying should include creation of new progressive technologies. Along with it, it is important to develop universal methods of the synthesis and analysis of dependences of heat and mass exchange characteristics of the process on thermal and physical properties of fruits.

Fundamentally important results of research of scientists, obtained earlier, do not completely reflect a complex multifaceted picture of kinetics and dynamics of heat and mass exchange processes of the objects, listed above. In particular, these studies disregard the changes between physical parameters of the environment, thermal-physical parameters of dried fruits and their relationship with the heat and mass exchange processes.

Tackling the issue of resource saving is complicated by the fact that fruits are characterized by high variability of thermal, physical-mechanical, structural-mechanical, and chemical properties. Therefore, creation of scientific and technical fundamentals of convective fruit drying with the aim of improving technology and technique of drying is a relevant task, which has a significant economic value for the intensification of the processes of drying.

## 2. Literature review and problem statement

Intensification of technology of fruit drying predetermines creation of new mathematical models that would adequately describe the mechanism of heat and mass transfer in the material that is dried.

Paper [2] develops a one-dimensional mathematical model of non-isothermal moisture transfer and viscous-elastic state of fruit in the process of drying. It considers the effect of anisotropy on mechanical, temperature and moisture properties of the dried material. In accordance with approaches to modeling, they obtained the system of equations of heat and mass transfer considering phase transformations and drying up of wet materials in the process of drying. However, the paper does not highlight the issue of the driving force of moisture transfer inside the material.

Authors of paper [3] performed modeling of the process of removing moisture from fruit within the framework of a Stefan problem. From a mathematical point of view, boundary problems of heat and mass transfer are fundamentally different from classical problems. A dependence of characteristic dimensions of the evaporation area on time complicates the use of classical methods of separation of variable or integral transformations. Analytical studies are carried out for limited cases of already known law of boundary motion, for example, linear or parabolic. For this purpose, they used methods of thermal potentials, contour integration, power series, and "instant" natural functions of Grinberg. Obtaining solutions to boundary problem of heat and mass transfer came down to defining the Voltaire second order integral equations with complex cores. These studies established only qualitative results of behavior of such systems. However, the model disregards diffusion coefficient and energy of bound moisture per one kilogram of removed moisture.

Construction of the mathematical model in article [4] describes heat and mass exchange and deformation-relaxation processes during fruit drying. They include, in particular, a mechanism of heat and mass transfer based on the phenomenological perceptions of the mechanics of hereditary environments and methods of non-equilibrium thermodynamics. Due to the complexity of structural composition of fruit as a heterogeneous anisotropic colloid capillary-porous body, the model fails to establish constant heat and mass exchange indicators.

In the framework of a different approach, mathematical models of the process of fruit drying were developed based on the theory of multiphase filtering in heterogeneous environments [5]. In these studies, effective characteristics of deformation-relaxation processes, averaged over the phases, were introduced. The conducted analysis of mathematical modeling of deformation-relaxation processes during fruit drying showed a shift in the emphasis of research to the uniformed homogeneous area. Therefore, construction of a mathematical model of rheological state of fruit in the range of change in the physical-mechanical properties considering the multiphase structure of the material is a complex and unresolved task.

Study [6] performed functional transformations of the boundary problem of heat and mass transfer, based on the Fick's law for moisture flow through a membrane. It makes it possible to obtain numerical-analytical solutions to a boundary problem of heat and mass transfer for boundary conditions of the third kind. However, the proposed method does not take into account the energy of bound moisture and entropy of the dried material per 1 kg of removed moisture.

Authors of paper [7] developed an engineering procedure for calculation of the processes of heat and mass transfer in fruits during their drying with consideration of the motion of deepening of the evaporation area. For some materials, a criterion of phase transfer that is changed by the coordinate of the body is taken into account in boundary conditions. The described procedure is very general and does not live up to modern achievements in the theory of heat and mass transfer and heat and mass exchange. In particular, results of the research into deepening of the zone of evaporation of moisture from fruit are described by the criteria for phase transfer. On the surface of fruit raw material, moisture, as a residue after washing, exists only at the stage of warming. For the rest of the time, the liquid phase is a multi-component solution of organic and mineral substances, rather that a free fluid, like in classic dispersed materials of inorganic origin. Therefore, during fruit drying, it is impossible to draw the line between criteria of phase transition of the process of removing moisture.

Study [8] solved the problem of defining viscous-elastic deformation of fruit as a three-phase system taking into account anisotropy of thermal-mechanical characteristics. A mathematical model of heat and mass transfer for the periods of the constant and decreasing speed of drying of capillary-porous materials was formulated. A mathematical model of rheological behavior of fruit as three-phase environment considering anisotropy of thermal-mechanic characteristics was constructed. The authors explored regularities of the influence of technological parameters of drying on processes of viscous-elastic deformation and heat and mass transfer inside the dried material. However, the proposed model does not examine the velocity of moisture yielding of the dried material in the operation zone of the heat carrier under conditions of the diffusion process of moisture transfer in the dried material.

