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The methodological foundations of the thermal efficiency in a convective drying unit of the chamber type

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Abstract. The article deals with the issue of increasing the efficiency of the drying plant, gives theoretical prerequisites and analytical calculations and a generalized formula for determining thermal efficiency is derived. The author and the staff conducted a number of experiments on a pilot plant. According to the results of the experiments, curves of the dependence of the efficiency of the drying unit on the heating temperature of the chamber surface and at the outlet of the spent drying agent from the drying chamber were obtained. It has been proven that with an increase in the temperature of the spent drying agent, the thermal efficiency decreases. The optimum temperature of the discharge heat of the agent is considered. The expediency of using a heat-accumulating rubble nozzle was also justified, which allows saving up to 14% of the thermal energy required for the drying process.

1 Introduction

One of the ways to conserve the nutritional properties of melons is its drying. At the same time, vitamins, trace elements and biologically active substances that are necessary for the maintenance of human life, are maximally preserved in the agricultural [1-6], livestock [7-11], poultry and fishers product [12]. Therefore, in terms of choosing methods and rational modes of the drying process, it is vital to be based on scientific foundations: from studying the physic-chemical properties of the product as an object of drying, selecting highly efficient and combined methods of energy supply that ensure the intensity of the process and create, as well as finding ways to save energy due to the wider use of other types of energy [13, 14].

Therefore, recently all scientific directions have been focused on the creation of energy–saving drying technology using combined (by energy) solar-fuel drying plants. The authors, based on the analysis of existing drying methods and design solutions of drying plants, put forward their concept for the modernization and optimization of the drying process, as well as energy saving. The two-chamber combined solar-fuel drying plant developed by us combines the use of both solar energy and traditional - electric. The issue of providing an

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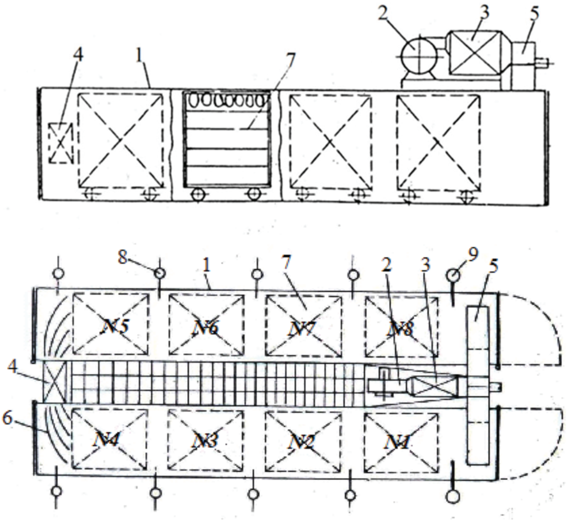
oscillating drying mode as an intensifying factor of this process has been solved constructively [15].

2 Materials and methods

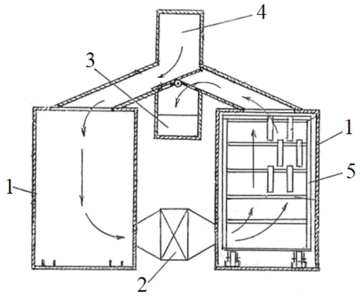
The objects of research are a two-chamber convective drying plant developed and tested by the Russians for drying annular melon slices [16], which contains two parallel–located drying chambers having a rectangular cross-section, a fan, main and auxiliary electric heaters, an air distribution manifold with a V-shaped weather vane valve. Inside the chambers, curved air-guiding ailerons and eight grocery carts are installed, located on corner guides (Figure1).

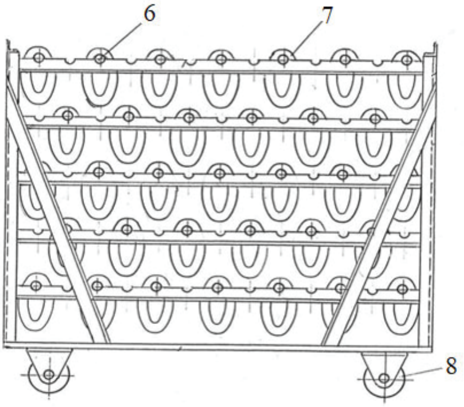


1-camera; 2-fan; 3,4-main and auxiliary electric heaters; 5-air distribution manifold; 6-ailerons; 7-grocery carts; 8-thermocouples; 9-mercury thermometer.

Fig. 1. Schematic diagram of the drying plant.

