Mathematical modeling of the drying chamber of the combined solar dryer-cooler unit

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Abstract.This research paper presents the mathematical model and numerical results of the heat and mass exchange processes in the drying chamber (DCh) of the combined solar air collector SAC indirect solar dryer (SD) designed for drying 30 kg of fresh apple slices in one drying cycle. This dryer allows you to reduce the moisture content of apple slices from 62% to 17%. Also, physical processes in the DCh are modeled on the basis of balance equations when various parameters affecting the product drying process change. The solution of these equations makes it possible to determine the temperature change in different elements of the SD, and then the drying kinetics of apple slices. It is possible to theoretically and experimentally determine the change in temperature and humidity of the product during drying of other types of products in the proposed SD.

1 Introduction

Production, processing and storage of agricultural products (AP) is one of the main sectors of the country's economy. Depending on the type of cultivated products and areas, from 10 to 60% of products are lost every year during the period of growing and storing the product [1]. Also, the problem of providing the population with continuous quality AP throughout the year is also increasing. To solve these problems, storing AP in drying and cooling chambers is the best solution.

Nowadays, SD drying method is widely used in many countries. In this method, products are dried directly under sunlight. The main purpose of SD is to remove moisture from the product, which is directly involved in the deterioration of product quality. As practice shows, drying under direct sunlight leads to damage of products by various bacteria, rapid release of vitamins A and C, and burning of the product [2]. However, the use of indirect SD can solve the above problems [3-7].

Indirect SD for drying AP were tested for the first time in Senegal, but there is no way to control the various drying parameters in this SD5]. Cabinet-type indirect SD was first made in Algiers, this SD was designed for drying apricots and had a capacity of 25 kg [6]. R. Dilip et al [8] studied a forced convection indirect SD. This SD consists of a SAC and a DCh, and is designed to dry several products, but the SD does not have the ability to adjust the air speed over the product.

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J. Dilip [9] proposed a natural convection SD with thermal accumulator. This SD is designed to dry 90 kg of onions, and it can dry onions twice as fast as a conventional dryer, but this dryer also does not have the ability to control the air speed over the product. S. Singh et al [10] conducted a pilot study on a simple greenhouse type SD. This type of SD does not have temperature and drying speed controls.

2 Material and methods

The forced convection indirect SD under study consists of two parts:

- SAC part producing hot air (SAC is placed at an angle of 39°).
- DCh (size), equipped with 3 drying racks with dimensions of 0.5×0.5 m.

Figure 1 shows the general view of the SD and the side walls of the DCh. These images were created using the AutoCAD software.

Figure 1. General view and side walls of the SD: (a) general appearance, (b) west side, (c) east side, (d) north side.

The numerical model based on the method of balances (heat and mass balance) was developed for mathematical modeling of an indirect SD with forced convection. The Page model was used to create the mass balance, and this model allows determining the change of moisture in product pieces over time. The creation of a numerical model is based on the following assumptions:

- The temperature in the absorber is the same on the surface.
- The temperature of the soil is equal to the temperature in the room.

- The air temperature inside the drying chamber does not change.
- The flow is directed in the same direction in all parts of the system.
- The distribution of product pieces placed on the rack is homogeneous.
- No chemical reaction occurs in the product.
- The amount of water in the product and the temperature of the product are the same.
- Does not deform the product during drying.

Modeling of solar air collector. Figure 2 shows the process of heat exchange in a SAC. The energy balance equation for a transparent surface:

$$\rho_c V_c C_p \frac{dT_c}{dT} = \alpha_c S_c A_c + h_5(T_{ab} - T_c)A_{ab} - h_3(T_c - T_a)A_c - (h_1 + h_4)(T_c - T_{am})A_c \qquad (1)$$

The energy balance equation for the absorber is:

$$\begin{aligned}\rho_{ab} V_{ab} C_p \frac{dT_{ab}}{dT} = \tau_c \alpha_{ab} S_{ab} A_{ab} - h_5(T_{ab} - T_c)A_{ab} - h_2(T_{ab} - T_a)A_{ab} \\ - h_6(T_{ab} - T_{am})A_{ab}\end{aligned} \qquad (2)$$

Energy balance equation for air flowing through the collector:

$$\rho_a V_a C_p \frac{dT_a}{dT} = h_3(T_c - T_a)A_c + h_2(T_{ab} - T_a)A_{ab} \qquad (3)$$

Where ρ_c, ρ_{ab}andρ_a-transparent coating, absorber and air density; V_c, V_{ab} and V_a-transparent coating, absorber and air volume; C_p-specific heat capacity; α_c-absorption coefficient of the transparent coating; S-solar radiation flux density; A_c and A_{ab}-transparent coating and absorber surface area; h_r-radiation heat exchange coefficient; T_{ab}, T_a, T_{am} and T_c-absorber, air, outside air and transparent coating surface temperatures; h_c-convective heat exchange coefficient.

