9. Zagirnyak M., Kalinov A., Maliakova M. Analysis of instantaneous power components of electric circuit with a semiconductor element // Archives of Electrical Engineering. 2013. Vol. 62, Issue 3. P. 473–486. doi: https://doi.org/10.2478/aee-2013-0038
10. Zagirnyak M., Mamchur D., Kalinov A. A comparison of informative value of motor current and power spectra for the tasks of induction motor diagnostics // 2014 16th International Power Electronics and Motion Control Conference and Exposition. 2014. doi: https://doi.org/10.1109/epepemc.2014.6980549
11. Zagirnyak M., Maliakova M., Kalinov A. Analysis of electric circuits with semiconductor converters with the use of a small parameter method in frequency domain // COMPEL – The international journal for computation and mathematics in electrical and electronic engineering. 2015. Vol. 34, Issue 3. P. 808–823. doi: https://doi.org/10.1108/compel-10-2014-0260
12. Rodkin D. The pricing formula for electricity in networks with periodic voltage and current // Elektromekhanichni i enerhozberihaiuchi systemy. 2014. Issue 3. P. 78–91.

UDC 631.364:621.311.243
DOI: 10.15587/1729-4061.2019.162948

RESULTS OF EXPERIMENTAL RESEARCHES INTO PROCESS OF OAK VENEER DRYING IN THE SOLAR DRYER

M. Babych
PhD*
E-mail: m.babych@ukr.net
R. Krygul
PhD*
S. Shapoval
PhD
Department of Heat and Gas Supply and Ventilation
Lviv Polytechnic National University
S. Bandery str., 12, Lviv, Ukraine, 79013
N. Tolstushko
PhD, Associate Professor**
S. Korobka
PhD, Senior Lecturer*
M. Tolstushko
PhD, Associate Professor**
*Department of Energy
Lviv National Agrarian University
V. Velykoho str., 1, Dublyany, Ukraine, 80381
**Department of Engineering and Forestry
Lutsk National Technical University
Lvivska str., 75, Lutsk, Ukraine, 43018

Розроблено нову конструкцію геліотермічної сушильної установки з активною системою використання сонячної енергії. Запропоновано для діагностики основних параметрів повітрообміну у геліосушарці і прогнозування інтенсивності протікання тепломасообмінних процесів сушіння дубового шпону використовувати автоматичну систему керування К1-102. Це дозволяє підвищити технологічну та енергетичну ефективність процесу сушіння дубового шпону у геліосушарці в 2 рази.

Визначено закономірності впливу фізичних параметрів навколишнього середовища та погодозалежних факторів на тепло-, масо- і вологообміні процеси сушіння дубового шпону у геліосушарці. Наведено оцінку енергетичних, кінетичних та динамічних параметрів процесу сушіння дубового шпону. Експериментально визначено тривалість технологічного процесу сушіння у геліосушарці. Досліджено робочі характеристики об'єкта сушіння, залежно від поставлених технологічних задач (прогрівання або сушіння матеріалу) за стандартних режимів сонячного освітлення і типових метеорологічних умов.

Встановлено, що необхідно регулювати повітрообмін, вологовиділення, раціональне видалення вологого теплоносія, концентрацію надходження сонячної енергії відносно прогнозованої зміни мінімальних та максимальних піків коливань погодозалежних факторів. Це є важивим для інтенсифікації процесів сушіння дубового шпону і зниження питомих енергетичних витрат на процес сушіння за рахунок сонячної енергії.

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

Ключові слова: сонячна енергія, геліосушарка, температурно-вологісні поля, тепломасоперенесення, інтенсифікація, конвективне сушіння

1. Introduction

High-quality drying of oak veneer is one of the most popular technological processes in the forest complex of Ukraine. Today in the market, there are many high-temperature automated devices for high-quality drying of wood in «soft modes». However, their application is unprofitable with small volumes of timber processing in small household and utility carpentry shops. This is primarily due to high capital investments. In addition, a major problem for small household and utility carpentry shops that provide timber drying services is the ultimate quality of wood after drying. There are also frequent cases when due to the unsatisfactory results of timber drying, owners of small household and utility carpentry shops have to pay damages instead of making a profit.

Now, according to consumers, timber organizations such as Zorya LLC in the city of Korets, Rivne region (Ukraine), solar drying units (solar dryers) are not yet widespread in Western Ukraine, as the demand for timber drying significantly outstrips supply. Because the majority of solar dryers have been developed by researchers for countries with different types of subtropical climate, and their research has been carried out in a laboratory or by computer simulation.

Thus, in order to prevent such situations, it is necessary to use modern drying units, in particular, solar systems with the active solar energy system and automated control system of the drying process. This will allow minimizing economic and energy factors of production and carrying out drying control at all stages. Therefore, the development of such solar-powered drying equipment is an ideal solution of the problem.

2. Literature review and problem statement

Today, there are many design options and varieties of solar drying units used in the forest complex of Ukraine. The main elements of the power unit of them are an air collector and a kiln. In particular, a new design of greenhouse-type solar dryer for timber drying is developed in [1]. In addition, the process of convection package drying of birch veneer is investigated. On the basis of theoretical-experimental studies, the heat and mass transfer coefficients depending on the coolant flow rate, the coefficient of internal diffusion of moisture from veneer sheets, with its temperature dependence, are determined. However, the kinetics and energetics of air exchange during moisture release and removal of moist coolant from the solar dryer are not described.

The authors of [2] have developed a new design of the solar tunnel dryer. The numerical method of solving the mathematical model for calculating stresses and moisture distribution in beech veneer during drying is substantiated and the problem of optimizing this model is formulated. A multi-stage mode of convection drying of beech veneer by solving the optimization problem is proposed. However, it is impossible to develop a general method of beech veneer drying in the solar dryer, but only to stabilize thermal parameters of the coolant in the kiln in the drying process. Because during timber drying with the material humidity W, % and timber weight m, kg, thermal parameters of the coolant substantially depend on physical parameters of the environment. In particular, solar energy flow, air temperature and humidity, atmospheric pressure, wind speed and strength. And their coincidence and repeatability within two successive drying periods of 24 hours are unlikely.