The grocery cart is made in the form of a spatial parallelepiped forming a rigid frame of a corner profile. On the longitudinal crossbars forming the tier, semicircular recesses are made for laying poles with melon slices, while the recesses are located on alternating crossbars with an offset of half a step. Melon slices on poles are also stacked with mixing, being placed in the volume of the cart in horizontal and vertical planes in a staggered order (Figure 2).





1-frame; 2-electric heater; 3-pipes; 4- air distribution manifold; 5- grocery cart; 6- wooden pole; 7- melon slice; 8- wheel.

Fig. 2. Grocery cart for laying melon slices.

The drying unit includes the following procedures: food carts with ring-shaped melon slices stacked on poles are loaded into both drying chambers, the doors are tightly closed and the air and heat supply system is turned on: a fan and electric heaters. At the same time, the fan pumps air through the main heater, in which it is heated to 70-80 ° C and enters one of the drying chambers through the air distribution manifold, in which it blows melon slices hung on trolleys. Due to the convective heat exchange between the hot air and the product, moisture evaporates and the air temperature drops. Then the air enters the intermediate heater, warms up to the required temperature and enters another chamber. The spent low-potential air with a temperature of 40-45 ° C is discharged through one of the sleeves of the air distribution manifold into the inter-chamber space, where poles can be suspended for pre-drying melons. By turning the V–shaped weather vane valve, the installation can be switched to an oscillating drying mode, which intensifies the dehumidification process. The oscillation period for drying melons is taken within 40-45 minutes.

3 Results and discussions

It can be observed that the regularity of the formation of the thermal efficiency of a drying plant consisting only of a solar collector (blackened chamber surface).

The thermal power supplied to the drying chamber is determined by the expression [15, 17, 18]

$$Q_n = \eta_{mn} \left[\eta_o q_n - k_n \left(\bar{t_f} - \bar{t_o} \right) \right] F_f, \qquad (1)$$

Here: η_{mn} is the efficiency coefficient of the heat receiver of the solar collector; η_n is the efficiency coefficient of absorption of solar radiation by the surface of the chambers; q_n is the density of the incident radiation flux on the frontal surface of the chambers; k_n is the coefficient of total heat loss of the collector per unit of the radiation–absorbing surface; $\bar{t}_f$ – the average temperature of the coolant along the length of the chambers;

$\bar{t}_o$–the average temperature of the coolant in the heat sink channel, ° CF_f; – the area of the frontal radiation-absorbing surface of the chambers, m2.

On the other hand, this thermal power is equal to [3,5,7,8]

$$Q_n = G_в c_в (t_1 - t_0), \qquad (2)$$

here:

$G_в$– drying agent(air) consumption,*кг*;

$c_в$ – specific heat capacity of air, К;

t_1 – air temperature heated by solar radiation,
$°C$; t_o - ambient air temperature, $°C$.

$$Q_{и} = G_{вл} r, \tag{3}$$

$$Q_{mn} = \sum k_n F_c (\overline{t}_{к}^{в} - t_0^{в}), \tag{4}$$

$$Q_c = G_{в} c_{в} (t_{к}^{в} - t_0^{в}), \tag{5}$$

Here: $G_{в}$ is the amount of evaporated moisture from the product; r is the latent heat of vaporization; k_n is the coefficient of heat loss through the *i*–the wall of the chamber;

$\overline{t}_{к}^{в}$- average air temperature along the length of the drying chamber, K; $t_0^{в}$- ambient air temperature, K; $G_{в}$ is the mass air consumption.

$$\overline{t}_f = \frac{t_1 - t_o}{ln t_1 / t_o} \tag{6}$$

and

$$f_l^{-в} = \frac{t_1 - t_2}{ln t_1 / t_2}. \tag{7}$$

The values of the thermal efficiency of the solar collector-η_c and the drying chamber-η_k are determined from the well-known ratios [15]

$$\eta_c = Q_n : Q_{no} \tag{8}$$

and

$$\eta_{к} = Q_n : Q_{no}, \tag{9}$$

Here: Q_n - the flow of total incident radiation to the front surface of the cameras

$$Q_n = q_n F_f. \tag{10}$$

DefiningQ_n from (4) and substituting the obtained into the relation (10) we get

$$\eta_k = 1 - \frac{Q_{mn} + Q_{б}}{Q_{no}}. \tag{11}$$

The total thermal efficiency of the drying plant is defined as the product of (9) and (10), etc.