A selection of rational technologies of convective drying of fruit with provision of maximum intensities of processes and minimum energy resources is an important task. Complexity of the process of fruit drying is predetermined by the progress of interconnected physical phenomena of heat and mass transfer and deformation under conditions of high variability of structural and physical properties of hygroscopic solids. For this purpose, it is necessary to take into account the changes between physical parameters of the environment, thermal and physical parameters of the dried fruit and their relationship with heat and mass exchange processes. Authors of the listed papers disregard these changes. For the study of heat and mass exchange characteristics of the process of convective fruit drying considering the motion of evaporation zone in the material under non-stationary operation mode of a solar dryer, we face the problem of development of the mathematical model of heat, moisture, and mass exchange. This process of modeling should be based on application of the theory of heat and mass transfer and heat and mass exchange. This makes it possible to use the main provisions of the laws and methods of classic physics, heat engineering, and mathematics for solving differential equations of heat and mass transfer using the stepwise method for calculation of the process of fruit drying. In particular, for the calculation of a simplified mechanism of heat and mass transfer, where it is necessary to apply the methods of mathematical statistics to process experimental data.

## 3. The aim and tasks of the study

The aim of present research is to explore theoretically and experimentally the process of convective fruit drying for a non-stationary operation mode of a solar dryer.

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

– to develop a mathematical model of heat, moisture and mass exchange during convective fruit drying in a solar dryer;

– to establish dependences of heat and mass exchange characteristics of the process of fruit drying on thermal and technical parameters of a heat carrier;

– to explore a technological process of fruit drying and to determine dependences of the duration of this process in a solar dryer on the velocity of moisture transfer of the dried material in the operation zone of a heat carrier.

## 4. Materials and methods of mathematical modeling of the process of fruit drying in a solar dryer

### 4. 1. Development of a mathematical model of technological process of fruit drying in a solar dryer

In the agricultural sector, solar-thermal plants found their wide application. For example, for drying vegetable raw materials, in particular fruit, solar energy is extensively used for the needs of drying farms. For the zone of western Polissya, it is possible to apply fully this type of dehydration of material. In particular, at Lviv National Agricultural University (Ukraine) at the Department of Power Engineering, there was developed a solar dryer with a thermal battery and a flat mirror concentrator, which is an active system for using solar energy [9]. Functional-parametrical schematic of the solar dryer is shown in Fig. 1.

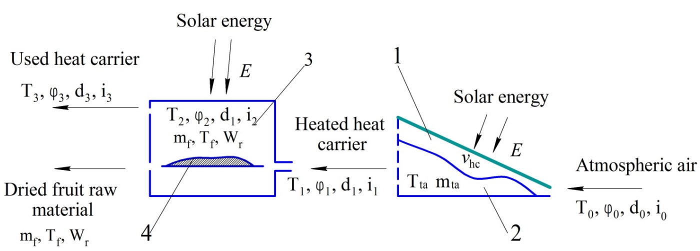


Fig. 1. Functional-parametrical schematic of solar dryer: 1 – air collector; 2 –heat battery; 3 – drying chamber; 4 – fruit raw material

Consider the principle of operation of a solar dryer. Air from the environment at a set velocity enters air collector 1, is heated between the elements of bulk heat battery 2 and enters drying chamber 3. Drying chamber 3 contains fruit raw material 4 that is dried. The used heat carrier is removed by natural convection to the environment [10]. In order to strengthen capture of solar energy, a mirror concentrator is mounted on the receiving surface of the air collector from both directions – western (in the morning) and eastern (in the evening). This makes it possible to improve energy parameters in operation of the solar dryer during morning and evening hours.

The designed solar dryer plant matches the concept of an active solar energy plant. At the same time, the air collector and the thermal battery, combined in one unit, do not agree with the classic examples of solar thermal plants. For the designed plant, the ratios between time dependences between kinetic and power parameters were not established theoretically. For example, it is impossible to conduct separate testing of the air collector and the mirror concentrator by the standard method, or to calculate the dynamic properties of the bulk heat battery, or to explore the drying process. That is why parameters, used to assess effectiveness of the adopted solutions, were determined experimentally during field testing of the power unit of the solar dryer (source of thermal energy (air collector) – solar dryer – battery – mirror concentrator – environment – object of drying).

Fruit drying in the solar dryer within 24 hours is characterized by uneven periodicity of solar energy inflow. That is why temperature of the heat carrier here changes over 24 hours depending on the weather and the season. In this connection, the patterns that describe the drying process must represent this periodicity.

Temperature of the heat carrier and that of fruits in a drying chamber changes by the sinusoidal law.

– for the heat carrier:

$$T_{dc}(\tau)=\left(\frac{T_{hc1}+T_{hc2}+T_{hc3}}{3}\right)+A_{Thc}\cdot\sin\left(\frac{2\pi}{\tau_d}\cdot\tau\right),\ ^{\circ}C; \tag{1}$$

– for fruit:

$$T_f(\tau)=T_f+A_{T_f}\cdot\sin\left(\frac{2\pi}{\tau_d}\cdot\tau\right),\ ^{\circ}C, \tag{2}$$

where $T_{dc}(\tau)$ is the heat carrier temperature in the drying chamber, °C; $T_f(\tau)$ is the temperature of fruit in the drying chamber, °C; $T_{hc1}$, $T_{hc2}$, $T_{hc3}$ are, respectively, the temperatures of inflows and outflows of the heat carrier, °C; $T_f$ is the temperature of fruit, °C; $A_{Thc}$ $A_{Tf}$ are, respectively, the amplitude of fluctuation of temperature of the heat carrier and the fruit, °C; $\tau_d$ is the day duration, s; $\tau$ is the duration of drying, s.