The paper [3] presents the results of experimental studies of convection drying of oak veneer under different heat-humidity conditions in the convective chamber solar dryer. The curves of oak veneer drying under different heat-humidity conditions in the convective chamber solar dryer are constructed. The influence of heat-humidity drying parameters on the rate of oak veneer drying is analyzed. However, the authors did not analyze the effect of energy, kinetic and dynamic parameters of the coolant and the dryable material on the heat and mass transfer characteristics of the process of oak veneer drying in the convective chamber solar dryer.

The authors of [4] have developed a stationary convection-infrared tunnel solar dryer. The processes of air temperature variation in the stationary convection-infrared tunnel dryer during oak veneer drying are considered. Boundary conditions of air (coolant) temperature, humidity and moisture content variation during oak veneer drying necessary for solving heat conduction equations are grounded and formulated. However, when substantiating the boundary conditions of air (coolant) temperature, humidity and moisture content variation during oak veneer drying necessary for solving heat conduction equations, the moisture content of the initial coolant flow is not taken into account.

In [5], the influence of the structure of the rotary-cut plywood raw material on the mechanism of timber drying processes is investigated. The kinetics of drying is studied on the example of three different types of wood, namely birch, oak, beech. A series of studies concerning water evaporation from the flat surface of rotary-cut plywood raw material of birch, oak, and beech are performed and limits of heating of the test material are estimated. The process of moisture evaporation for three groups of samples of different breeds is investigated, drying rate is calculated, and key process factors are determined. However, in the thin rotary-cut plywood raw material with the thickness from 3 to 6 mm, the result of determining moisture release indicators can not be considered sufficiently equivalent. Because in thin veneer sheets it is difficult to determine a zone of heat and moisture removal from the center of the dryable material to the surface due to small temperature gradients.

The authors of [6] analyzed drying features of timber, namely, oak veneer. They proposed a new design of the chamber convective solar dryer. The expediency of oak veneer drying simulation and its program realization is substantiated. However, the work lacks assessment of performance characteristics, namely power performance of the solar dryer under standard insolation and meteorological conditions.

The main direction of [7] is an analysis of the kinetics of pine veneer drying in the tunnel semi-greenhouse-type solar dryer. The authors determined dehydration regimes and developed ways to intensify the process based on using a low-moisture coolant. The results are analyzed and duration of pine veneer drying in different modes is determined. The equation that allows determining the duration of the pine veneer drying process in the tunnel semi-greenhouse-type solar dryer with sufficient accuracy is proposed. However, the proposed method does not take into account the verification of the obtained data of absolute and relative humidity with equilibrium moisture content. In particular, to evaluate the correctness of determining the arbitrary dry weight of the dryable material.

Justification of the best operation modes of solar drying units with the highest efficiency and intensity of the drying process with minimum power consumption is an important task. Since the complexity of this process is due to the flow of interrelated, namely, energy, kinetic, dynamic parameters and heat and mass transfer processes and high variability of physical properties of wood.

At the same time, the issue of wood veneer drying efficiency due to the use of solar energy and solar dryers remains little studied. The majority of the developed designs of existing solar dryers are made for countries with hot climate, and their operation principle and drying process are investigated in a laboratory or by simulation models during computer simulation. Therefore, known designs of solar dryers require modification and improvement in order to increase efficiency in conditions of temperate continental climate of Western Ukraine and reduce capital and operating costs.

The given arguments allowed determining the main directions of increasing the technological and power efficiency of the drying process using solar energy. The absence of such dryers in the market formulates the problem of designing a solar dryer with rational technological parameters, which could be used in small household and utility carpentry shops.

3. The aim and objectives of the study

The aim of the study is to intensify the process of oak veneer drying using solar energy by combining the air collector and the kiln into a single power unit in the solar dryer.

According to the aim, it was necessary to accomplish the following objectives:

– to evaluate the performance characteristics (power characteristics of the dryer, heat and mass transfer characteristics of the oak veneer drying process) of the solar dryer under standard insolation and meteorological conditions;

– to investigate the technological process of timber drying in the solar dryer, depending on the slicing thickness and physical parameters of the environment;

– to conduct full-scale tests of the solar dryer.

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

4. 1. Justification of the flow sheet and structure of the solar dryer

In the forest complex of Ukraine, solar plants with the active solar energy system are widely used, in particular in household and utility carpentry shops. For example, for storage and drying of small volumes of timber up to 1 m^3, namely oak veneer.

The mini solar dryer with a flat air collector for oak timber drying is given in Fig. 1, 2. This prototype of solar plant was developed at the Department of Energy, Lviv National Agrarian University (Ukraine) [8]. The process of oak timber drying was investigated at the Department of Forestry Equipment and Theory of Machines and Mechanisms, Lutsk National Technical University (Ukraine). Justification of the design and technological parameters of the solar dryer and the methodology of their calculation, concerning the recommendation for creating parameters series of performance, overall dimensions, charged weight of the dryable material, is given in [8].

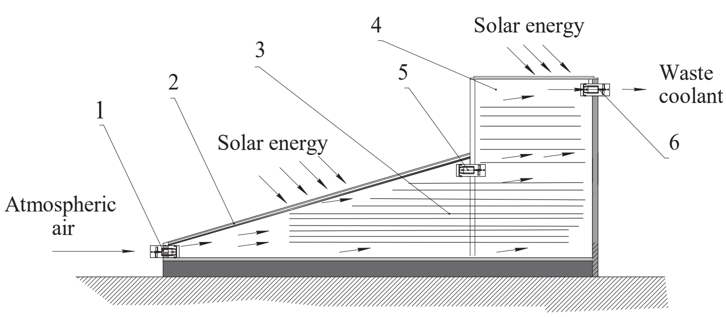


Fig. 1. Solar dryer flow sheet:
1 — axial fan; 2 — air collector; 3 — dryable material (veneer); 4 — kiln; 5 — axial fan, 6 — exhaust axial fan

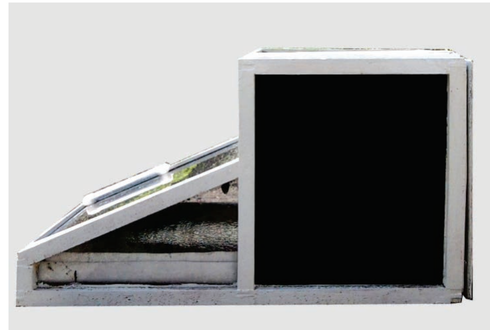


Fig. 2. General view of the solar dryer for timber drying

The solar dryer has a frame design of 2.800×1.200××1.200 mm made of 50×50 mm planed pine bar. The 1500×1200 mm air collector 2 is placed on the frontal at an angle β_{opt}=40.4° to the horizon and consists of a translucent material and an absorber. The translucent material is glass with a composition of 72 % SiO_2, 13 % (Na_2O+K_2O), 11 % Ca, 4 % (R_2O_3+MgO)). The absorber is made of 1.000×1.500 mm sheet copper and burnt with a cutting torch to form surface roughness of 390 μm. The absorber surface was coated with a selective paint with the thickness $\lambda\approx$4.40 μm with coefficients of short-wave absorption $\alpha\approx$0.92 and long-wave radiation $\varepsilon\approx$48.8. A detailed description of the design and operation of the air collector and the results of the study of its thermal characteristics are given in [9].

