Combined solar drying plant continuous operation

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Abstract. Studies of the drying processes of various vegetables and fruits were carried out in order to intensify the process, as well as the results of experiments conducted on a combined solar drying plant. The relations between the amounts of heat used to heat the material and the evaporation of water from the material for low-temperature drying conditions are determined. Calculated studies to determine the change in temperature and humidity conditions along the length of the drying chamber are presented.

1. Introduction
Drying processes are widely used in the processing of fruits and vegetables, pasta and crackers, marmalade and pastille products, etc. Drying is, on the one hand, a complex process of both heat and mass transfer, and on the other—a technological physical and chemical process, during which the original properties of the materials must be not only preserved, but in some cases even improved One of the promising directions in ensuring the safety of fruit and vegetable products is the development of processing industries, including the improvement and development of new energy-saving plants and methods of drying fruits and vegetables, which are characterized by a significant intensification of heat and mass transfer processes, increasing the energy efficiency of drying plants and preserving the most important physiological active substances (vitamins, carbohydrates and minerals), achieved in various ways; an increase in the contact surface between the product to be dried and the drying agent; a decrease in the relative humidity of the drying agent; an increase in the relative speed of movement of the reacting phases and the use of a combined energy supply, with a combination of dewatering with various technological processes. In this case, the use of solar energy is an important tool in improving the energy supply of agricultural processing industries.

2. Methods
According to our research, the most effective method for drying agricultural food is the convective method in solar installations, where the coolant is blown through a layer of dried material.In this regard, we have designed and built (in the heliolabor Buch.ITI) combined (helioelectroconvective) continuous drying unit (figure 1), which allows for intensive drying, determination of optimal modes of dehydration of agricultural food products, as well as to obtain a high-quality product while reducing its cost [1,2]. The installation consists of a solar air heater-heat accumulator 1, air ducts 2 and 3, a fan 4, an electric heater 5 and a drying chamber 6.

The air heater-heat accumulator is a chamber of the "hot box" type. It contains a wave-shaped air heater, the upper part of which is blackened with varnish, and in the lower part there is a heat-
accumulating material (THERE). As a TAM, we used technical paraffin with a melting point almost equal to the optimal drying temperature of agricultural products.

**Figure 1.** Scheme of the experimental installation:
1-a solar air heater with a heat storage element; 2, 3 - air ducts; 4-a fan; 5-an electric calorifier; 6 - a drying chamber; 7-a heat exchanger; 8-a heat storage device.

**Figure 2.** Various types of combined solar drying plant.

In the drying chamber, multi-tiered racks are installed to accommodate the dried products. In the upper part of the drying chamber, an air duct is installed, which is connected to the heat storage part of the "hot box".

The drying unit works as follows: by absorbing the sun's rays coming through the glazed surface, the air heater and the air in it are heated [3]. The heated air, due to convection or with a slight convective current by means of a fan (4) through the air duct (2), enters the drying chamber and, giving part of its potential to the dried product through the air ducts (3), enters the heat-accumulating part of the solar heater. Wet potential air, passing through the heat exchanger (7) located in the heat-accumulating part of the solar air heater, giving it a significant part of its potential, is released into the air. At a sufficiently high temperature of the incoming air from the solar air heater, such a system can provide drying in the daytime with the electric heater turned off. When the temperature in the chamber decreases below the typical mode of the drying process, especially at night, the electric heater is switched on. Thus, the proposed design promotes continuous, uniform and intensive drying, and also allows you to utilize the energy of the spent drying agent. [4].

Static and dynamic characteristics of the dryer can be obtained analytically and experimentally. The experimental methods used to study the installation do not differ from the methods used to study other objects. Analytical methods of research are related to the specifics of the drying process and they should be discussed in more detail. According to the classification of P. A. Rebinder, there are several forms of...
connection of moisture with the material in a solid, according to which surface, sorption and crystallization moisture are distinguished. During the drying process, the dried material is released from the surface and part of the sorption (or only surface) moisture; the process of removing the crystallization moisture-dehydration—is usually considered separately. The drying process in accordance with the two forms of binding of moisture removed from the material includes two periods. When removing surface moisture (the first period), the drying rate is actually limited only by the supply of energy to the material from external sources. At this stage, the partial vapor pressure of the liquid can be considered equal to evaporation, resulting in drying at a constant rate. The first period continues until the moisture content on the surface of the body becomes less than the maximum hygroscopic moisture content that characterizes the body, combined with a humidity of 100%. The value of \( W_{\text{hygro}} \) determined by the molecular structure of the material and its temperature is achieved at a certain average or critical moisture content of \( W_{\text{cr}} \). The \( W_{\text{cr}} \) value is determined by the size and shape of the body, the drying intensity, and the potential-conductivity coefficient [5].

The removal of sorption moisture (the second period) occurs at a decreasing rate, since the drying process here is mainly characterized by the mixing of moisture inside the body. In other words, the drying rate is primarily affected by the rate of moisture entry from the depth of the body to the evaporating surface. During this period, the vapor pressure of the liquid above the surface of the body continuously decreases [6].