Moisture content of the heat carrier is determined by formula:

$$d_{0...n}=622\cdot\frac{\frac{\varphi_{0...n}}{100}\cdot p_{vhc}^{O}}{P-\frac{\varphi_{0...n}}{100}\cdot p_{vdc}^{O}},\ g/kg$$

or

$$X_{0...n}=0{,}622\cdot\frac{\frac{\varphi_{0...n}}{100}\cdot p_{vhc}^{O}}{P-\frac{\varphi_{0...n}}{100}\cdot p_{vdc}^{O}},\ kg/kg, \tag{3}$$

where $d_{0...n}$ is the moisture content of the heat carrier, g/kg; $\phi_{0...n}$ is the relative moisture of the air, %; $p_{vhc}$ is the pressure of saturated vapor in the inflow at a given air temperature, Pa; $p_{vdc}$ is the pressure of saturated vapor in the drying chamber at a given air temperature, Pa; $X_{0...n}$ is the moisture content of the heat carrier, kg/kg.

Based on an analysis of the theory of heat and mass transfer and heat and mass exchange, we improved the mathematical model of convective drying, based on the simplified mechanism of heat and mass exchange. In particular, it was accepted that moisture in the material is in a liquid state, the heat and mass exchange between the heat carrier and the material is carried out by convection. In this case, temperature gradient of the material is low, and the driving force of moisture transfer inside the material is diffusion. It is described by differential levels of heat and mass transfer as follows:

– equation of heat transfer:

$$c_f \cdot \rho_f \cdot \frac{\partial T_f(\tau)}{\partial x} = \frac{\partial}{\partial x}\left(\lambda \cdot \frac{\partial T_f(\tau)}{\partial x}\right) + $$
$$+\varepsilon \cdot q_{bm} \cdot \frac{\partial}{\partial x}\left(D \cdot \rho_f \cdot \frac{\partial U}{\partial x}\right) + $$
$$+\varepsilon \cdot q_{bm} \cdot \frac{\partial}{\partial x}\left(D \cdot \rho_f \cdot \delta_T \cdot \frac{\partial T_f(\tau)}{\partial x}\right), \qquad (4)$$

– equation of moisture transfer:

$$\frac{\partial U}{\partial \tau} = \frac{\partial}{\partial x}\left(D \cdot \frac{\partial U}{\partial x}\right) + \frac{\partial}{\partial x}\left(D \cdot \delta_T \cdot \frac{\partial T_f(\tau)}{\partial x}\right), \qquad (5)$$

where $T_f(\tau, x)$ is the temperature of fruit, which is a function of duration of fruit drying $\tau$; $U(x)$ is the change of the field of moisture content of the dried material along coordinate x; $c_f$ is the specific thermal capacity of fruit, kJ/(kg·°C); $\lambda$ is the coefficient of thermal conductivity, W/(m²·°C); $\rho_f=(\rho_o-\rho_i)$ is the density of fruit, kg/m³; U is the moisture content of fruit, kg of moist/kg of dry material; $\varepsilon$ is the criterion of the phase transition, equal to the ratio of the amount of vapoured moisture to moisture content in a certain volume (at $\varepsilon$=1 water moves in the form of vapor, at $\varepsilon$=0 – in the form of liquid); D is the diffusion coefficient, m²/s; x is the spatial coordinate, mm; $\delta_T$ is the thermo-gradient coefficient, 1/°C; $\frac{\partial U}{\partial x}$ and $\frac{\partial T_f(\tau)}{\partial x}$ – are, respectively, gradients of moisture content and temperature of material.

Diffusion coefficient is calculated by formula [11]:

$$D=(0{,}36 \cdot T_{hc}-2{,}31 \cdot v_{hc}-4{,}5) \cdot 10^{-10},\ m^2/s, \qquad (6)$$

where $T_{hc}$ is the temperature of the heat carrier, °C; is the heat carrier velocity, m/s.

Original conditions of the mathematical model will take the 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 the moisture content of fruit in the initial moment of period of drying.

The boundary conditions may be written as follows:

– in the center of the dried material (condition of symmetry is shown in Fig. 2):

$$\frac{\partial T_f(\tau)}{\partial x_{x=0}} = 0;\ \frac{\partial U}{\partial x_{x=0}} = 0; \qquad (7)$$

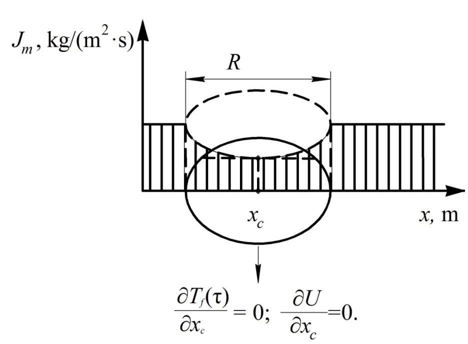


Fig. 2. Schematic of convective fruit drying

– on the surface of dried material (condition of the third kind):

$$\alpha \cdot \left[T_{dc}(\tau) - T_f(\tau)_R\right] =$$
$$= \lambda \cdot \frac{\partial T_f(\tau)}{\partial x_{x=R}} - \left|\rho_f \cdot (1-\varepsilon) \cdot q_{bm} \cdot \beta \cdot (U_{x=R} - U_e)\right|; \qquad (8)$$

$$\alpha \cdot (U_{x=R} - U_e) = D \cdot \frac{\partial U}{\partial x_{x=R}} + \left|D \cdot \delta_T \cdot \frac{\partial T_f(\tau)}{\partial x_{x=R}}\right|, \qquad (9)$$

where $\alpha$ is the coefficient of thermal exchange, W/(m²·°C); $\beta$ is the coefficient of mass exchange, m/s; $U_e$ is the equilibrium moisture content, kg of moist./kg of dry material; R is the thickness of fruit cutting, mm.