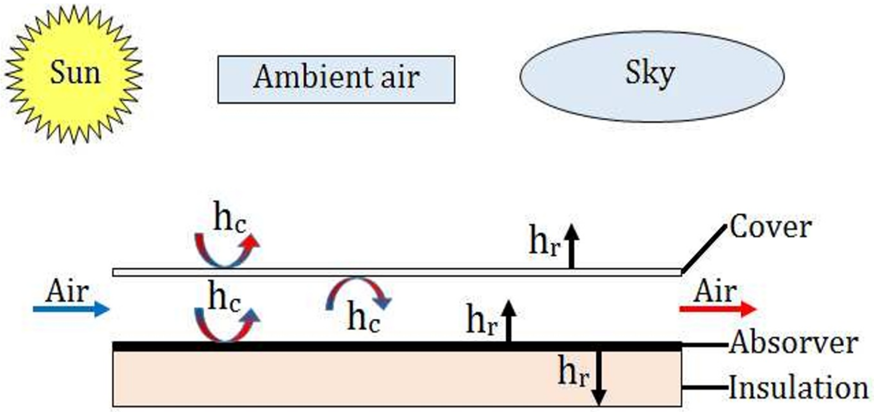

Figure 2. Illustration of the heat exchange process in a SAC.

Modeling the drying chamber. Figure 3 shows the process of heat exchange in the DCh.

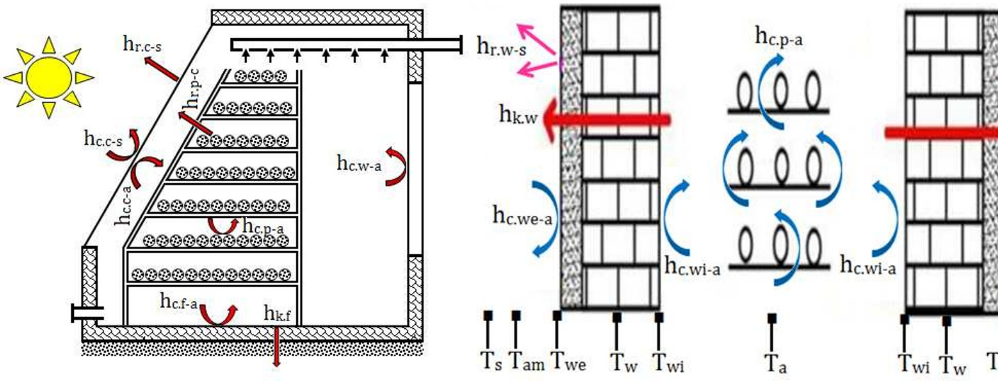

Figure 3. Image of the heat exchange process in the DCHh.

The heat exchange process in the DCh is modeled on the basis of the following balance equations:

For the outer and inner wall of the east side of the SD (wall 1):

$$b_w \rho_w C_p \frac{dT_{we1}}{dt} = \alpha_w S h_{r.w1-s} + h_{c.we1-am}(T_{am} - T_{we1}) + h_{c.we1-s}(T_s - T_{we1}) + \\ + h_{k.w}(T_{w1} - T_{we1}) \tag{4}$$

$$b_w \rho_w C_p \frac{dT_{wi1}}{dt} = h_{c.wi1-a}(T_a - T_{wi1}) + h_{k.w}(T_{w1} - T_{wi1}) \tag{5}$$

For the outer and inner wall of the west side of the SD (wall 2):

$$b_w \rho_w C_p \frac{dT_{we2}}{dt} = \alpha_w I h_{r.w2-s} + h_{c.we2-am}(T_{am} - T_{we2}) + h_{c.we2-s}(T_s - T_{we2}) + \\ + h_{k.w}(T_{w2} - T_{we2}) \tag{6}$$

$$b_w \rho_w C_p \frac{dT_{wi2}}{dt} = h_{c.wi2-a}(T_a - T_{wi2}) + h_{k.w}(T_{w2} - T_{wi2}) \tag{7}$$

