Energy 134 (2017) 382–391

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Modeling of the drying process of apple slices: Application with a solar dryer and the thermal energy storage system

Halil Atalay [a, *], Mustafa Turhan Çoban [b], Olcay Kıncay [c]

[a] Department of Mechanical Engineering, Faculty of Engineering, Bozok University, TR-66000, Yozgat, Turkey
[b] Department of Mechanical Engineering, Faculty of Engineering, Ege University, TR-35100, Izmir, Turkey
[c] Department of Mechanical Engineering, Faculty of Machine, Yıldız Teknik University, TR-34000, Istanbul, Turkey

A R T I C L E I N F O

Article history:
Received 24 January 2017
Received in revised form
3 June 2017
Accepted 6 June 2017
Available online 7 June 2017

Keywords:
Drying
Solar energy
Dried apple
Packed bed thermal energy storage
Renewable energy resources

A B S T R A C T

In this study a solar air heater was developed to determine the drying rate of apple (Golden Delicious). In order to provide the drying process continuously a packed bed thermal energy storage system was designed and manufactured. Also, a recuperator unit was used for waste heat recovery. In the recuperator unit, it is provided the mixing of the fresh air with the drying air whose moisture content increases, at a specified rate. So at the rate of 50–60% waste heat is recovered and reutilized in the drying system. The advantage of the system is that it consumes less energy at the rate of 76.8% than other drying technologies. Experiments on the drying system were repeated twice a day. In the experiments the drying kinetics of apple slices (5 ± 2 mm thick) was determined at constant temperatures ranging from 50 – 60°C. Also, Diffusion Approximation model was used for drying of apple slices in constant temperature. A mathematical model was developed to calculate the prediction of the moisture ratio during time and it is observed that the model is complied with the studies in the literature.

1. Introduction

Drying of foods has been applied for antiquity, is the oldest protection method. The method is usually materialized on one's own in nature, such as most of grains and agriculture products dry automatically in field and can become durable. Driying of foods in nature are usually materialized with solar energy. But it is not true that all products are dried in solar. So many works were made about various food products drying with the other methods.

There are many works in the literature about food drying systems and dried products. Therefore drying parameters were determined by both experimental and mathematical methods. Drying behavior of food products is different from each other. So air temperature, relative humidity, air velocity, circulation way according to product, heat and mass transfer effects have to be determined for drying products. Lee and Kim [1] dried thin-sliced radish with heat pump dryer and warm air stove. They compared the two drying systems with each other. They observed that the heat pump dryer consumed at the rate of 58.9–69.5% less energy according to warm air stove. Queiroz et al. [2] studied drying of tomato by using heat pump dryer and electric resistance dryers with parallel and crossed airflow. Also they supported the drying process with mathematical model. They showed that heat pump dryer saved approximately 40% of energy than electrical oven drying. Hawlader et al. [3], designed and tested solar energy supported heat pump dryer in Singapore. Outer ambient air temperature was used for evaporating refrigerant in system. Also air collector was used for heating drying air. Tosun [4] developed and designed a heat pump dryer with dehumidifier for some agro-foods with high moisture. Also it was observed that the drying process positively affected the quality of the product due to the heat pump dryer that worked in low moisture and temperatures. Aktaş et al. [5] examined drying apple with heat pump drying oven. In this work, apples were sliced 4 mm thick, and dried from 4.8 (g water/g dry matter) moisture content to 0.18 (g water/g dry matter) at 3.3 $kg^*m^{-2*}s^{-1}$ and 2.4 $kg^*m^{-2*}s^{-1}$ mass air velocity for 3.5 h in a heat pump dryer. Apples were also dried at the range of 3.3 $kg^*m^{-2*}s^{-1}$ and 2.9 $kg^*m^{-2*}s^{-1}$ mass air velocity from 4.8 (g water/g dry matter) moisture content to 1 (g water/g dry matter) moisture content in the same period in a solar dryer. For both systems, the moisture ratio was analyzed with a stat graphic program by using semi-theoretical models and compared to the empirical values. Koukouch et al. [6] presented an experimental

---

* Corresponding author.
E-mail address: halilatalay16@gmail.com (H. Atalay).

http://dx.doi.org/10.1016/j.energy.2017.06.030

study to dry the raw olive pomace with a convective solar drying system. In this investigation, the desorption/adsorption equilibrium water content of the product has been determined at the drying temperatures of 30°C 40°C and 50°C by using the gravimetric static method. Also they used four mathematical models to predict the hygroscopic behavior of the product during drying process. Nabnean et al. [7] presented a performance of a new design solar dryer for drying osmotically dehydrated cherry tomatoes. Misha et al. [8] presented a solar-assisted solid desiccant for drying crushed oil palm fronds. Solar energy was used to heat water with a solar collector and heat was transferred to the air through two heat exchangers. The hot air was used for regeneration of desiccant wheel and increase temperature of the drying air after dehumidification. The drying time for reducing the moisture content of crushed oil palm fronds from 69% to 29% under open sun drying determined as approximately 30 h and 40 min. Jain and Tewari [9] presented a solar crop dryer was developed with phase change thermal energy storage to maintain continuity of drying of herbs according to their color and flavor vulnerability. Kant et al. [10] presented a solar dryer based on phase change thermal energy storage materials was quite effective for continuously drying agriculture and food products at steady state in the temperature range (40°C – 60°C). In this study, packed bed thermal energy storage system was used for saving energy and providing with continuity of the drying process. Saini et al. [11] developed a simulation model for determining packed bed thermal energy storage system performance and parameters. They revealed that in the simulation model the system parameters had an important role on heat transfer and the fluid's flow characteristic in packed bed. Singh et al. [12] made experimental studies for analyzing void ratio in packed bed and using packed sizes effects under operating conditions. They developed various correlations based on Nusselt number and friction factor in order to predetermine performance effects in packed bed thermal energy storage system.