On the side wall of the air collector 2, an inlet duct to supply air to the kiln 4 is made. Air is fed by the ebm-papst 3200J Series Axial Fan 1 to the 12 V DC with a capacity of 50 W and productivity of 280 m^3/h. Circulation of the heated coolant at a speed of 1...3 m/s in the kiln is provided by the ebm-papst 3200J Series Axial Fan axial 5 to the 12 V DC mounted on the rotary hinge mechanism. Removal of waste coolant in the upper part of the kiln is carried out by controlling the rotation of the ebm-papst 3200J Series Axial Fan 6 to the 12 V DC.

The automated control system for moisture release, moisture removal and air exchange in both the self-contained and mains solar dryer is developed. This system is equipped with the advanced K1-102 panel controller and control sensors of circulation, temperature, moisture of the coolant and dryable material. The controller in the control system is the K1-102 panel controller with sensors, and the actuator is 3 axial fans. The automated control system and axial fans are powered offline by:

1) two Linuo/ABi-Solar P60260-D 260 W photomodules;
2) SL0912 Abi-Solar inverter;
3) C&T Solar 3024 Pulsar charge controller;
4) Ventura 12 V 150 A·h storage battery.

The solar dryer works as follows. The kiln is filled with oak veneer 5 (0.6×2500×100 mm in size). Air from the environment comes to the air collector, heats up and enters the kiln. The waste coolant is removed by forced convection to the environment through the exhaust duct.

In the case of variable cloudiness in the solar dryer, a significant part of the drying cycle are transients, and with prolonged shading and at night – it passes to atmospheric drying.

Thus, the developed design of the solar dryer corresponds to the concept of active solar power plant. At the same time, the air collector and the kiln combined into a single power unit do not structurally correspond to classical samples of solar drying plants. For the developed plant, the relationships between the energy parameters are not theoretically determined. For example, it is impossible to independently test the air collector and the kiln according to the standard procedure or to calculate the thermal parameters of the collector or the kiln or to investigate their operation and compare the obtained data. In particular, the quality of the heat energy obtained depends on changes in the physical parameters of the environment. Therefore, the parameters for determining the effectiveness of decisions made are revealed during experimental studies based on the analysis of the process of oak veneer drying in the solar dryer.

4. 2. Justification of the technological parameters of the dryable material

In the process of oak veneer drying in the solar dryer during the day there is a variation in the thermal parameters of the coolant and physical parameters of the environment, namely, the flow of solar energy. Heat and mass transfer characteristics of the drying process, power characteristics of the solar dryer and properties of wood vary within a day depending on weather and season. In order to evaluate oak veneer humidity, relative values are used, where all ratios relate to the arbitrary weight of the material.

By the ratio of moisture (vapor) weight in the material, kg, to the weight of the total moist material, humidity of the material is determined:

$$W=\frac{m}{m+m_d},\ \text{kg/kg of current material weight,} \tag{1}$$

where m is the current weight of water in moist material, kg; m_d is the weight of dry material, kg.

By the ratio of the moisture weight in the material, kg, to the weight of dry material, the moisture content of the material is determined:

$$U=\frac{m}{m_d},\ \text{kg/kg of dry weight.} \tag{2}$$

By the ratio of moisture (vapor) weight in the material, kg, to the weight of the total moist material, the equilibrium humidity of the material is determined:

$$W_{eq}=\frac{m_{eq}}{m_{eq}+m_d},\ \text{kg/kg of current material weight,} \tag{3}$$

where m_{eq} is the moisture equilibrium, determined from the array of experimental data, when they are stabilized, kg.

By the ratio of moisture (vapor) weight in the material, kg, to the weight of the total moist material, the equilibrium moisture content of the material is determined:

$$U_{eq}=\frac{m_{eq}}{m_d},\ \text{kg/kg of dry weight.} \tag{4}$$

The moisture content of the coolant can be determined [10]:

$$X_i=X_o=0.622\cdot\frac{\frac{\varphi_a}{100}\cdot p_{va}}{P-\frac{\varphi_o}{100}\cdot p_{vs}^{O}},\ \text{kg/kg,} \tag{5}$$

where φ_a, φ_o is the relative humidity of the input and output coolant, respectively, %; p_{va} is the pressure of saturated vapor in the inlet flow at a given air temperature, Pa; p_{vs} is the pressure of saturated vapor in the kiln at a given air temperature, Pa.

For example, for oak veneer drying $m_0+m_d=7.73$ kg; $m_d=4.16$ kg; $m_0=3.58$ kg, $m_0/m_d=0.8601$; $\Delta\tau=24$ h; $U_0=$ $=75.3$ %, where m_0 is the initial weight of water in moist material, kg; $m_0=m_d$ is the initial weight of moist material; $\Delta\tau$ is the duration of one cycle of oak veneer drying, h; U_0 is the initial moisture content, %.

Let we have a series of consistent results of measuring the relative humidity of veneer $W_0=0.463$, $W_1=0.444$, $W_2=0.424$; $W_3=0.401$; $W_4=0.396$, which is expressed through the current values of water weight m_{wi} and the constant value of dry weight m_d:

$$W=\frac{m_w}{m_w+m_d},\ \text{kg/kg of current material weight,} \tag{6}$$

where m_{w0} – the initial weight of water in moist material; m_{w1} – after the first day of drying; m_{w2} – after the second day of drying, etc.

They correspond to the current weight values of moist material 7.73, 7.59, 7.48, 7.16...