Energy of bound moisture in fruits $q_{bm}$ is calculated by formula:

$$q_{bm} = 4200 \cdot \frac{U_o - U_r}{2} + c_{hc} \cdot T_{hc2} +$$
$$+(c_s \cdot T_{hc2} + r) \cdot d_2 + (T_f(\tau) \cdot S_f),\quad kJ/kg, \qquad (10)$$

where $q_{bm}$ is the energy of bound moisture in fruit, kJ/kg; $U_o$, $U_r$ are, respectively, original and resulting moisture content of fruit, kg of moist./kg of dry material); $c_s$, $c_{hc}$ are, respectively, specific heat capacity of water vapor and of the heat carrier, kJ/(kg·°C); r is the specific heat of vaporization, kJ/kg; $T_{тн2}$ is the heat carrier temperature, °C; $d_2$ is the moisture content of the heat carrier g/kg; $S_f$ is the entropy of the dried material per one kilogram of removed moisture, kJ/(kg·°C).

To determine mass transfer in the period of drying, we shall compile a parametric scheme of mass transfer when drying in a solat drier, which is shown in Fig. 3.

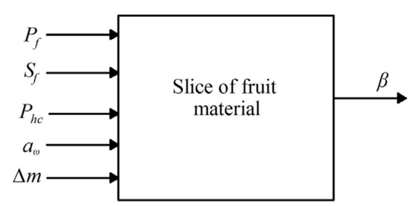


Fig. 3. Parametric schematic of the process of mass transfer during fruit drying in a solar dryer

Coefficient of mass transfer $\beta$ is calculated by formula:

$$\beta = \frac{\Delta \tau}{S_f \cdot (a_\omega \cdot (P_{hc} - P_f))},\ m/s, \qquad (11)$$

where $\Delta\tau$ is the mass of fruit material in the process of drying, kg; $a_\omega$ is the coefficient of water activity; $S_f$ is the area of heating of the surface of fruit raw material, m²; $P_f$ is the pressure of water vapor over the product, Pa; $P_{hc}$ is the vapor pressure in the heat carrier, Pa.

Coefficient of water activity is determined by formula:

$$a_\omega = \exp\left[-\frac{\Delta p \cdot m_{mol}}{\rho \cdot R \cdot (T_f(\tau) + 273)}\right], \qquad (12)$$

where $m_{mol}$ is the molecular weight of water, g/mol; $\rho$ is the density of water (or of a solvent), kg/m³; R is the universal gas constant ($R=8.314\cdot10^3$), J/(mol·K); $\Delta p$ is the pressure drop, equal to the difference between pressure in the liquid and vapour pressure of the heat carrier at a given air temperature, Pa.

External and internal transfer of heat and moisture in the raw material is affected by the shape of a material. Coefficients of mass exchange at the same condition of air will take different values depending on the shape of the material. That is why when using the specified coefficients for the calculation of a drying process, it is necessary to take into account the surface area of heating of raw fruit materials.

The total duration of fruit drying $\tau$ depends on the design and technological parameters of solar dryer and physical parameters of the environment and is determined by formula:

$$\tau=\frac{W_o-W_c}{N}+\frac{1}{K}\cdot\ln\left[\frac{W_c-W_e}{W_r-W_e}\right]+$$
$$+\frac{\Delta\tau\cdot c_f\cdot\left(T_{f2}-T_{f1}\right)+h_l\cdot\rho_f\cdot\left(\sum S_r\right)\cdot c_f\cdot\left(T_{hc3}-T_{hc2}\right)}{S_{dc}\cdot\upsilon_{hc}\cdot\rho_{hc}\cdot c_{hc}\cdot\left(T_{hc2}-T_{hc1}\right)/\tau_h-(S_{as}\cdot E)-S_s\cdot K\cdot\left(T_{hc3}-T_{at}\right)-V_{ta}\cdot\rho_{ta}\cdot c_{ta}\cdot\left(T_{ta2}-T_{ta1}\right)/\tau_{dd}},\quad(13)$$

where $\tau$ is the duration of fruit drying, s; $W_o$ is the original fruit moisture, which is determined experimentally, %; N is the speed of drying, which is determined with the help of experiments, %/s; K is the coefficient of drying, which is determined experimentally, s; $W_r$ is the resulting moisture of fruit, which is determined experimentally, %; $W_c$ is the critical moisture of fruit at the critical point of the drying process, which is determined experimentally, %; $W_e$ is the equillibrium moisture of fruit for the assigned mode of drying, %; E is the power illuminance, W/m$^2$; $S_{dc}$ is the area of the drying chamber, m$^2$; $\tau_h$ is the duration of drying chamber heating, s; $v_{hc}$ is the heat carrier velocity, m/s; $\rho_f$, $\rho_{hc}$, $\rho_{ta}$ are, respectively, the density of fruit, heat carrier, and thermo-accumulating material, kg/m$^3$; $c_{hc}$, $c_f$, $c_{ta}$ are the specific capacity of the heat carrier, fruit and thermo-accumulating material, respectively, J/(kg·°C); $h_l$ is the height of the layer of fruit material on residues, mm; $T_{ta1}$, $T_{ta2}$ are the temperature at the inlet of the thermal battery and at the outlet from it, °C; $S_r$ is the area of residues, m$^2$; $S_s$ is the area of the solar dryer, m$^2$; $T_{at}$ is the ambient temperature, °C; K is the coefficient of thermal transfer through the case of the solar dryer, W/(m$^2$·°C); $\tau_{dd}$ is the duration of discharge of thermal battery, s.