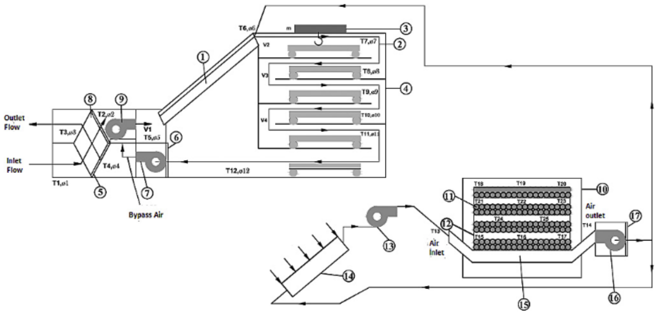

Fig. 1. Schematic of the solar dryer and packed bed thermal energy storage system.

In the literature solar energy and heat pump systems were usually used in most of the studies for drying processes. Also phase change materials were usually used for thermal energy storage in drying processes. In this study, a solar air heater and packed bed thermal energy storage system was designed and manufactured for drying of the apple slices. An important novelty of this study is the using thermal energy stored in the packed bed thermal energy storage system for the first time in the drying process. The amount of thermal energy that is stored in the packed bed has provided more than enough energy for the drying of the apples. The other important novelty is a recuperator unit has been integrated into the drying unit so that 50–60% of waste heat is recovered and used again in the system. The advantage of this system compared to other drying technologies in the literature is that it consumes 76.8% less energy in drying process. Drying curves for the apple slices were obtained as a result of experimental studies on apple slices with a thickness of 5 ± 2 mm at constant drying temperatures. A mathematical model was developed to determine the drying curves in Java language. The drying curves obtained by mathematical modeling are consistent with the different equations given in the literature.

2. Materials and method

A schematic of the industrial solar dryer and packed bed thermal energy storage system are shown in Fig. 1. Also assembly drawing of the systems is shown in Fig. 2. The solar dryer consists of two air collectors (1), drying cabin (4), fans (7–9) and a recuperator unit (8). There are ten drying drawers (2) in the drying cabin. Designing parameters for the solar dryer, packed bed thermal energy storage system and recuperator unit were shown in Table 1.

For the experimental studies, after the apples were washed and the core nests have been cleaned, they were sliced in a thickness of 5 ± 2 mm with the help of a slicer and placed in the perforated trays in the drying drawer.

The working principle of this system can be briefly expressed as follows:

Fig. 2. Assembly drawing of solar dryer and packed bed thermal energy storage system.

Table 1
Design parameters for the solar dryer, packed bed thermal energy storage system and recuperator unit.

Solar Dryer Component	Dimension
Length of Collector [m]	2
Width of Collector [m]	1
Length of Drying Cabin [m]	2.3
Width of Drying Cabin [m]	2.3
Height of Drying Cabin [m]	2.3
Distance Between Trays [m]	0.2
Packed Bed Thermal Energy Storage System Component	
Length of Packed Bed [m]	2
Height of Packed Bed [m]	1
Width of Packed Bed [m]	1
Recuperator Unit	
Length [m]	1.1
Height [m]	0.4
Depth [m]	0.4

Hot air coming from the solar collectors flows into the drying cabin with the help of drying fan and the moisture of apples within the drying cabin are evaporated with the heat, providing mix to the drying air and so the dehumidification capacity of the drying air disappears. The drying air loses its ability to absorb the moisture after a certain period of time and descends downward in the system. Then it is transferred to the recuperator unit (waste heat recovery unit) integrated in the drying system. This unit, it is providing that the mixing of the fresh air taken from the outside with the drying air whose moisture content increases, at a specified rate. Thus, at the rate of 50–60% waste heat is recovered and reutilized in the system. In addition, the weight of the apple slice samples is measured every 30 min with the aid of a precision scale (3) placed in the upper region of the drying system. Also T, φ, V and P symbols on the flow diagram shown in Fig. 1 are expressed respectively temperature, relative humidity, air velocity and air pressure. A closed cycle of a packed bed thermal energy storage system was developed for providing to continuity of drying process. The system is independent of the solar dryer and it consists of three air collectors (14), fans (13–16), a packed bed (10), perforated plates (12) and approximately two tones pebbles (11). In this system hot air leaving the collectors enters into the bed. During charging time, temperature of lower portion of the bed starts to rise, which may change the temperature of air at the outlet of the collector. Thermal energy stored in the bed is transferred to the drying cabin with the help of the fan which is outside of the packed bed. Perforated plates are placed between the pebbles in the packed bed in order to provide easy and quick heat transfer between air and the pebbles.

In this study moisture, temperature, pressure, air velocity and solar energy measurement systems were used for testing. Anemometer was used for air velocity measurement and similarly pyranometer was used for solar energy measurement in the system. Measurement system characteristics of the solar dryer system are presented in Table 2. The measurements were transferred to the database through data logger then they were processed to the database. For the determination of the drying kinetics, the temperature and relative humidity of the airflow obtained at the inlet of the drying cabin are presented in Fig. 3. The drying conditions shown in Fig. 3 can be employed during the drying process of the apple slices at variable conditions in the solar dryer tests. The temperature and relative humidity values in the drying cabin were measured with the help of temperature and humidity sensors placed at the input and output of the drying cabin. As can be seen in Fig. 3, depending on the amount of solar radiation during the day, the temperature within the cabin increased up to 60°C in the first 240 min and then began to fall. Similarly, it has been observed that the relative humidity value in the drying cabin also decreased rapidly in the first 210 min time period and then, started to increase.

2.1. Mathematical model

In this study a mathematical model was developed using finite difference method in Java language for determine of temperature and moisture changes on apple slice and the performance of the packed bed thermal energy storage system. The objective of developing the model was to obtain values of various parameters like temperature and moisture changes on apple slices, temperature of air at the outlet of the packed bed, mean temperature of the packed bed, thermal energy stored in the bed. The required data were generated for time intervals of 15 min. In the mathematical model, the operating parameters used for the solar dryer and packed bed thermal energy storage system were shown in Table 3.