Then the current values of water weight and dry weight, respectively are:

$$0:\ m_{w0}=W\cdot(m_d+m_{w0})=0.463\cdot 7.73=3.579;$$

$$m_d=7.73-3.579=4.15;$$

$$1:\ m_{w1}=W\cdot(m_d+m_{w1})=0.444\cdot 7.59=3.370;$$

$$m_d=7.59-3.37=4.22;$$

$$2:\ m_{w2}=W\cdot(m_d+m_{w2})=0.424\cdot 7.48=3.172;$$

$$m_d=7.48-3.172=4.308;$$

$$3:\ m_{w3}=W\cdot(m_d+m_{w3})=0.401\cdot 7.31=2.931;$$

$$m_d=7.31-2.931=4.379;$$

$$4:\ m_{w4}=W\cdot(m_d+m_{w4})=0.396\cdot 7.16=2.835;$$

$$m_d=7.16-2.835=4.325.$$

The average dry weight $m_d=4.1612$.

Here the residual weight of water in moisture equilibrium m_{eq}:

$$m_{eq}=m_0-\Sigma(\Delta m)=3.58-2.69=0.89\ \text{kg},$$

where Δm is the difference in the moisture loss in the dryable material, kg.

By the difference of weights of moist m_s and dry m_0 veneer, the filling weight m is determined. During the first and next day of drying there is a decrease in the weight of the dryable material, which is taken equal to the difference in weights:

$$\left.\begin{aligned}\Delta m_1&=m_s-m_1,\\ \Delta m_2&=m_1-m_2,\\ \Delta m_n&=m_{n-1}-m_n.\end{aligned}\right\} \tag{7}$$

When determining oak veneer humidity, it is necessary to compare the absolute and relative humidity of the dryable material between the ratios of the arbitrary weight of the material with the equilibrium moisture content, that is:

$$U_{eq} = \frac{m_{eq}}{m_d} = \frac{0.89}{4.16} = 0.213;$$

$$W_{eq} = \frac{m_{eq}}{m_{eq} + m_d} = \frac{0.89}{4.16 + 0.89} = 0.176;$$

$$U_0 - U_{eq} = 78.1 - 19.9 = 58.2.$$

Check:

$$W_{eq} = \frac{U_{eq}}{1 + U_{eq}} = \frac{0.213}{1 + 0.213} = 0.17559. \quad (8)$$

Thus, the absolute and relative humidity of the dryable material W_{eq}=0.176 with the equilibrium moisture content U_{eq}=0.213 with the refinement of the mass transfer mechanism W_{eq}=0.17559 is 0.00041 %. This allows asserting that the final value of weight m_d=4.41 kg and humidity W_k=6 % of the dryable material during drying in the solar dryer is determined correctly.

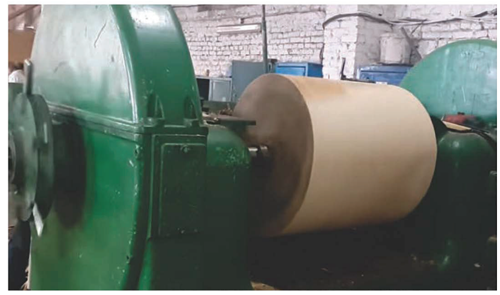
4. 3. Preparation of oak veneer for drying in the solar dryer

The veneer is obtained by planing steamed bars of grade 1 or 2 round timber [11]. For example, grade 2 oak (Fig. 3) with an initial humidity W_s=61.2 %, which was steamed in the steaming chamber (Fig. 4) in a 5 % copper sulfate solution.

Fig. 3. Harvested oak raw material of grade 2 with initial humidity W_s=61.2 %

Fig. 4. Steaming chamber

Steaming of the bars passes at a solution temperature of 90 °C. After steaming, timber is cut into 500 mm chocks and placed in the LFS-2587A horizontal slicing machine (Fig. 5). By the method of rotary cut of wood (plywood) raw material, veneer of a 0.6×2,500×100 mm chock with an initial humidity W_v=75.3 % and weight m=7.73 kg is obtained (Fig. 6).



a

b

Fig. 5. Rotary cut of plywood raw material by the LFS-2587A horizontal machine [12]: *a* – projection cross-section; *b* – longitudinal section

Fig. 6. Raw dried oak veneer with humidity W=6 % and weight m_d=4.41 kg

In the analysis of data it is evident that after steaming of the bars, the material humidity increased from W_s=61.2 % to W_v=75.3 %, namely by ΔW=14.1 % (due to wood saturation with excess moisture).

The raw material was harvested at the Korets forestry shareholders site, Rivne Forestry, SE, located in the quarter 18, office 48 –17.0 ha of the Ustia village council, Korets district, Rivne region (Ukraine).

The resulting planed material (veneer) is subjected to convective chamber drying for $\Delta\tau$=52 days to the weight m=4.41 kg and humidity U=11.1 %.

After drying, the veneer is removed from the kiln and left for $\Delta\tau$=5 days to remove internal strain and cracking where it dries to an absolutely dry state with a weight m_d=4.16 kg, humidity U=6 % and surface roughness of 320 microns.

4. 4. Kinetics and energetics of air exchange in the solar dryer

The process of air exchange or circulation of the coolant in the solar dryer is to purge the dryable material in the kiln with atmospheric air.

Let us determine the moisture content in g/m^3 and accept the following notation:

– z_0 – initial moisture content in the atmospheric air at the solar dryer inlet at the moment of fan activation;

– z – current moisture content of the coolant at the inlet of the solar dryer kiln;

– z_1 – moisture content at the solar dryer inlet;

– z_2 – rate of moisture release in the solar dryer, g/m^3·s, g/m^3·min or g/m^3·h;

– L – fan capacity, m^3/s, m^3/min or m^3/h;

– V – solar dryer volume, m^3.

At an arbitrary time, the change in moisture removal in the ventilated solar dryer Vdz is determined by the balance of receipts and expenditures:

– $L\cdot z_1\cdot d\tau$ – increase due to moisture in the solar dryer environment;

– $z_2\cdot d\tau$ – increase due to gas release;

– $(-L\cdot z\cdot d\tau)$ – decrease due to ventilation.