Equillibrium moisture of fruit for the assigned mode of drying is determined by formula:

$$W_e=K_1(T)+K_2(T)\left[\lg\left(\frac{1}{1-\varphi_{0\ldots n}}\right)\right]^{1/2},\quad(14)$$

where $W_e$ is the equilibrium moisture of fruit in the period of desorption, %; $\phi_{0\ldots n}$ is the relative moisture of the air, $\varphi_{0\ldots n}=\frac{P_v}{P_{sv}}$; $P_{sv}$ is the partial pressure of saturated vapor, kPa; $P_v$ is the partial pressure of vapor, kPa.

The resulting mathematical model of the process of fruit drying in the solar dryer allows us to calculate the temperature of the heat carrier and fruit in the drying chamber (1), (2) and the moisture content of the heat carrier (3). It also describes the patterns of change in thermo-technical parameters of the heat carrier (4), patterns of change in thermal parameters of the material, subject to drying in the drying chamber (5), diffusion (6), the process of fruit drying (7)–(9), the energy of bound moisture in fruit (10), coefficient of mass transfer (11), duration of the process of drying (13) and equilibrium moisture of fruit for an assigned mode of drying (14).

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

To examine the operation of a solar dryer, we selected the end of summer-autumn season, which coincides with the period of ripening of the majority of fruits – months from July to September: 15.07–03.09.2015, and 15.07–03.09.2016. During this season, stable sunny weather sets in, which is close to optimal for testing solar energy plants. For the present study, we used results of weather monitoring of the nearest Koretskaya first-grade meteorological station of Rivne oblast (Ukraine).

In the process of drying, physical parameters of the environment changed in the range:

– air temperature $T_{at}$ – 16...30 °C;

– relative moisture of the air $\phi_{at}$ – 26...86.8 %;

– energy illuminance E – 100...800 W/m$^2$;

– angle of falling of direct solar radiation $q_1$ and $q_2$ – from 20° to 60°.

Thermo-technical parameters of the heat carrier, which were in the drying chamber, were

– daytime temperature (from 8$^{00}$ to 21$^{00}$) $T_{at}$ – 20...60 °C, during night (from 22$^{00}$ to 7$^{00}$) $T_{at}$ – 30...20 °C;

– circulation velocity $v_{hc}$ – 1...3 m/s;

– relative moisture $\phi_{hc}$ – 9.8...86 %.

Heating efficiency of air collector Q ranged from 117 to 480 W for the area of absorption surface $S_{as}$=1.5 m$^2$. Battery temperature $T_{ta}$ in daytime (from 8$^{00}$ to 21$^{00}$) was 30.5...45.6 °C, during night (from 22$^{00}$ to 7$^{00}$) – 45.6...20.9 °C.

Even under optimal conditions of the clear sky, fruit drying requires at least a two-day period. Nevertheless, as a result of natural weather-dependent factors, complete coincidence of the key parameters of solar energy flow, temperature and humidity of the outside air, illuminance, as well as the strength of the wind over two consecutive sunny days is most unlikely. Therefore, an objective criterion of the influence of one or another parameter on the final result is only a comparison of temporal dependences of appropriate magnitudes. Results of measurement of intensity of drying for 50 hours from 15 to 17.07.2016 were established by numerical integration. In particular, over three days, 1.5 m$^2$ of the surface of the air collector received 30.2 kW·h or 108.5 MJ of thermal energy. At evaporation of 2.792 kg of moisture, energy transfer of the process is 10.7 kW·h/kg or 38.8 MJ/kg (Fig. 4).

All tests of the solar dryer started at exactly 12 o'clock by summer Kyiv time in the town of Korets of Rivne oblast (Ukraine), located at the meridian 27° of eastern longitude, which is 3° to the west of Kyiv ($\Delta\psi$ =– 3°). For this settlement (number of the day in a year m=197, correction for elipticity of the Earth's orbit E=–6 min), the solar noon starts:

$\tau_0$=(12+1) o'clock+(E–4$\Delta\psi$) min=
=13 o'clock+[–6+4 (–3)] min=12.42.

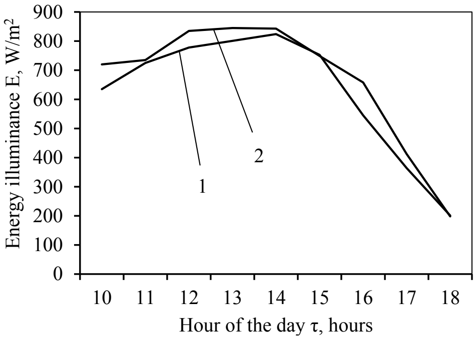


Fig. 4. Current energy illuminance of air collector over a day: 1 –15.07.2016; 2 – 16.07.2016

Thus, the beginning of the experiment, on July 16, 12 p.m. corresponds to the local solar time τ=+42 min, that is, 42 minutes prior to solar noon. The estimated duration of sunshine under condition of cloudless weather is:

– for a horizontal plane 15.54;

– for the air collector, inclined at the optimum angle to the horizon β=40°, 14.24.

The mode of operation of the solar dryer always depends on weather conditions, which are rarely repeated. That is why conclusions about effectiveness of specific solutions may be drawn only based on an analysis of results of several studies in order to separate general patterns from random phenomena.

Configuration of the solar dryer with objective conditions of its operation for the performed series of studies are summarized in Table 1.