In this model moisture changes on apple slice have been calculated as: [18,20]

$$X_i^* = \frac{x_i - x_e}{x_0 - x_e} = \frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2n-1)^2}\exp\left(-(2n-1)^2\left(\frac{\pi^2 D_{eff}}{4xl^2}\right)xt_k\right) \tag{1}$$

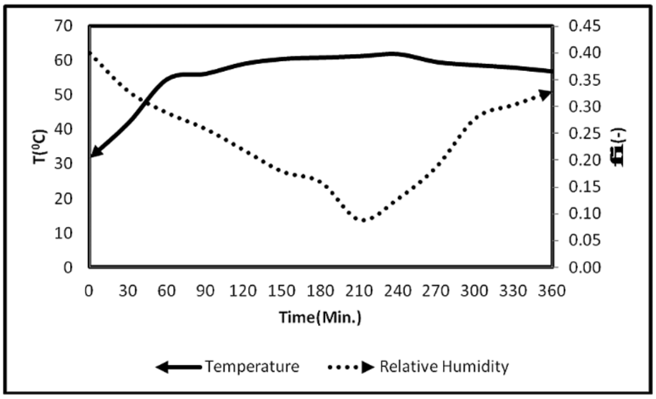

Fig. 3. Temperature and relative humidity obtained at the inlet of the drying cabin.

Table 2
Measurement system characteristics of the solar dryer system.

Measuring Device	Location	Type of Measurement	Accuracy
PLC Datalogger	Outlet of the drying cabin	Data transfer device	–
Anemometer	Inlet of the drying cabin	Air velocity	±1
T- type thermocouple	Inlet and outlet of the collector, drying cabin and packed bed.	Temperature of the airflow (°C)	±0.3
Capacitive sensor	Inlet and outlet of the drying cabin	Relative humidity of the airflow (%)	±%2
Pyranometer	Outlet of the collector	Solar energy	±%5
Assay Balance	Outlet of the drying cabin	Weight loss of the apple slices	0.01gr

Table 3
Operating parameters for drying apple slices and packed bed thermal energy storage system.

Parameter	Value
Volume of packed bed (V_b)	2m^3
Initial bed temperature (T_{bi})	25 °C
Equivalent diameter of material element (pebble) (D_e)	50 mm
Sphericity of material element	1
Void fraction	0.57
Density of storage material	1920 kg m^{-3}
Density of air	1.20 kg m^{-3}
Specific heat of storage material	835 J kg^{-1}K^{-1}
Specific heat of air	1008 J kg^{-1}K^{-1}
Dynamic viscosity of air	18.5 × 10^{-5} kg m^{-1}s^{-1}
Ambient temperature (T_{amb})	25 °C
Inlet air temperature to bed (T_{ai})	25 °C
Collector area (Ac) (For Solar Dryer)	4 m^2
Collector area (Ac) (For Packed Bed)	6 m^2
Initial inlet air temperature to the collector	25 °C
Time interval for packed bed	15 Min.
Apple temperature before drying	20 °C
Apple slice thickness	5 mm($\pm 2mm$)

X_i^* is an average of moisture value for apple slice, is expressed time moisture content during drying time. Moisture diffusion is a function of moisture and temperature [16,17].

Diffusion coefficient can be calculated as:

$$D_{eff} = D_0 \exp\left(\frac{E_a}{R(T+273)}\right) \tag{2}$$

Diffusion coefficient was calculated with optimum parameters using the correlation proposed by Simal et al. [17]

$$D_{eff} = 2.74x10^{-6} \exp\left(\frac{24034.2}{R(T+273)}\right) \tag{2.a}$$

Temperature changes on apple slice has been calculated with an energy balance which was given by Datta [19].

$$\frac{d(MCp\overline{T})}{dt} = Qu + hA(Ta - \overline{T}) + \lambda\frac{dM}{dt} \tag{3}$$

The energy balance is equal to rate of temperature increase, the amount of useful heat (Qu) coming from the air collectors, and the amount of heat obtained or lost from the evaporation that occurs as a result of convection.

Temperature distribution which is occurred during drying of apple slice can be calculated by using mass and specific heat exchange [14,15,20].

$$\frac{d\overline{T}}{dt} + \frac{2.5Ms(d\overline{X}/dt) + hA}{Ms(1.675 + 2.5\overline{X})}\overline{T} = \frac{Qu + hATa + \lambda Ms(d\overline{X}/dt)}{Ms(1.675 + 2.5\overline{X})} \tag{4}$$

Temperature and moisture change can be calculated according to finite difference method as in below:

$$\overline{X} = \frac{\overline{X}_{n+1} - \overline{X}_n}{2} \tag{5}$$

$$M = Ms(1 + \overline{X}) \tag{6}$$

$$\frac{d\overline{X}}{dt} = \frac{\overline{X}_{n+1} - \overline{X}_n}{\Delta t} \tag{7}$$

$$\frac{d\overline{T}}{dt} = \frac{\overline{T}_{n+1} - \overline{T}_n}{\Delta t} \tag{8}$$

$$\overline{T} = \frac{\overline{T}_{n+1} + \overline{T}_n}{2} \tag{9}$$

Also, the performance of packed bed thermal energy storage system has been predicted with the help of the mathematical model. Inlet air temperature, mean temperature in packed bed and amount of stored thermal energy were calculated using finite difference equations. In closed cycle of a packed bed thermal energy storage system, hot air leaving the collector enters into the bed. Therefore temperature of air at collector outlet and bed inlet will be same. During charging phase, temperature of lower portion of the bed starts to rise, which may change the temperature of air at the outlet of the collector. The hot air from collector to the bed should be supplied at a constant temperature by varying flow rate of air. Therefore, in the present mathematical model, flow rate of air during charging of the bed has been allowed to vary, in order to maintain a constant inlet air temperature to the bed. In this study, for predicting thermal performance of a packed bed, many mathematical models have been reported in the literature. However, most of the investigators have used Mumma and Marvin model reported by Howell et al. [13]. This model has been adopted to carry out the present simulation study [11].

$$T_{a,m+1} = T_{b,m} + (T_{a,m} - T_{b,m})\exp(-\varphi_1) \tag{10}$$

where

$$\varphi_1 = \frac{h_v AL}{N(mc_p)_a} = \frac{NTU}{N} \tag{11}$$

$$N = \frac{L}{\Delta X} \tag{12}$$

$$T_{b,m(t+\Delta t)} = T_{b,m(t)} + \begin{bmatrix} \phi_2(T_{a,m} - T_{a,m+1}) \\ -\phi_3(T_{b,m} - T_{amb}) \end{bmatrix}\Delta t \tag{13}$$

where

$$\varphi_2 = \frac{(mc_p)_a N}{\rho_s A L (1-\varepsilon) c_{ps}} \tag{14}$$

$$\varepsilon = \frac{V_b - V_s}{V_b} \tag{15}$$

$$\varphi_3 = \frac{(U\Delta A)}{(mc_p)_a}\varphi_2 \tag{16}$$

Thermal energy stored in the bed is calculated by using the following general equation;

$$Q_t = \int_0^L (\rho c)_s (1-\varepsilon) A (T_{mm} - T_{im}) dx \tag{17}$$

Initially bed is assumed at uniform temperature of T_{bi} and has been divided into “N” number of elements of equal thickness. The above equation for thermal energy stored “Q” can be written in finite difference form as:

$$Q_t = (\rho c_p)_s (1-\varepsilon) A \frac{L}{N} \left(\sum_{n=1}^{N} T_{nm} - N T_{bi} \right) \tag{18}$$

Void ratio and sphericity ratio of the packed bed thermal energy storage system were determined respectively in experimental study as 0.57 and 1. So both values were used in the mathematical model and experimental studies.