The ratio between these increments is described by the balance equation:

$$L\cdot z_1\cdot d\tau+z_2\cdot d\tau-L\cdot z\cdot d\tau=V\cdot dz, \tag{9}$$

which, after dividing by $d\tau$, will be reduced to the form:

$$L\cdot z_1+z_2-L\cdot z=V\cdot\frac{dz}{d\tau};\ \ \frac{dz}{d\tau}-\frac{L}{V}\cdot z=\frac{L\cdot z_1+z_2}{V} \tag{10}$$

or

$$z'+\frac{L}{V}\cdot z=\frac{L\cdot z_1+z_2}{V}. \tag{11}$$

The last record is typical of linear first-order differential equations:

$$y'+P(x)y=Q(x) \tag{12}$$

with the difference that the functional values here take constant values:

$$P(x)\Rightarrow\frac{L}{V}=\text{const}\ \text{ and }\ Q(x)\Rightarrow\frac{L\cdot z_1}{V}=\text{const}. \tag{13}$$

Such equations are solved by the following standard method.

First, partial solution z^* for the case $Q(x)=0$ is sought, for which separation of variables is allowed:

$$z'+\frac{L}{V}\cdot z=0, \tag{14}$$

$$\frac{dz}{d\tau}+\frac{L}{V}\cdot z=0\ \text{ or }\ \frac{dz}{z}=-\frac{L}{V}\cdot d\tau, \tag{15}$$

$$\int\frac{\mathrm{d}z}{z}=-\frac{L}{V}\int\mathrm{d}\tau, \tag{16}$$

$$\ln z+C=-\frac{L}{V}\cdot\tau, \tag{17}$$

$$z^*=C\cdot e^{-\frac{L}{V}\tau}. \tag{18}$$

The unknown integration constant is subsequently replaced by the function $u(\tau)$, and the general view of the variable of moist coolant removal from the solar dryer z_τ is determined by the dependence:

$$z=u\cdot e^{-\frac{L}{V}\tau}. \tag{19}$$

So, the variable z is substituted in the original standard equation:

$$\frac{d}{d\tau}\left(u\cdot e^{-\frac{L}{V}\tau}\right)+\frac{L}{V}\left(u\cdot e^{-\frac{L}{V}\tau}\right)=\frac{L\cdot z_1+z_2}{V} \tag{20}$$

and in the first summand we perform the differentiation according to the rule of the product of two functions:

$$e^{-\frac{L}{V}\tau}\frac{du}{d\tau}-u\frac{L}{V}e^{-\frac{L}{V}\tau}+u\cdot\frac{L}{V}\cdot e^{-\frac{L}{V}\tau}=\frac{L\cdot z_1+z_2}{V}. \tag{21}$$

After the mutual destruction of the second and third terms, the equation is reduced to a kind with separating variables:

$$du=\frac{L\cdot z_1+z_2}{L}\cdot e^{\frac{L}{V}\tau}\cdot d\tau. \tag{22}$$

The left part is integrated with a new unknown constant C_1, and the right one – in the range from 0 to τ:

$$\int\mathrm{d}u=\frac{L\cdot z_1+z_2}{V}\cdot\int_0^\tau e^{-\frac{L}{V}\tau}\mathrm{d}\tau, \tag{23}$$

$$u+C_1=\frac{L\cdot z_1+z_2}{V}\left(\frac{V}{L}\cdot e^{-\frac{L}{V}\tau}-\frac{V}{L}\right)=\frac{L\cdot z_1+z_2}{L}\left(e-^{\frac{L}{V}\tau}-1\right). \tag{24}$$

The variable u is the multiplier of the exponent, which determines the decrease in the moisture content of the circulating coolant in the solar dryer over time and at the moment of fan activation was equal to z_0. But the last expression for $\tau=0$ turns to zero. Therefore, in order to maintain the initial value of moisture content of the coolant in the solar dryer, the integration constant must be moved to the right and given the value z_0:

$$u=\frac{L\cdot z_1+z_2}{L}\left(e^{-\frac{L}{V}\tau}-1\right)+z_0. \tag{25}$$

The final expression for the general solution of the time dependence of the moisture content of the coolant in the solar dryer will be obtained by multiplying:

$$z=u\cdot z^*=\left[\frac{L\cdot z_1+z_2}{L}\left(e^{-\frac{L}{V}\tau}-1\right)+z_0\right]\cdot e^{-\frac{L}{V}\tau}. \tag{26}$$

After conversions, the expression for the current moisture content of the coolant in the solar dryer will look like:

$$z=\frac{L\cdot z_1+z_2}{L}\left(1-e^{-\frac{L}{V}\tau}\right)+z_0\cdot e^{-\frac{L}{V}\tau}. \tag{27}$$

The duration of fan operation to reduce the content of moist coolant in the solar dryer from the initial z_0 to the specified content z is calculated by the formula:

$$\tau=\frac{V}{L}\cdot\ln\frac{L\cdot(z_0-z_1)+z_2}{L\cdot(z-z_1)+z_2}. \tag{28}$$

In the absence of moisture release $z_2=0$ (for example, in the night period of drying when the humidity of atmospheric air is 1.5 times lower than that of the coolant in the kiln), the last expression takes the form:

$$\tau=\frac{V}{L}\cdot\ln\frac{z_0-z_1}{z-z_1}. \quad (29)$$

In the absence of moisture release and moisture removal $z_1=0$, the expression is simplified to the form:

$$\tau=\frac{V}{L}\cdot\ln\frac{z_0}{z}. \quad (30)$$

The moisture content around the solar dryer inlet ($z_1=0$), or the rate of moisture release in the solar dryer ($z_2=0$), decreases the fastest. Therefore, the duration of fan operation in the solar dryer is calculated based on the time of moisture removal of waste coolant from the solar dryer.