For the outer and inner wall of the western side of the SD (wall 3):

$$b_w \rho_w C_p \frac{dT_{we3}}{dt} = \alpha_w I h_{r.w3-s} + h_{c.we3-am}(T_{am} - T_{we3}) + h_{c.we3-s}(T_s - T_{we3}) + \\ + h_{k.w}(T_{w3} - T_{we3}) \tag{8}$$

$$b_w \rho_w C_p \frac{dT_{wi3}}{dt} = h_{c.wi3-a}(T_a - T_{wi3}) + h_{k.w}(T_{w3} - T_{wi3}) \tag{9}$$

For Wall 1:

$$b_w \rho_w C_p \frac{dT_{w1}}{dt} + h_{k.w}(T_{w1} - T_{we1}) = b_w \rho_w C_p \frac{dT_{w1}}{dt} + h_{k.w}(T_{w1} - T_{wi1}) \tag{10}$$

For Wall 2:

$$b_w \rho_w C_p \frac{dT_{w2}}{dt} + h_{k.w}(T_{w2} - T_{we2}) = b_w \rho_w C_p \frac{dT_{w2}}{dt} + h_{k.w}(T_{w2} - T_{wi2}) \tag{11}$$

For Wall 3:

$$b_w \rho_w C_p \frac{dT_{w3}}{dt} + h_{k.w}(T_{w3} - T_{we3}) = b_w \rho_w C_p \frac{dT_{w3}}{dt} + h_{k.w}(T_{w3} - T_{wi3}) \tag{12}$$

Heat exchange between product and drying air:

$$\begin{gathered} m_p\left(C_{pg} + C_{pp}M_p\right)\frac{dT_p}{dt} = A_p h_{c.p-a}\left(T_a - T_p\right) + A_p h_{r.p-c}\left(T_c - T_p\right) + IA_c \alpha_p \tau_c + \\ + b_p A_p \rho_p\left[L_p + C_{pv}\left(T_a - T_p\right)\right]\frac{dM_p}{dt} \end{gathered} \tag{13}$$

Where b_w and b_p-wall and product thickness; $\rho_w$and ρ_p-wall and product density; $T_{we}$and T_{wi}-external and internal wall surface temperatures; h_k-conductive heat exchange coefficient; T_s-sky temperature; T_p-product temperature;m_p and M_p-product mass and moisture; A_p-product surface; L_p-latent heat of evaporation of moisture from the product.

Mass balance. The process of removing moisture from the product is similar to the convective loss of heat from a boiling body (Newton's law of cooling). The drying rate is proportional to the difference between the moisture content of the material being dried and the equilibrium moisture content [10]. The mathematical expression of this process is as follows:

$$\frac{dM}{dt} = -k(M_t - M_e) \tag{14}$$

We solve this equation under the condition $M(t=0) = M_0$:

$$\frac{M_t - M_e}{M_0 - M_e} = MR = exp(-kt) \tag{15}$$

Recalculated to dry mass, moisture content (M) is the mass of moisture present in the product [11]:

$$M = \left[\frac{W_0 - W_d}{W_d}\right] \times 100\% \tag{16}$$

Where W_d and W_0-dried product and initial product mass. The amount of evaporated moisture when recalculated to dry mass is determined according to the following equation [11]:

$$M_t = \left[\frac{(M_0 + 1)W_t}{W_0} - 1\right] \times 100\% \tag{17}$$

Where M_0-initial moisture content when converted to dry mass; W_t-product mass included in drying.

The most universal model of moisture balance is Henderson's semi-theoretical model, which represents the relationship between the equilibrium amount of moisture and relative humidity at a given temperature:

$$1 - rh = exp\left(-cT_{dp}M_e^n\right) \tag{18}$$

Where c and n-are empirical constants for a specific product and are determined based on experimental results.

3 Results and discussions

Changes in air temperature and solar radiation in the SAC and SD are shown in Figure 4. During the drying experiments, the outside air temperature varies from 30 to 46.4°C, the temperature of the drying air at the inlet to the DCh varies from 51.5 to 66.3°C, and the temperature at the outlet varies from 44.1 to 62,4°C. During the experiments, solar radiation varies from 561.5 to 939 W/m^2, wind speed varies from 0.2 to 0.8 m/s.