The performance of the solar dryer and packed bed thermal energy storage system could be calculated step by step with the help of the computer program developed in Java language, by converting the above equations to the finite difference equations and using them. Thus, parameters related to drying can be predicted in advance.

The algorithm related to the mathematical model has given as follows:

Step 1- Initial parameters related to the system are defined.

Step 2- A subprogram written in Java language which provides the calculation of the average solar radiation amount and collector efficiency according to the location of solar dryer and packed bed thermal energy storage system is introduced into the main program and calculations related to solar radiation are computed through this subprogram.

Step 3- Since humid air is used within both the systems, the thermodynamic and thermo-physical properties of the humid air are computed using the real gas equations with a subprogram developed in Java language and the properties of humid air are read through this subprogram.

Step 4- After the parameters related to the humidity change on the apple slice are defined, the eq. (1) is converted to the finite difference equation and enter the program.

Step 5- During the drying process, after defined the parameters related to the temperature change on the apple slice, the eq. (4) is converted to the finite difference equation and enter the program.

Step 6- Once the relevant parameters have been defined to study the temperature change of the air entering the packed bed thermal energy storage system, the eq. (10) is converted to finite difference equation and enter the program.

Step 7- After defined the relevant parameters for the mean temperature change in the packed bed, eq. (13) is converted to the finite difference equation and enter the program.

Step 8- Once the relevant parameters have been defined to calculate the amount of thermal energy stored in the packed bed thermal energy storage system, the eq. (18) is converted to finite difference equation and enter the program.

Step 9- For both systems, the initial operating parameters given in Table 3 are defined and the data is calculated step by step.

3. Results and discussion

In this study, drying of apple slices was researched. So a solar dryer based on the dehumidification principle was designed and manufactured. However a packed bed thermal energy system that is independent to solar dryer was designed and manufactured in order to providing to the drying process continuously. After the designing and manufacturing processes, experimental studies were started for both the two systems. In an important part of this study parameters of designing and operating for both the solar dryer and the packed bed thermal energy storage system were examined.

Apples were sliced using a slicer set to 5 ± 2 mm thick after their cores were cleaned. Studies show that the moisture content of dried fruits is generally around 20%. However, in order to prevent the growth of microorganisms in apples, moisture content must be below 10%. Thus, it will protect its freshness for a longer time. Considering that the direct use of solar energy is limited especially during daytime drying processes, thin layered apple slices (average 4–5 mm) reach this moisture content much shorter than the thick layered apple slices (average 6–10 mm). According to the standards for dried apple slices, it is observed that the apples are sliced to an average of 3–5 mm (min. 1/8 inch) in order to achieve the desired moisture values in a shorter time [36,37]. For this reason, the drying performance of apple slices with a thickness of 5 ± 2 mm was examined in this study. No additional processing has been required on the apple slices since no oxidation event occurred during this process. 12 experiments were made between at the end of August and the beginning of September repeated twice a day and average 7 kg apples were dried each experiment. First drying process was made with solar energy between 10.00 a.m. and 16.00 p.m. and average temperature within the drying cabin was determined as 50°C – 60°C. The temperature and moisture values in both systems were measured clearly with the help of the temperature and moisture sensors placed in both the drying system and the packed bed thermal energy storage system. For this reason, the temperature values in the drying cabin were determined as 50°C -60°C by averaging the obtained data. Second drying process was made by use stored energy in packed bed thermal energy storage system between 17.00–23.00 p.m. and average temperature within drying cabin was observed as approximately 45°C -55°C. Packed bed thermal energy storage system was charged with solar energy between 08.00 a.m. and 16.00 p.m. During the charging time the temperature of air at inlet to packed bed was determined as 65°C, mean temperature of packed bed was determined as between 55°C -60°C and stored thermal energy in packed bed was determined as about 200 MJ. The temperature values in the packed bed were measured clearly with the aid of temperature sensors placed at various points within the packed bed thermal energy storage system, taking into account the sensitivity of the device. The amount of thermal energy stored in the packed bed was determined to be about 200 MJ considering the measured temperature values, the mass of the pebble stones and the specific heat value. It has also been observed in experimental studies on the system that this amount of thermal energy obtained is quite sufficient for the drying of apple slices even at times when solar radiation is absent.

In each of the experiments the weight of the apple slices were measured before and after drying and so the total amount of moisture leaving the product was determined. Also amount of electrical energy consumed by fans was calculated by electricity meter on the drying system. For each experiment specific moisture extraction rate (SMER) and moisture extraction rate (MER) of the dried apple slices were calculated based on the equations (19) and (20) respectively and shown in Table 4.

$$SMER_{ts} = \frac{Mwb}{Eg} \tag{19}$$

$$MER = \frac{Mwc}{t_a}\eta \tag{20}$$

In quantities ranging from 5 to 7.5 kg apple was dried on the drying system during experiments. It was observed that SMER and MER values for the dried apple slices gave approximation results. Also amount of the drying apple slices are the one of the important factor for determining of the SMER and MER values.

During the drying experiments, it was observed that the temperature difference between the inlet and outlet of the drying cabin was max. 8°C – 10°C from the beginning of drying. Towards the end of the experiment, the value of the temperature difference can fall 1°C – 2°C. This result revealed that the dehumidification efficiency within the drying cabin is high.