Fan capacity is mainly calculated for the stationary air exchange conditions. When moisture release from the dryable material is compensated by the inflow of fresh coolant having a moisture content of 1.5 times lower than that of the coolant removed from the kiln. Such a regime corresponds to the conditions:

$$\tau\to\infty \text{ and } e^{-\frac{L}{V}\tau}=0, \quad (31)$$

and the current moisture content in the coolant is stabilized at the level:

$$z=\frac{Lz_1+z_2}{L} \text{ or } L=\frac{z_2}{z-z_1}. \quad (32)$$

Therefore, air exchange duration in the solar dryer must be calculated separately for each component of the power unit of the solar plant, namely the air collector and the kiln. If this feature is neglected, the coolant air exchange will not be perceived as effective. Even with repeated active ventilation of the dryable material, when the moisture content of the material is compensated by the inflow of fresh coolant in comparison with the coolant removed from the kiln. That is why it is necessary to calculate ventilation heat loss in proportion to the time of operation of the solar dryer power unit. At a constant temperature, dynamic equilibrium is established between the amount of heat withdrawn by the coolant removed from the solar dryer and replaced thermal power of the air collector. Mathematically, it is described by the heat balance equation:

$$\Delta Q=L\cdot c_a\cdot\Delta t, \quad (33)$$

$$P_Q=\frac{dQ}{d\tau}=G\cdot c_a\cdot(t_o-t_i), \quad (34)$$

where t_i, t_o are the coolant temperatures at the solar dryer inlet and outlet, respectively, °C; c_a is the volumetric heat capacity of air; $G=dL/d\tau$ is fan capacity.

So, the resulting equations allow calculating the kinetics and energetics of air exchange in the solar dryer.

5. Results of the study of the technological process of oak veneer drying in the solar dryer

Full-scale tests of the solar dryer at Zorya LLC, located in Korets, Rivne region (Ukraine), engaged not only in the cultivation and processing of agricultural products, but also in wood harvesting and wood processing at the Korets forestry shareholders site, Rivne Forestry, SE are carried out. Drying of 5 oak veneer sheets (0.6×2,500×100 mm in size) was carried out in the summer period from 01.06.2018 to 07.29.2018.

During full-scale tests of the solar dryer, weather-dependent factors and typical (seasonal) meteorological conditions were determined by the results of weather monitoring at the first-level Korets meteorological station in the Rivne region (Ukraine) [13]. Weather-dependent factors are the flow of solar energy, air temperature and humidity, irradiance, atmospheric pressure, as well as wind strength and speed.

On the basis of the analysis of natural weather-dependent factors, it was found that the complete coincidence of the parameters of the solar energy flow, air temperature and humidity, insolation, atmospheric pressure, wind strength and speed for the two consecutive months is unlikely. Therefore, the impartial factor of influence of this or that parameter on the final result is the comparison of time dependencies of the corresponding quantities. For example, power parameters of the solar dryer were different, namely, variations of temperature and irradiance peaks, as shown in Fig. 7.

Irradiance that comes to the horizontal surface of the air collector at an angle $\beta_{opt}=40.4°$, latitude (for Korets, Rivne region – 50.61°) for two months from 01.06.2018 to 29.07.2018 varied within E from 450 W/m^2 to 1269 W/m^2. Such minimum and maximum variation peaks of irradiance can be attributed to cloudiness, atmospheric opacity and pollution. In particular, if you look at the bar histogram, it can be seen that the minimum values of irradiance in different periods of drying $\Delta\tau$ were from 13 to 20 day or from 42 to 47 day. This is due to a sharp change in weather-related factors, namely the rainy season, for example, in 13.06.2018 the weather was cloudy with precipitation. The degree of atmospheric transparency varied from 0.42 to 0.6. The air mass flow (wind) varied from 1.3 m/s to 2.8 m/s. The maximum irradiance peaks can be explained by the fact that, for example, in 25.06.2018, namely $\Delta\tau=25$ day of oak veneer drying, the weather remained clear, without precipitation. The degree of atmospheric transparency varied from 0.72 to 0.86. The air mass flow (wind) varied from 1 m/s to 2.2 m/s.

The ambient temperature, namely at the solar dryer inlet t_a, varied from 18.5 °C to 32.3 °C. The coolant temperature in the air collector t_i ranged from 20.5 °C to 57.3 °C, and at the kiln outlet t_o ranged from 21.3 °C to 56.9 °C.

In the course of experimental studies, measurement of temperature, thermal parameters of air (coolant) was carried out in degrees Celsius (°C), and during the calculations, they were converted into units of thermodynamic temperature (K). Correlation of the adequacy of the results of theoretical and experimental studies to maintain the experimental integrity was carried out in degrees Celsius (°C).

The relative air humidity, namely, at the air collector inlet φ_a varied from 28.9 to 82 %. The relative coolant humidity at the kiln outlet φ_o ranged from 30.8 to 85.3 %.

The comparative analysis of the results obtained (Fig. 9) shows that the moisture content of atmospheric air during the tests X_i varied from 0.019 to 0.0055 kg/kg, and waste coolant at the kiln outlet X_o varied from 0.024 to 0.067 kg/kg.

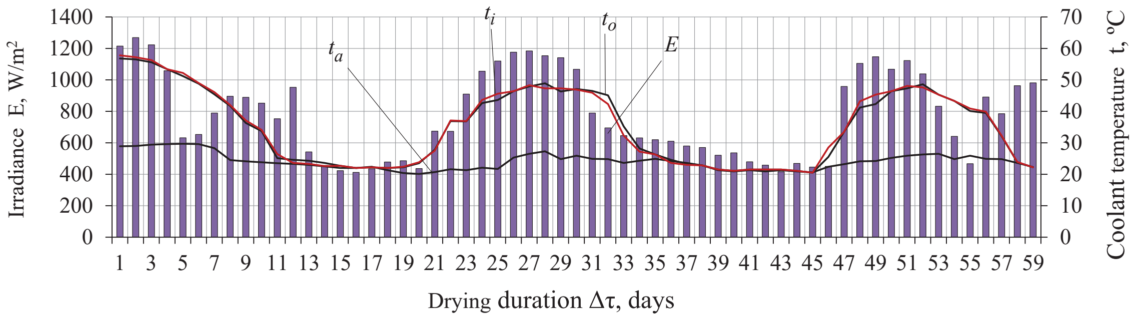


Fig. 7. Power parameters of the solar dryer in the period from 01.06.2018 to 07.29.2018: t_i, t_o, t_a – temperature of the input and output coolant and the environment, respectively, °C; E – irradiance, W/m^2