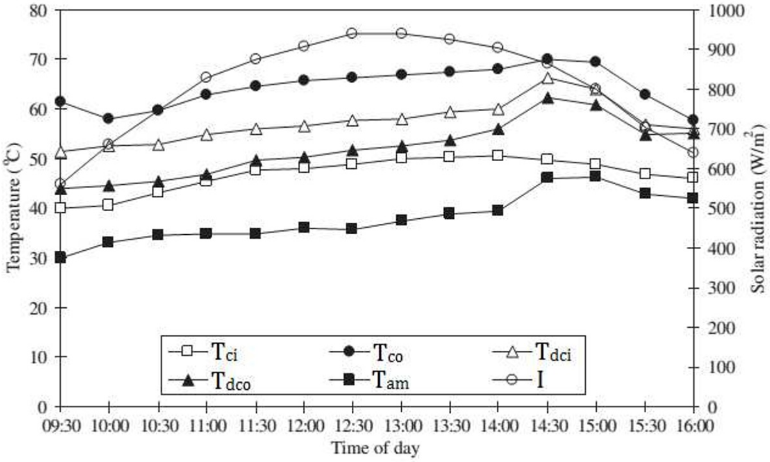

Figure 4. Changes in temperature and solar radiation in a SD: T_{ci} and T_{co}-collector inlet and outlet temperatures; T_{dci} and T_{dco}-dryer inlet and outlet temperatures; T_a-air temperature; I-solar radiation.

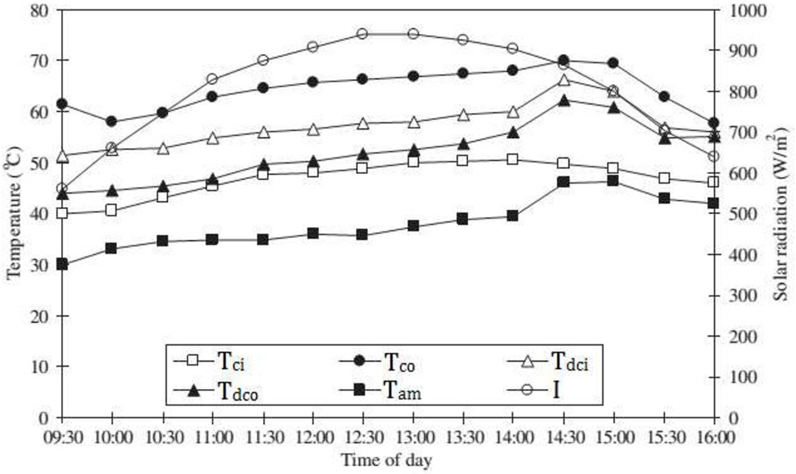

Figure 5. Theoretical and experimental values of air (a) and apple (b) temperatures inside the DCh.

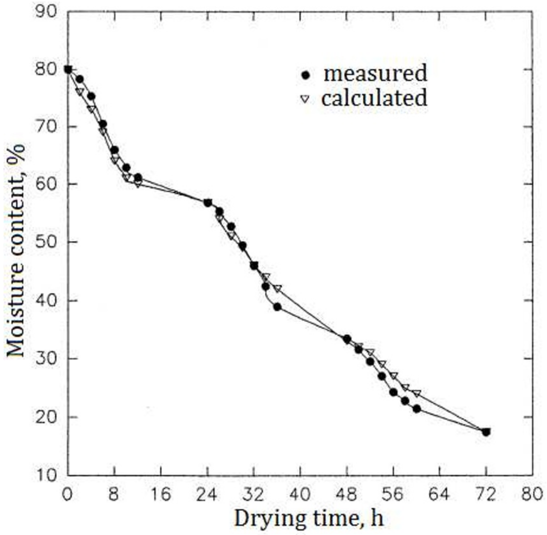

Figure 6. Changes in moisture in apple slices.

Figure 5 shows changes in the temperature of the air inside the DCh and the temperature of the apple slices during drying of apple slices. As can be seen from the results of these figures, the theoretical and experimental results are in agreement. The maximum error between the theoretical and experimental values in figure 5, a does not exceed 5.2%. 5, and in figure b does not exceed 3.9%.

Figure 6 shows the results of experimental and theoretical calculations on changes in moisture in apple slices. As can be seen from Figure 6, the theoretical and experimental results agree very closely. Deak, the mathematical model proposed above can be fully used to determine the changes of air temperature, product temperature and product moisture in the DCh of the SD.

4 Conclusions

Based on the research on mathematical modeling of the DCh of the combined SD-cooler device, the mathematical modeling of heat and mass exchange processes in the SAC and DCh of the combined SD was carried out using the method of balance equations.

The proposed mathematical model allows to determine the temperature changes of glass, absorber and air in the SAC, air and product temperatures in the DCh and product humidity.

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