During experimental study moisture loss of the apple slices, temperature, relative humidity, pressure and air velocity of the drying system were measured. The measurements were transferred to the database on data logger and from there sent to the computer and processing through the database. A crafting user interface program was developed in Java language in order to transferring data which were obtained to experimental study into the computer every 10 min. Also, solar radiation values were measured with a pyranometer every 10 min. The pyranometer is independent of the solar dryer. The weight change of the apple slice samples were measured with a precision scale which has 0.01 g sensitivity every 30 min. Photograph of the apple slices before and after the drying process was shown in Fig. 4.

During the experimental study, apples were sliced 5±2 *mm* thick and dried from 5.84 g_w/g_{dm} moisture content to 0.13g_w/g_{dm} in the solar dryer system. There are many equations in the literature capable of predicting the evolution of the mass of the sample during the falling rate period of the drying process. The drying process is characterized by the moisture ratio, MR, a dimensionless parameter that quantifies the reduction of the moisture content of the sample with time [21–23]. The moisture ratio is defined as;

$$MR = \frac{M_{d,i} - M_e}{M_{d,0} - M_e} \tag{21}$$

where $M_{d,i}$ is the moisture content (wet basis) after a time t, M_e is the equilibrium moisture content and $M_{d,0}$ is the initial moisture content. The moisture ratio MR varies between MR = 1, at the beginning of the drying process, and MR = 0, once the sample is dried at equilibrium with the drying air.

Different equations based on the drying models available in the literature were used to model the evaluation with time of the moisture ratio of apples dried at a constant temperature of 50°C. The moisture ratio was calculated using equation (21). The moisture ratio (MR) considered is between 1 and 0.1, since after the value, the drying rate decreases drastically and so the samples are almost dry. Table 5 shows the equations proposed by different authors for the prediction of the moisture ratio during time, together with the values of the fitting parameters of each equation

Table 4
Comparing of specific moisture extraction rate and moisture extraction rate for apple slices in the drying experiments.

Experiment No	Dried Apple Quantity (gr)	Consumed Energy Quantity (KW)	Evaporated Moisture Quantity (gr)	SMER (kg_w/kWh)	MER (kg_w/h)	Drying Temperature (°C)	Drying Time (Hour)
1	5800	9.15	5283.36	0.577	0.88	56.5	6
2	6500	8.05	5885.55	0.731	0.98	56.5	6
3	6200	7.7	5543.56	0.720	1.11	58.0	5
4	6100	7.58	5514.40	0.727	0.92	60.0	6
5	7000	7.65	6293.81	0.823	0.97	55.0	6
6	7300	7.62	6498.34	0.853	1.08	59.0	6
7	6900	7.58	6220.48	0.821	1.04	58.3	6
8	7100	7.6	6347.94	0.835	1.06	58.4	6
9	7300	7.59	6467.30	0.852	0.99	58.5	6
10	7500	7,99	6680,64	0.819	0,95	58.9	6
11	7200	7.71	6464.50	0.838	0.92	59.8	6
12	7100	7.69	6385.01	0.830	0.91	58.6	6


(a) (b)

Fig. 4. Image of the apple slices (a) before drying (b) after drying.

Table 5
Fitting parameters of different drying equations available in the literature applied to the moisture ratio obtained drying apples [25].

Equation	Model Name	Parameters	Reference
$MR = \exp(-kt)$	Lewis	k = 0.47164min^{-1}	[26]
$MR = a.\exp(kt)$	Herderson and Pabis	a = 0,81865 k = 0.0469min^{-1}	[27]
$MR = \exp(-kt^n)$	Page	k = 0.46901min^{-n} n = 0.83	[28]
$MR = a.\exp(-kt) + c$	Logarithmic	a = 1.767 k = 0.00471min^{-1} c = − 0.93	[29]
$MR = a.\exp(-k_1t) + b.\exp(-k_2t)$	Two Terms	a = 17.672 k_1 = 0.00275min^{-1} b = −16,83 k_2 = 0.00236min^{-1}	[30]
$MR = a.\exp(-kt) + (1-a).\exp(-kat)$	Two Terms Exponential	a = 1.967 k = 0.01542min^{-1}	[31]
$MR = a.\exp(-k_1t) + (1-a).\exp(-k_2t)$	Verma	a = 4.719 k_1 = 0.00315min^{-1} k_2 = 0.0017min^{-1}	[32]
$MR = a.\exp(-k_1t) + b.\exp(-k_2t) + c.\exp(-k_3t)$	Modified Henderson and Pabis	a = −4.691 k_1 = 0.0469min^{-1} b = 1.767 k_2 = 0.0649min^{-1} c = 3.915 k_3 = 0.0235min^{-1}	[33]
$MR = \exp(-kt^n) + b.t$	Midilli	a = 0.971 k = 0.00471min^{-1} n = 1.13 b = −0.00138min^{-1}	[34]
$MR = 1 + a.t + b.t^2$	Wang and Singh	a = −0.00767min^{-1} b = 1.04 × 10^{-5}min^{-2}	[35]

obtained from the experimental results. In this study Diffusion approximation model was used for constant temperature and drying of apple slices. A different mathematical model was developed for calculating of the prediction of the moisture ratio during time using "Nelder-Mead Least Squares Method" in Java language. The moisture ratio, as a function of time, obtained in the diffusion approximation model for isothermal process at 50°C is plotted in Fig. 5 together with the fitting of Lewis Model and Page Model. Several drying processes of apples were conducted in the solar dryer for constant temperatures ranging from 50°C – 60°C using temperature intervals of 5°C. Fig. 6 shows the change in moisture ratio, MR, over time, t, at different constant temperatures tested. The tendency of the moisture ratio is similar for all the temperatures studied. The obtained results were entitled as MR1 for the first experiment (T = 50°C), MR2 for the second experiment (T = 55°C), and MR3 for the third experiment (T = 60°C) and shown in equation (22)–(25) [24,25].