3. Results

To study the temperature and thermal conditions, as well as the efficiency of the plant, we conducted a number of experiments with dried products (grapes, apricots, figs, melons, sliced pumpkins, etc.) in different meteorological conditions and at different times. To control the drying process, the temperature of various parts of the plant was measured with copper-constantan thermocouples.

Continuous measurement and recording of various thermophysical parameters were carried out inside and outside the drying chamber. Drying experiments were carried out in a natural way under identical conditions. The drying rate, i.e., the change in humidity over time, was determined by weighing the product samples at the beginning of drying and during a certain period of time. The relative humidity of the material was calculated from the mass of the samples and a curve of the dependence of humidity on time was constructed. For the practical calculation of the process occurring in a helioconvective dryer, it is necessary to know the dependence of the drying rate \( N \) in the first period on the main parameters of the process: speed, temperature and moisture content of the coolant, size and height of the material to be dried. We studied the drying of various fruits at a coolant temperature of 60-65 °C, an air flow rate of 0.1-3 m/s with a single-layer layout of fruits (the height of the fruit layer is 0.015 - 0.05 m). Experiments on drying various agricultural products were carried out both in the drying plant described above and in the open air. The results of the experimental studies are shown in figures 3 and 4.

**Figure 3.** Dependence of moisture content on the duration (a) and speed (b) of drying of apricots (1), kishmish (2) and tomato (3). 1, 2, 3 – in a solar installation at \( t\leq 65 \text{ S}, U = 0.8 \text{ m/s}; 1/, 2/, 3/ \text{ in the open air.}
Calculate the drying kinetics of the entire product layer. Drying speed:

\[ N = \frac{\alpha \cdot f \cdot \Delta t}{2} \]  

(1)

Where \( \alpha \) is the coefficient of heat transfer during the movement of air through the layer, determined by the formula of A.V. Chechetkin:

\[ \alpha = 0.0146 \cdot a^{0.17} \cdot \lambda_b \left( \frac{\varrho \cdot \gamma_b^{0.83}}{\mu_b} \right) \]  

(2)

Then the drying rate in the first period:

\[ N = 0.0146 \cdot a^{0.17} \cdot \lambda_b \left( \frac{\varrho \cdot \gamma_b}{\mu_b} \right) \cdot f \cdot (t_i - t_m) / r \]  

(3)

There \( \Delta t = t_i - t_m \) is the difference between the temperature of the coolant at the entrance to the layer and the temperature of the wet thermometer; \( f \) is the specific surface area of the wet material per 1 kg of dry material; \( r \) is the heat of vaporization at the temperature of the wet thermometer, J/kg; \( a \) - coefficient; \( \varrho \cdot \gamma_b \) is the mass velocity of air, kg/m²·s; \( \mu_b \) is the dynamic viscosity, N·s/m². The analysis showed that with sufficient accuracy for practical purposes, the dependences in semilogarithmic coordinates can be represented as straight lines, the angles of inclination of which are numerically equal to the drying coefficient.

\[ K = \chi \cdot N = 2.3 \cdot Lg \left[ (W_i - W_p) / (W_2 - W_p) \right] / (\tau_2 - \tau_1) \]  

(4)

Moisture content in the second drying period:

\[ (W_{kp1} - W_p) / (W_k - W_p) = \exp \left( -N \chi \tau \right) \]  

(5)

Figure 4. Dependence of the drying curves of pumpkin (a), figure (b) and melon (c) on the layer thickness. 1) \( \delta = 2 \) sm; 2) \( \delta = 4 \) sm; 3) \( \delta = 5 \) sm.

Where \( W_{kp1} \) is the critical moisture content corresponding to the beginning of the second drying period; \( W_k \) is the final moisture content; \( \chi \) is the relative drying coefficient [7].
\[ \chi = 1.8W_0^{-1} \]  

(6)

In the second period, the experimental values of \( \chi \) for apricot - 0.54, kishmish - 0.45, tomato - 0.2.

Drying time \( \tau \) for various agricultural products in the blown layer from the initial moisture content \( W_h \) to the final \( W_k \) in general form.

\[ \tau = \frac{1}{N} \left\{ (W_h - W_{kp_i}) + \frac{2.3}{x} \cdot \lg \left[ \frac{(W_{kp_i} - W_p)}{(W_k - W_p)} \right] \right\} \]  

(7)

Substituting the experimental values \( N, W_{kp}, \chi, W_k \) in (7), we obtain

\[ \tau_a = \frac{r(W_h - 19.2)}{5.92 \cdot 0.83 \cdot \Delta t} \]  

(8)

\[ \tau_{kish} = \frac{r(W_h - 24)}{8.2 \cdot 0.83 \cdot \Delta t} \]  

(9)

\[ \tau_{tom} = \frac{r(W_h - 26.05)}{6.3 \cdot 0.83 \cdot \Delta t} \]  

(10)

The results of calculations for (8) - (10) satisfactorily coincide with the experimental data. The proposed method allows you to calculate the drying time in a wide range of changes in the process parameters [8].

4. Conclusion

Thus, the proposed experimental installation reduces the drying process by 4 - 5 times compared to air-solar, and the finished products are of high quality. Due to the accumulation of solar energy and the circulation of the drying agent, the productivity and efficiency of the plant are increased by 1.5-2 times compared to similar installations.

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