Table 1

Summarized conditions and results of examined drying of apples and pears in the solar dryer over the period 15.07–03.09.2016

| No. of entry | Date | Duration, h | Configuration | | $\sum H_{\beta}^{d}$, kW·h/MJ | Power transfer, MJ/kg |
|---|---|---|---|---|---|---|
| | | | TA | MC | | |
| 1 | 15–17.07 | 50 | + | + | 30.15/108.5 | 47.6 |
| 2 | 15–21.07 | 119 | – | – | – | 0 |
| 3 | 28–31.07 | 74 | – | – | 34.2/123.1 | 44.1 |
| 4 | 07–10.08 | 77 | – | – | 30.7/110.5 | 39.6 |
| 5 | 10–12.08 | 50 | + | + | 31.2/74.8 | 26.8 |
| 6 | 15–17.08 | 50 | + | + | 23.0/81.3 | 29.1 |
| 7 | 31–03.09 | 98 | – | – | 26.6/95.8 | 35.7 |

Duration of the process of fruit drying in the solar dryer is determined by velocity of moisture yield of the dried material in the operation zone of the heat carrier. Velocity of moisture yield $J_m$ describes specific features of internal and external heat and mass exchange. During drying, the material and the heat carrier change their parameters in space and over time. In this case, parameters of drying are linked to the assigned coordinate x. Moisture content of material U is constant in time, but the velocity of motion of heat carrier $v_{hc}$, temperature of material $T_f$ and heat carrier $T_{hc}$ are variable.

As a result of external heat and mass exchange, the balance inside material, where the gradients of moisture content VU and temperature VT occur, is broken, in particular:

– directions of vectors of gradient of temperature and moisture content inside the material during period of heating are opposite to moisture transfer inside the dried material under these conditions:

$$J_{т} = -D \cdot \rho_f \cdot \left(\Delta U - \delta_T \cdot \Delta T(\tau)\right),\ \text{kg/(m}^2\text{·s)}; \quad (15)$$

– in the period of cooling, gradient of temperature and moisture transfer decreases under the following conditions:

$$J_{т} = -D \cdot \rho_f \cdot \left(\Delta U + \delta_T \cdot \Delta T(\tau)\right),\ \text{kg/(m}^2\text{·s)}. \quad (16)$$

Solution of differential equations of heat and mass transfer (15), (16) was performed in the programming environments MathCAD 14 and Microsoft Office Excel 10. In particular, we used a stepwise method of calculation of the process of fruit drying for a system of simplified differential equations at automated step selection.

As a result of stepwise calculation of the process of fruit drying for the assigned parameters of the dried material and the heat carrier, we obtained diagrams (Fig. 5–10) that represent the dependences:

– diffusion coefficient D on the temperature of heat carrier $T_{hc}$ and motion velocity of heat carrier $v_{hc}$;

– energy of bound moisture in fruit $q_{bm}$, intensities of drying $J_m$ on the moisture content of material U along coordinate x, which is calculated in the direction of a decrease in moisture in the dried material.

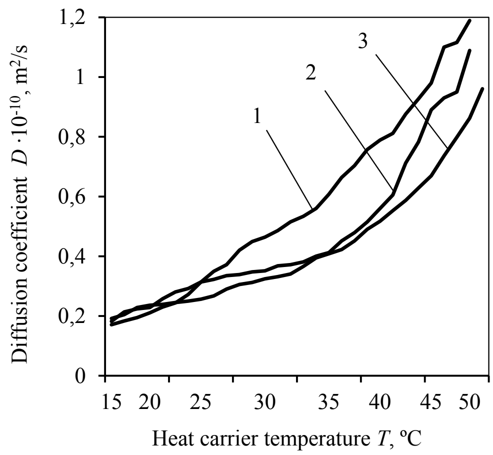


Fig. 5. Dependence of diffusion coefficient on temperature of a heat carrier flow in a solar dryer: 1 – 20 °C; 2 – 30 °C; 3 – 60 °C

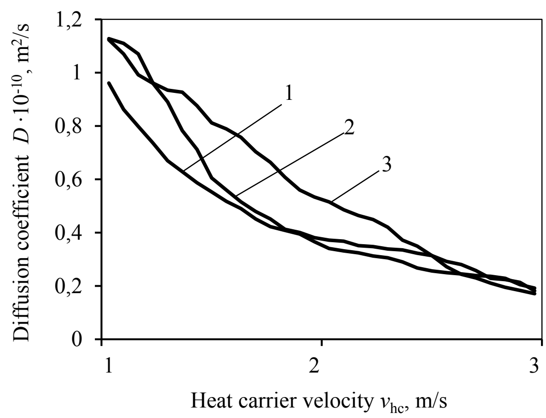


Fig. 6. Dependence of diffusion coefficient on heat carrier velocity in a solar dryer: 1 – 1 m/s; 2 – 2 m/s; 3 – 3 m/s

The dependences, shown in Fig. 5, 6, allow us to argue that moisture transfer inside the dried material is determined not only by the magnitude of gradients of temperature and moisture content, but also by diffusion coefficient D. In this case, diffusion coefficient depends on temperature and velocity of the heat carrier in the solar dryer and changes within 0.17...1.2·10$^{-10}$ m$^2$/s. If we increase temperature of the heat carrier in the drying chamber $T_{hc}$ from 20 to 60 °C, diffusion coefficient D increases (Fig. 5), and with an increase in heat carrier velocity $v_{hc}$ from 1 to 3 m/s, it decreases nonlinearly (Fig. 6).