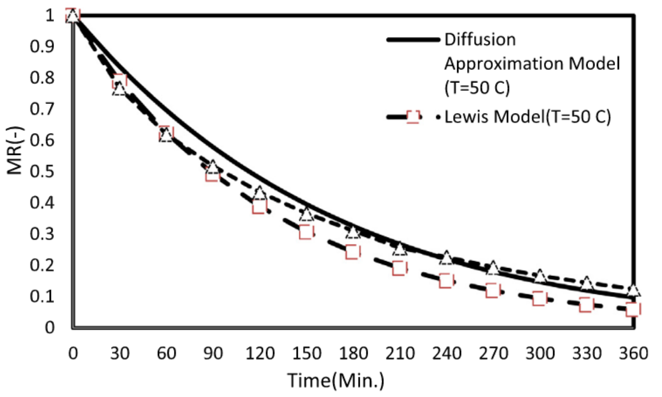

Fig. 5. Moisture ratio as a function of time obtained in the diffusion approximation model for isothermal process at 50 °C together with the fitting of Lewis Model and Page Model.

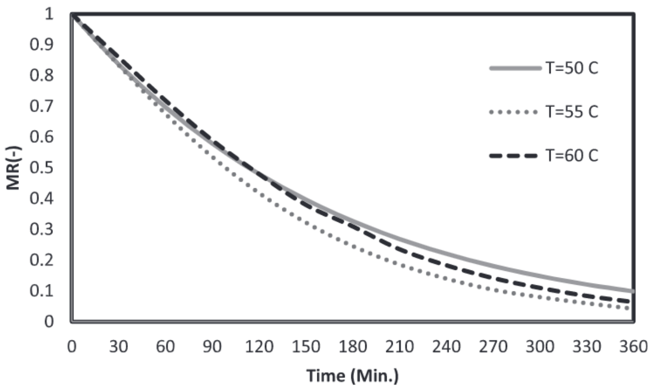

Fig. 6. Evolution of the moisture ratio with time for the different constant temperatures during the drying of apple slices using the solar dryer system.

$$MR = a\exp(-kt) + (1-a)\exp(-kbt) \tag{22}$$

$$MR_1 = 12.887\exp(-0.479\ t) + (1-12.887)\exp(-0.479*1.022*t) \tag{23}$$

$$MR_2 = 15.4203\ \exp(-0.723\ t) + (1-15.4203)\exp(-0.723*1.038*t) \tag{24}$$

$$MR_3 = 17.672\exp(-0.649\,t) + (1-17.672)\exp(-0.649*1.035*t) \tag{25}$$

Similarly, several drying processes of apple slices were carried

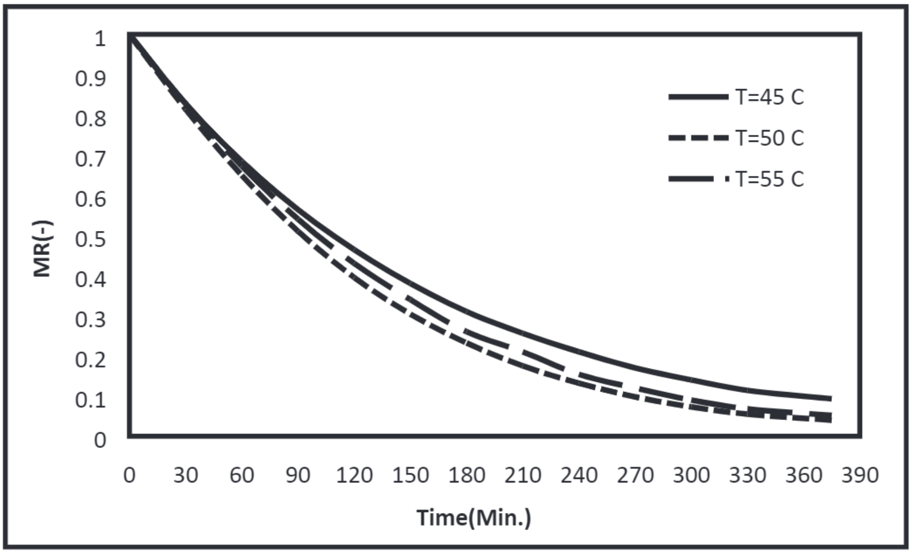

Fig. 7. Evolution of the moisture ratio with time for the different constant temperatures during the drying of apple slices using the packed bed thermal energy storage system.

out using thermal energy stored in the packed bed thermal energy storage system at constant temperatures of 45°C – 55°C with thermal intervals of 5°C. Fig. 7 shows the change in moisture ratio, MR, over time, t, at different constant temperatures tested. It was observed that the results in Fig. 7 are similar to the results of the drying experiment that was carried out with the solar dryer in the day, in addition to this, the moisture ratio has been decreased with respect to the decreasing moisture content and time. Also for the packed bed thermal energy storage system, the results obtained from system both the experiments and the developed mathematical model were compared with each other and shown in Figs. 8–10.

4. Conclusions

The drying process of the apple slices were experimentally analyzed by means of the industrial solar dryer. During the drying tests, the drying curves of the apple slices were obtained as a function of temperature. The diffusion approximation model was employed to fit the experimental drying curves obtained for constant temperatures. A novel model was proposed based on diffusion approximation model to predict the evaluation of the moisture ratio during the drying process. The model was validated using experimental results of the drying of apples. The proposed model for the evolution of the moisture ratio was in perfect agreement with the experimental measurements, obtaining a maximum deviation from the experiments of 1%, a deviation that is inside the uncertainty associated with the measurements.

Also a packed bed thermal energy storage system was designed and manufactured in order to provide continuity to the drying process. As a result of the experimental studies with energy obtained from this unit have shown that the resulting drying curves are compatible with both the results of drying experiments with the solar dryer and the results obtained from studies conducted in the literature. In the experimental studies, the amount of thermal energy that is stored in the packed bed has provided more than