$$\eta = \eta_c \eta_{к} = Q_n : Q_{no}. \tag{12}$$

Substituting the valuesη_c and η_k , respectively from (9) and (10) into (13) and taking into account the values$Q_{п}$, $Q_{по}$, and from (2), (1), (4), (5) and (6), as well as$\overline{t}_f$ and $\overline{t}_k$ from (7) and (8), after the corresponding mathematical transformations, we obtain:

$$\eta = \eta_{mn} \left[\eta_m - \frac{k_{np}}{q_{no}} \left(\frac{t_1 - t_o}{ln \frac{t_1}{t_o}} - t_o \right) \right] \cdot \left[1 - \frac{t_2 - t_o}{t_1 - t_o} - \frac{\sum k_i F_i \left(\frac{t_1 - t_2}{ln \frac{t_1}{t_2}} - t_o \right)}{\eta_{mn} \cdot q_{na} \cdot F_f \left[\eta_{on} - \frac{k_{np}}{q_{na}} \left(\frac{t_1 - t_o}{ln \frac{t_1}{t_o}} - t_o \right) \right]} \right]. \tag{13}$$

4 Research results and their discussion

Figure 3 depicts the curves of the dependence of the thermal efficiency of the drying unit (η) on the heating temperature of the blackened surface of the chamber(t_1) and at the outlet of the drying chamber(t_2), which in the first approximation are close to the real operational characteristics of solar-fuel convective type installations.

As follows from the graphs of Figure 3, other things being equal, an increase in the temperature of the spent drying agent (t_2) leads to a decrease in the thermal efficiency of the dryer. So, $t_1 = 70^0 C$ with an increaset_2 from 35 ° C (during a constant drying rate) to 50 ° C in the final stage of the drying process, the decreaseη is from 0.38 to 0.23, i.e. by 39.5%.

It also follows from the graphs that the dependence$\eta = f(t)$ is almost linear only att_2=*35 °C*. Att_2=*45 °C*, with an increase oft_1= *60 °C* , the value η first rises to 0.29, and then drops. At t_2=*50* °the maximum efficiency valueη is at t_1= *70 °C* and corresponds to 0.24.

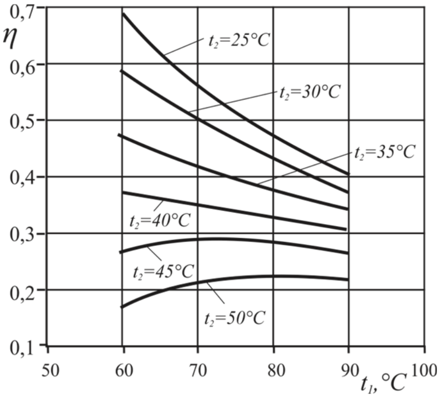


Fig. 3. The dependence of the efficiency of the drying unit on the heating temperature of the chamber surface (t_1) and at the outlet of the drying chamber (t_2).

According to the based solution (14) and graphical dependencies$\eta = f(t_1, t_2)$, it is possible to optimize the temperature of the discharge drying agent. The energy-saving mode of operation of the drying unit is possible with the use of regenerative heat accumulators. In the second period of the drying process, when the temperature of the drying agent at the outlet of the chambers becomes higher than the temperature of the wet thermometer (t_m), for example by 8-10 ° C or more, the drying agent is passed through a rubble heat accumulator, which gives its heat to the nozzle and is released into the environment. At night, the sucked air passes through the rubble nozzle and is heated by accumulated energy. The temperature controller in the "on-off" mode reduces the power of the main heat source (electric heater) and thereby provides an energy-saving mode. The overall, thermal and aerodynamic characteristics of regenerative nozzle accumulators are determined depending on the performance of the drying unit, taking into account the thermo-physical properties of the nozzle, its porosity and the dimensions of the nozzle elements.

As the results of preliminary studies have shown, the heat savings during the drying of agricultural products according to the proposed scheme is 27-28%, including 14-15% from the use of solar radiation and up to 14% due to the regeneration of waste heat through nozzle batteries.

5 Conclusions

Due to the conducted research followings can be concluded:

1. The upgraded two-chamber combined solar-fuel drying plant combines the use of both solar energy and traditional - electric, optimizing the drying process. Such a constructive solution provides an oscillating drying mode, where the intensity of moisture extraction is achieved by 30-35%.
2. Based on the solution of graphical dependencies$\eta = f(t_1, t_2)$, it is possible to optimize the temperature of the discharge drying agent. The energy-saving mode of operation of the drying unit is possible with the use of regenerative heat accumulators.
3. It is established that the temperature controller in the "on-off" mode reduces the power of the main heat source (electric heater) and thereby provides an energy-saving mode.
4. Heat savings during the drying process according to the proposed scheme is 27-28%, including 14-15% from the use of solar radiation and up to 14% due to the regeneration of waste heat through the nozzle batteries.

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