An analysis of obtained results shows that at the beginning of drying, energy of bound moisture $q_{bm}$ for apples at moisture content U from 2.89 to 0.24 kg of moist./kg of dry substance ranged from 232.6 to 2623.2 kJ/kg (Fig. 7). For pears at moisture content U from 3.36 to 0.39 kg of moist./kg of dry substance, $q_{bm}$ ranged from 342 to 3976 kJ/kg (Fig. 8).

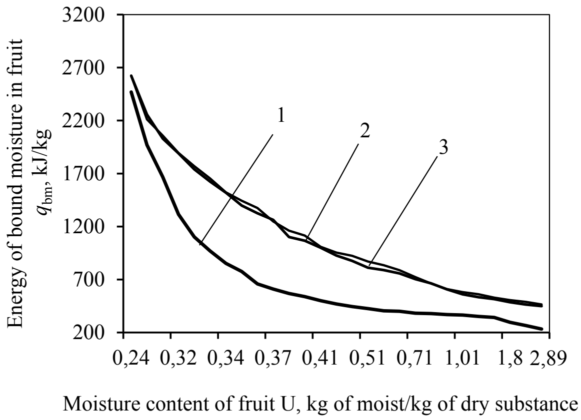


Fig. 7. Dependence of energy of bound moisture on moisture content of apples with a thickness of cut-out circles: 1 — 5 mm; 2 — 8 mm; 3 — 11 mm

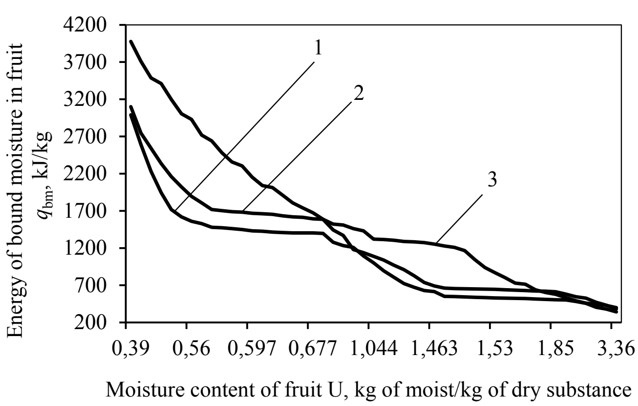


Fig. 8. Dependence of energy of bound moisture on moisture content of pears with a thickness of cut-out slices: 1 — 5 mm; 2 — 6 mm; 3 — 7 mm

It was found that the curves of drying intensity over different operation periods of the solar dryer have the same nature, despite a diversity of modes of drying, physical parameters of environment and weather conditions (Fig. 9, 10). Intensity of the drying $J_m$ for apples, at moisture content U from 2.89 to 0.24 kg of moist./kg of dry substances, was established within 1.57...0.18 kg/(m$^2$·s) (Fig. 9). For pears, at moisture content U from 3.36 to 0.39 kg of moist/kg of dry substance, the intensity of drying $J_m$ is 1.58...0.049 kg/(m$^2$·s) (Fig. 10).

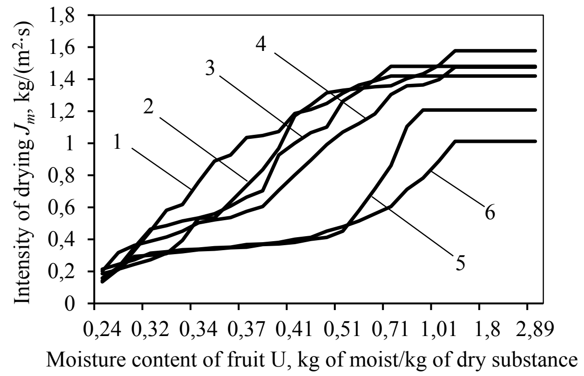


Fig. 9. Curves of intensity when drying apples with a thickness of cut-out circles: 1, 2 — 5 mm; 3, 4 — 8 mm; 5, 6 — 11 mm

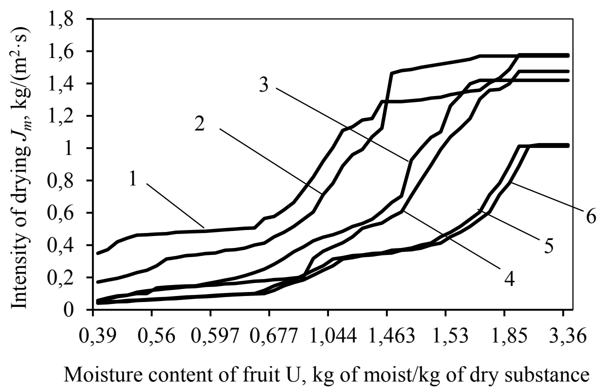


Fig. 10. Curves of intensity when drying pears with a thickness of cut-out slices: 1, 2 — 5 mm; 3, 4 — 6 mm; 5, 6 — 7 mm

Thus, a comparative analysis of the curves of intensity of drying (Fig. 9, 10), allows us to argue that during drying the solar dryer provides uniform intensity and duration of this process and does not permit overcooling of the dried material.