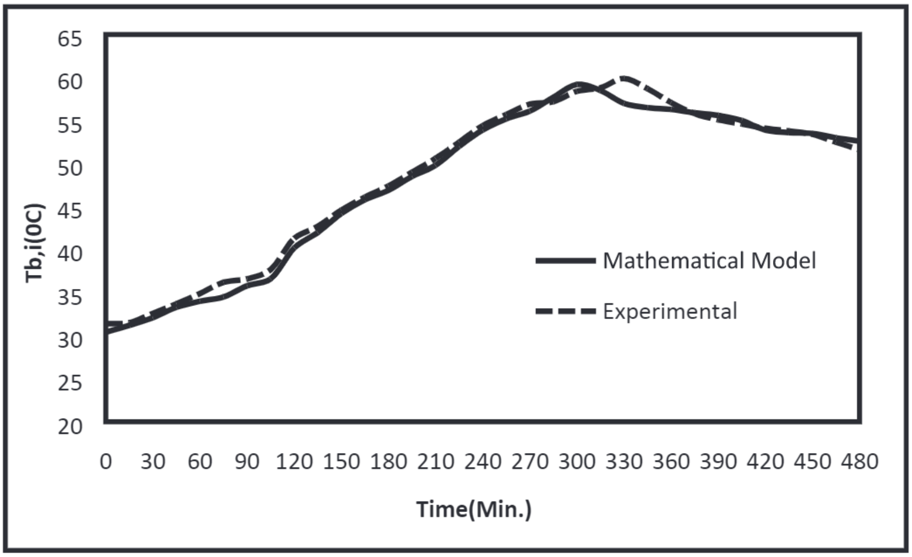

Fig. 8. Mean temperature of the packed bed during the charging time.

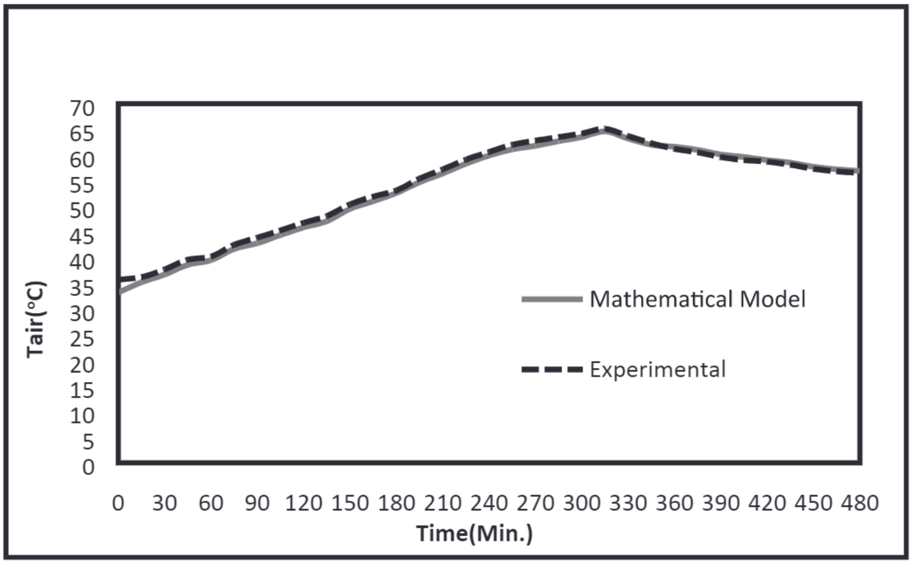

Fig. 9. Temperature of air at inlet to packed bed during the charging time.

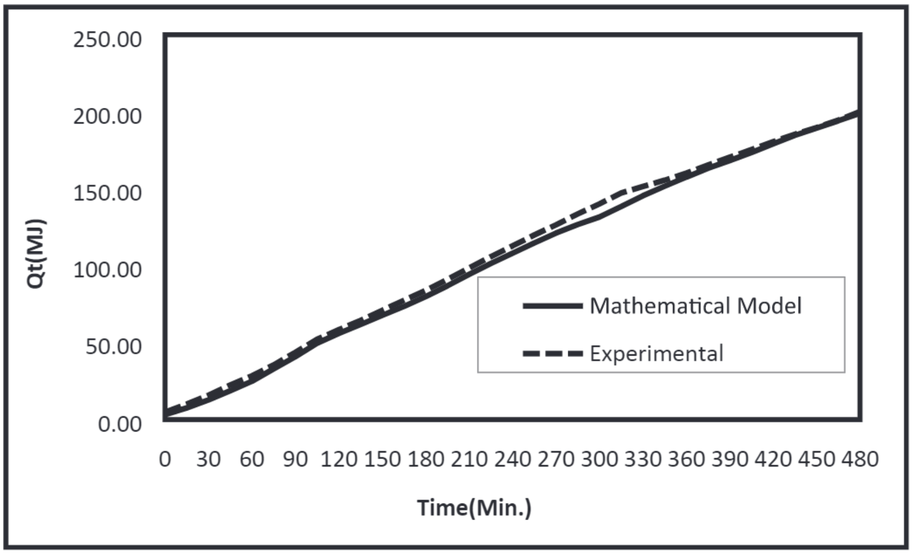

Fig. 10. Stored thermal energy in the packed bed during the charging time.

enough energy for the drying of the apples. This further expands the use of energy storage systems.

Acknowledgements

The study was supported by Republic of Turkey Ministry of Science, Industry and Technology as a San-Tez Project.

Nomenclature

A	Surface Area (m^2)
C_{pa}	Specific heat capacity for air ($J^*kg^{-1}K^{-1}$)
C_{ps}	Specific heat capacity for packed bed($J^*kg^{-1}K^{-1}$)
D_{eff}	Diffusion coefficient
D_o	Pro-exponential factor
E_a	Activation energy (j^*mol^{-1})
E_g	Energy input (for all system) (kWh)
h	Heat convection coefficient ($W^*m^{-2*}K^{-1}$)
h_v	Volumetric heat transfer coefficient ($W^*m^{-3*}K^{-1}$)
L	Length or height of the packed bed(m)
M	Apple mass(kg)
M_s	Dried apple mass(kg)
Mwb	Moisture mass to be removed from the apple slice(kg_w)
Mwc	Moisture mass removed from the apple slice(kg_w)
Q_t	Thermal energy stored in packed bed (MJ)
Q_u	Useful energy gain in collector (W)
R	Gas constant ($kPa^*m^{3*}kg^{-1*}K^{-1}$)
t	Time(Min.)
t_a	Drying time (min.)
$\overline{T}$	Average temperature change (^0C)
T_a	Air temperature in the system (^0C)
$T_{a,\ m}$	Entrance temperature of the air to the packed bed (^0C)
T_{amb}	Ambient temperature (^0C)
$T_{b,m}$	Mean temperature of the packed bed(^0C)
U	Over all heat transfer coefficient ($W^*m^{-2*}K^{-1}$)
V_b	Volume of the packed bed (m^3)