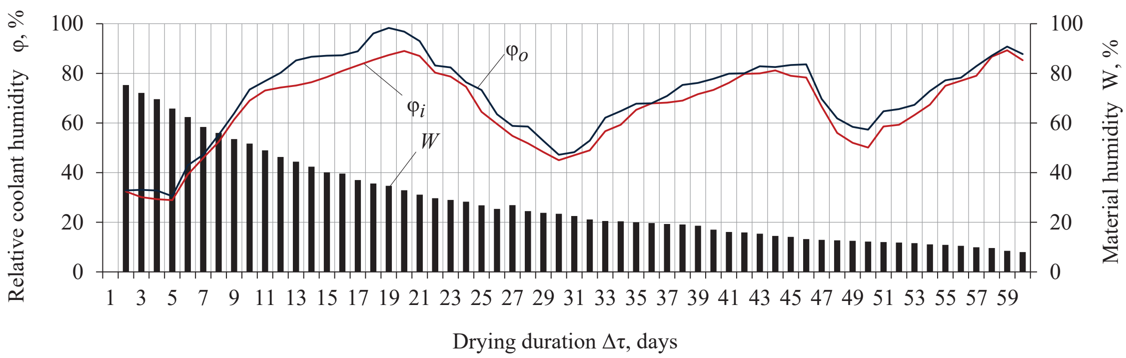


Fig. 8. Kinetic parameters of moisture transfer processes in the solar dryer in the period from 01.06.2018 to 07.29.2018: φ_i, φ_o – relative humidity of the input and output coolant, respectively, %; W – humidity of the dryable material, %

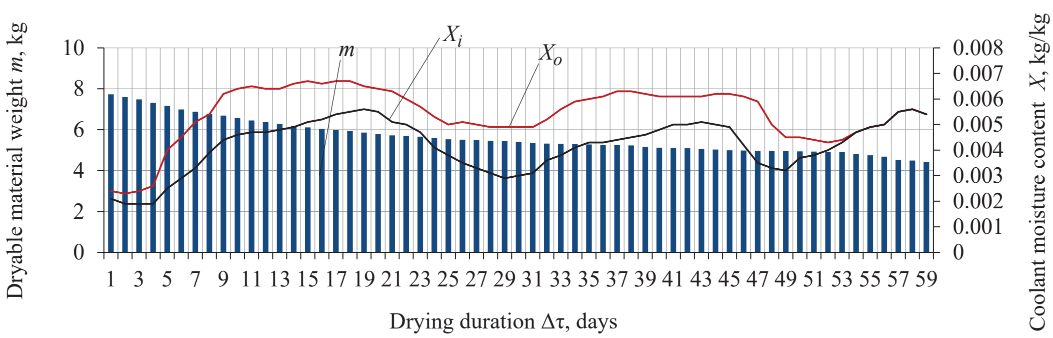


Fig. 9. Dynamics of mass transfer processes in the solar dryer in the period from 06.01.2018 to 07.29.2018: X_i, X_o – moisture content of the input and output coolant, respectively, kg/kg; m – daily weight change of the dryable material, kg

Consequently, the coolant temperature in the solar dryer varies from 18.5 °C to 56.9 °C. Such minimum and maximum variation peaks of coolant temperature in the solar dryer in different periods of oak veneer drying are due to the large discrepancy and uneven intensity of the energy potential of solar energy. Therefore, the parameters of the coolant in the kiln with increasing temperature and proportional increase in relative air humidity are controlled by an increase in coolant circulation from 1 to 3 m/s and vice versa. Thus, during veneer drying, coolant parameters should be t_i=25 °C, and t_o=31 °C, relative humidity φ_a=72.1 %, and φ_o=75.9 %, moisture content X_i=0.0055 kg/kg, and X_o=0.067 kg/kg. That is, the outlet temperature, humidity of the coolant should be 1.5 times higher than the inlet $t_i<t_o$, $\varphi_a<\varphi_o$, $X_i<X_o$. If this condition in the solar dryer is not provided, it is necessary to increase forced convection of the coolant. Because on the solar dryer walls and on the dryable material surface there will be a dew point, due to the coolant oversaturation with excess water vapor condensate.

In conclusion, we note that the main disadvantage of solar dryers is control over uncontrolled parameters of the drying process, which are reduced to humidity and moisture content regulation, and temperature control is possible only towards reduction of their values. Because temperature, humidity, and moisture content of the coolant in the solar dryer vary in a fairly wide range depending on weather conditions, time of day, intensity of the solar energy flow. Therefore, the process of oak veneer drying must be controlled by kinetic and dynamic parameters, namely, changes in weight m, humidity W and moisture content U of the dryable material and the resulting quality of raw materials.

6. Discussion of the study of the technological process of oak veneer drying in the solar dryer

The work is devoted to the study of the technological process of oak veneer drying in the developed solar plant with the active solar energy system. In addition, the power equipment is selected and the automated control system for moisture release, moisture removal and air exchange in the self-contained or mains solar dryer is developed. The control system is based on the advanced K1-102 panel controller with control sensors of circulation, temperature, moisture content of the coolant and dryable material. The self-contained power supply system includes two Linuo/ABi-Solar P60260-D 260 W photomodules; SL0912 Abi-Solar inverter; C&T Solar 3024 Pulsar charge controller; Ventura 12 V 150 A·h storage battery. This technological solution allows the solar dryer to operate autonomously without centralized power equipment and mains supply, although this is provided in the control system.

The technological parameters of the dryable material, namely oak veneer and its preparation for the drying process in the solar dryer, are substantiated. The kinetics and energetics of the air exchange process in the solar dryer are described. This allows calculating the required duration of air exchange in the solar dryer separately for each component of the power unit, namely the air collector and the kiln. In addition, the K1-102 controller can be correctly programmed to control the technological process of oak veneer drying in the solar dryer.

The technological process of drying 5 oak veneer sheets ($0.6\times2500\times100$ mm in size) conducted in the summer period from 01.06.2018 to 29.07.2018 is investigated.

On the basis of comparison of the obtained energy, kinetic and dynamic parameters, it is found that with the same coolant parameters, the duration of veneer drying in the solar dryer depends only on predicted changes in weather-dependent factors. In particular, the obtained data of humidity and weight of the dryable material enable to predict the process of oak veneer dehydration, taking into account air exchange in the solar dryer under various physical parameters of the environment. In addition, the study of the kinetics and dynamics of oak veneer drying in the solar dryer showed that the process of drying can be significantly intensified with the correct approach to heat and mass transfer processes in household and utility carpentry shops.