## 6. Discussion of results of mathematical modeling of the process of fruit drying in a solar dryer

Based on an analysis of existing technologies and theories of fruit drying, it was found that their application is ineffective for the study of technological process of fruit drying in the solar dryer. This is primarily due to the specificity of heat and mass transfer in the dried material under operation mode of the solar dryer, because thermal, physical-mechanical, chemical and other properties of fruit as an object of drying change chaotically over 24 hours. This can be explained by the fact that solar dryers are characterized by a periodicity of incoming solar radiation flow. Temperature of the heat carrier changes here within 24 hours depending on the weather and season. Due to this fact, the patterns that describe the drying process should reproduce this periodicity in a mathematical model of technological process of fruit drying in the solar dryer.

In present paper, we explored a technological process of convective drying of fruit under non-stationary operation modes of the solar dryer. The problem of heat and mass transfer in the process of convective fruit drying was solved. The mathematical model of the mechanism of heat and mass exchange during diffusion process of moisture transfer inside the dried material was developed.

In the course of studying a technological process of convective fruit drying in the solar dryer, it was found that moisture in the dried material exists in three phases. In particular, at the beginning of drying, in the center of the dried material moisture is in a liquid phase. The moisture from the central layers under the influence of convection between the heat carrier and the material moves to the surface where transforms into vapor and evaporates. Then the vapor phase arrives. On the surface of fruit raw material, moisture is a multi-component solution of organic and mineral substances. That is why, in fruit drying, a boundary between the second and the third stages of drying is called a solid phase.

During drying, temperature of the heat carrier and the fruit inside and outside is equal, which is why a temperature gradient of the material is small. This may be explained by a small thickness of fruit slices.

It was established that moisture yielding velocity on the surface of the material decreases with an increase in the external pressure of water vapor over the product and the heat carrier, and depends on mass transfer. That is why a constant of moisture yielding velocity will be proportional to the magnitude of diffusion flow of moisture, which in turn is proportional to the permeability of layers of the dried material. This may be explained by a recognized complexity of the mechanism of heat and mass exchange during diffusion process of moisture transfer inside the dried material. Therefore, the obtained values of moisture yielding velocity, coefficients of diffusion and mass exchange that depend on moisture content of the material and thermal and physical parameters of the heat carrier are important when developing a mathematical model of the mechanism of heat and mass exchange.

Based on the conducted research, we obtained the equations to calculate a change in the temperature of heat carrier and fruit in the drying chamber, moisture content of the object of drying, duration of the process of fruit drying. It was shown that intensification of the process of drying should be based on exploration of thermal-physical, physical and chemical, and other properties of fruit. That is why creation of a unified generalized theoretical base of convective fruit drying required a comprehensive combination of thermal and physical-chemical properties of fruits with their kinematic heat and mass transfer characteristics.

It was described that the magnitude of heat and mass exchange indicators in fruit during convective heat exchange is significantly influenced by a depth of penetration of heat flow, thickness of the object of drying, temperature and velocity of the heat carrier circulation. It is expedient to employ low velocity of the heat carrier circulation at the beginning of drying when temperature of the surface of fruit is low, and intensity of heat exchange has the maximum value.

In line with obtained results of the present study, we established the influence of parameters of a heat carrier on the diffusion process of moisture transfer, heat and mass exchange characteristics and intensity of drying process. A comparative analysis of the experimental curves of intensity of drying allows us to assert that the solar dryer provides a uniform intensity of drying, moisture yield and heat and mass exchange between the material and the heat carrier. That is why the mathematical model of technological process of fruit drying in the solar dryer is reliable and fully applicable for subsequent use.

However, the research does not include a procedure for performing a multi-factor experiment of obtaining the regression equation in natural values for dependence of diffusion coefficient on temperature $T_{hc}$ and velocity of circulation of heat carrier $v_{hc}$. It might prove advisable for the formulation of a unified procedure to study the technological process of fruit drying in the solar dryer.

Thus, the proposed mathematical model, methods of research and established regularities of the process might be used to develop the systems of automated modeling and analysis of such processes. In addition, obtained results will be useful in order to improve technology and equipment for fruit drying with the use of solar energy.

## 7. Conclusions

1. We developed a mathematical model of heat, moisture, mass exchange for convective fruit drying taking into account moisture yielding velocity of the dried material in the operation zone of the heat carrier under conditions of diffusion process of moisture transfer in the dried material. We proposed the systems of differential equations of heat and moisture transfer (4)–(12) in the process of convective drying for parabola-like and uniform distribution of temperature and moisture content.

2. Based on the obtained mathematical models (6)–(11) and (15), (16), we established the regularities of influence of technological parameters of drying, in particular diffusion coefficient, energy of bound moisture, moisture yielding velocity on the processes of viscoelastic deformation of the dried material and heat and mass transfer in the solid, liquid and vapor phases of moisture removal from fruit.

3. Based on the results of theoretical and experimental research, we established an impact of parameters of the heat carrier on diffusion process of moisture transfer, heat and mass exchange characteristics and intensity of drying process. In particular, diffusion coefficient D, which depends on temperature ($T_{hc}$ from 20 to 60 °C) and heat carrier velocity ($v_{hc}$ from 1 to 3 m/s), varies within $0.17...1.2\cdot10^{-10}$ m$^2$/s. Mean values of energy of bound moisture $J_m$ are different for different periods of the drying process. In particular, for apples, at moisture content U from 2.89 to 0.24 kg of moist./kg of dry substances, $q_{bm}$=232.6...2623.2 kJ/kg, and $J_m$=1.57...0.18 kg/(m$^2$·s). For pears, at moisture content U from 3.36 to 0.39 kg of moist./kg of dry substances, $q_{bm}$=342...3976 kJ/kg, and $J_m$=1.58...0.049 kg/(m$^2$·s).

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