On the basis of the analysis of the obtained data it is revealed that it is impossible to develop the general method of oak veneer drying in the solar dryer, but only to stabilize the thermal parameters of the coolant in the kiln. The coolant parameters during oak veneer drying with humidity W from 75.3 % to 6 % must vary within the temperature t_i=25 °C and t_o=31 °C, relative humidity φ_a=72.1 % and φ_o=75.9 %, moisture content X_i=0.0055 kg/kg and X_o=0.067 kg/kg. That is, the outlet temperature and humidity of the coolant should be 1.5 times higher than the intlet $t_i<t_o$, $\varphi_a<\varphi_o$ or $X_i<X_o$. If this condition is not provided, it is necessary to increase forced convection of mixing of air masses of the coolant (actively ventilate) in the kiln. Because there will be a dew point on the solar dryer walls and surface of the dryable material. This is because the coolant reaches the state of saturation with water vapor at constant pressure, temperature and given moisture content.

However, the regression equation in natural values is not given for the determination of kinetic and dynamic parameters. It would be advisable to formulate a unified methodology for studying the technological process of oak veneer drying in the solar dryer.

In addition, it should also be noted that in the work little attention is paid to the substantiation of the economic efficiency of the solar dryer in the process of drying other veneer materials, namely, walnut, lime, poplar in different climatic zones. In particular, in the northern, eastern and southern dry regions of Ukraine. Therefore, the second stage of research will be the justification of the economic efficiency of the solar dryer, as well as the study of the drying process of other veneer materials, namely walnut, lime, poplar in different climatic zones of Ukraine. This will allow formulating a unified methodology for studying the technological process of veneer drying in the solar dryer and substantiating the cost-effectiveness of the process in comparison with traditional drying means.

Thus, the presented results are the initial stage of a comprehensive study to improve the effectiveness of the wood drying process on the basis of design and justification of solar dryer operating modes, which will reduce power consumption due to solar energy. The developed design of the solar dryer refers to a complex of solar drying units. This solar dryer was developed for Zorya LLC, located in western Polissya, namely in the city of Korets, Rivne region (Ukraine).

7. Conclusions

1. A new type of solar drying equipment with the active solar energy system is developed. Power characteristics of the solar dryer, the heat and mass transfer characteristics of the oak veneer drying process under standard irradiance and meteorological conditions are analyzed.

2. The influence of physical parameters of the environment and weather-dependent factors on the heat, mass and moisture exchange processes of oak veneer drying in the solar dryer is investigated. On their basis, histograms of energy, kinetic and dynamic parameters of the oak veneer drying process are constructed to determine the drying time, assess the quality of the dryable material and solar dryer performance.

3. Based on the study of the process of oak veneer drying in the solar dryer, the use of the K1-102 automated control system is substantiated and for the first time proposed for diagnosing the key parameters and predicting the intensity of heat and mass transfer processes. It is shown that using the obtained data on the performance of the drying object, depending on the technological task of drying, it is necessary to regulate air exchange and coolant removal, as well as solar energy flow in relation to weather-dependent factors. In particular, to intensify the processes of oak veneer drying (to change the action of temperature and humidity in the material) and reduce specific power consumption of the drying process due to solar energy.

References

1. Janjai S., Intawee P., Kaewkiew J. A Solar Timber Drying System: Experimental Performance and System Modeling // International Energy Journal. 2010. Vol. 11, Issue 3. P. 131–144.
2. A review on development of solar drying applications / Pirasteh G., Saidur R., Rahman S. M. A., Rahim N. A. // Renewable and Sustainable Energy Reviews. 2014. Vol. 31. P. 133–148. doi: https://doi.org/10.1016/j.rser.2013.11.052
3. Mustayen A. G. M. B., Mekhilef S., Saidur R. Performance study of different solar dryers: A review // Renewable and Sustainable Energy Reviews. 2014. Vol. 34. P. 463–470. doi: https://doi.org/10.1016/j.rser.2014.03.020
4. Multiphysics modelling of convective drying of food materials / Kumar C., Karim A., Saha S. C., Joardder M., Brown R., Biswas D. // Proceedings of the Global Engineering, Science and Technology Conference. Dhaka, 2012. P. 1–13.
5. Importance of wood drying to the forest transport and pulp mill supply / Zanuncio A. J. V., Carvalho A. G., Silva M. G. da, Lima J. T. // CERNE. 2017. Vol. 23, Issue 2. P. 147–152. doi: https://doi.org/10.1590/01047760201723022223
6. Seetapong N., Chulok S., Khoonphunnarai P. Thermal Efficiency of Natural Convection Solar Dryer // Journal of Physics: Conference Series. 2017. Vol. 901. P. 012044. doi: https://doi.org/10.1088/1742-6596/901/1/012044
7. Distributed mathematical model supporting design and construction of solar collectors for drying / Amankwah E. A. Y., Dzisi K. A., van Straten G., van Willigenburg L. G., van Boxtel A. J. B. // Drying Technology. 2017. Vol. 35, Issue 14. P. 1675–1687. doi: https://doi.org/10.1080/07373937.2016.1269806
8. Korobka S., Babych M. Substatiation of the constructive-technologocal parameters of a solar fruit dryer // Eastern-European Journal of Enterprise Technologies. 2017. Vol. 1, Issue 8 (85). P. 13–19. doi: https://doi.org/10.15587/1729-4061.2017.90299
9. Substantiation of parameters and operational modes of air solar collector / Korobka S., Babych M., Krygul R., Zdobytskyj A. // Eastern-European Journal of Enterprise Technologies. 2018. Vol. 3, Issue 8 (93). P. 16–28. doi: https://doi.org/10.15587/1729-4061.2018.132090
10. Results of research into kinetic and energy parameters of convection fruit drying in a solar drying plant / Boyarchuk V., Korobka S., Babych M., Krygul R. // Eastern-European Journal of Enterprise Technologies. 2018. Vol. 6, Issue 8 (96). P. 74–85. doi: https://doi.org/10.15587/1729-4061.2018.147269
11. Sazhin B. S. Osnovy tekhniki sushki. Moscow: Himiya, 1984. 320 p.
12. Rasev A. I. Sushka drevesiny. Moscow: Vysshaya shkola, 1980. 181 p.
13. Results of research into technological process of fruit drying in the solar dryer / Korobka S., Babych M., Krygul R., Zdobytskyj A. // Eastern-European Journal of Enterprise Technologies. 2018. Vol. 1, Issue 8 (91). P. 64–73. doi: https://doi.org/10.15587/1729-4061.2018.122816