V_s	Volume of storage material packed in the bed (m^3)
X	Moisture content for apple slice ($kg_w*kg_{dm}^{-1}$)
X_i^*	Average moisture content for apple slice ($kg_w*kg_{dm}^{-1}$)

Greek Symbols

Δt	Time interval (min.)
η_{th}	Efficiency of collector (dimensionless)
ε	Void fraction(dimensionless)
λ	Latent heat of vaporization ($J*kg^{-1}$)
ρ_a	Density of the drying air ($kg*m^{-3}$)
ρ_s	Density of the packed bed ($kg*m^{-3}$)
ϕ	Sphericity (dimensionless)

Subscripts

MER	Moisture extraction rate
T_0	The outlet temperature of the air from the collector (^0C)
MR	Moisture ratio
SMER	Specific moisture extraction rate

References

[1] Lee KH, Kim OJ. Investigation on drying performance and energy savings of the batch- type heat pump dryer. Dry Technol 2009;27:565–73.
[2] Queiroz R, Gabas AL, Telis VRN. Drying kinetics of tomato by using electric resistance and heat pump dryers. Dry Technol 2004;22:1603–20.
[3] Hawlader MNA, Rahman SMA, Jahangeer KA. Performance of evaporator-collector and air collector in solar assisted heat pump dryer. Energy Convers Manage 2008;49:1612–9.
[4] Tosun S. Thermodynamic analysis and developing of a heat pump dryer for some agricultural products. Ph.D. thesis. Turkey: Ege University; 2009.
[5] Aktaş M, Ceylan İ, Yılmaz S. Determination of drying characteristics of apples in a heat pump and solar dryer. Desalination 2009;239:266–75.
[6] Koukouch A, Idlimam A, Asbik M, Sarh B, Izrar B, Bah A, et al. Thermophysical characterization and mathematical modeling of convective solar drying of raw olive pomace. Energy Convers Manage 2015;99:221–30.
[7] Nabnean S, Janjai S, Thepa S, Sudaprasert K, Songprakorp R, Bala BK. Experimental performance of a new design of solar dryer for drying osmotically dehydrated cherry tomatoes. Renew Energy 2016;94:147–56.
[8] Misha S, Mat S, Ruslan MH, Salleh E, Sopian K. Performance of a solar-assisted solid desiccant dryer for oil palm fronds drying. Sol Energy 2016;132:415–29.
[9] Jain D, Tewari P. Performance of indirect through pass natural convective solar crop dryer with phase change thermal energy storage. Renew Energy 2015;80:244–50.
[10] Kant K, Shukla A, Sharma A, Kumar A, Jain A. Thermal energy storage based solar drying Systems: a review. Innovative Food Sci Emerg Technol 2016;34:86–99.
[11] Singh R, Saini RP, Saini JS. Simulated performance of packed bed solar energy storage System having storage material elements of large size part 1, 2, 3. Open Fuels& Energy Sci J 2008;1:91–6.
[12] Singh R, Saini RP, Saini JS. Nusselt number and friction factor correlations for packed bed solar energy storage system having large sized elements of different shapes. Sol Energy 2006;80:60–71.
[13] Howell JR, Bannerot RB, Vliet GC. Solar thermal energy systems-analysis and design. McGraw – Hill Book Co; 1982.
[14] Duffie JA, Beckman WA. Solar engineering of thermal processes. second ed. John, Wiley& Sons. Inc; 1991.
[15] Abbud IA, Löf GOG, Hittle DC. Simulation of solar air heating at constant temperature. Sol Energy 1995;54:75–83.
[16] Mumma SA, Marvin WC. A method of simulating the performance of a pebble bed thermal energy storage and recovery systems. ASME Paper 76- HT-73; ASME/AICHE National Heat Transfer Conference St. Louis; 1976.
[17] Simal S, Deya E, Frau M, Rossello C. Simple modeling of air drying curves of fresh and osmotically pre- dehydrated apple cubes. J Food Eng 1997;33:139–50.
[18] Hatamipour MS, Mowla D. Shrinkage of carrots during drying in an inert medium fluidized bed. J Food Eng 2002;55:247–52.
[19] Datta AK. Fundamentals of heat and moisture transport for microwaveable food product and process. In: Handbook of microwave Technology for food; 2001.
[20] Askari GR, Emam-Djömeh Z, Mousavi SM. Heat and mass transfer in apple cubes in a microwave-assisted fluidized bed drier. Food Bio Prod Process 2013;91:207–15.
[21] Doymaz I. An experimental study on drying on green apples. Dry Technol 2009;27:478–85.
[22] Zlatonovic I, Komatina M, Antonijevic D. Low- temperature convective drying of apple cubes. App Therm Eng 2013;53:114–23.
[23] Panchariya PC, Popovic D, Sharma AL. Thin-layer modeling of black tea drying process. J Food Eng 2002;52:349–57.
[24] Togrul IT, Pehlivan D. Mathematical modeling of solar drying of apricots in thin layers. J Food Eng 2002;55:209–16.
[25] Blanco- Cano L, Soria-Verdugo A, Garcia- Gutierrez LM, Ruiz-Rivas U. Modeling the thin-layer drying process of Granny Smith apples: application in an indirect solar dryer. Appl Therm Eng 2016;108:1086–94.
[26] Lewis WK. The rate of drying solid materials. J Ind Eng Chem 1961;13:427–32.
[27] Henderson SM, Pabis S. Grain drying theory.I.temperature effect on drying coefficient. J Agric Eng Res 1961;6:169–74.
[28] Page G. Factors influencing the maximum rates of air drying shelled corn in layers. M.S.thesis. Purdue University; 1949.
[29] Sacilik K, Elicin AK. The thin layer drying characteristics of organic apple slices. J Food Eng 2006;73:323–8.
[30] Madamba PS, Driscoll RH, Buckle KA. The thin layer drying characteristics of garlic slices. J Food Eng 1996;29:75–97.
[31] Ertekin C, Yaldız O. Drying of egg plant and selection of a suitable thin layer drying model. J Food Eng 2004;63:349–59.
[32] Verma LR, Bucklin RA, Endan JB, Wratten FT. Effects of drying air parameters on rice drying models. Trans ASAE 1985;28:296–301.
[33] Karathanos VT. Determination of water content of dried fruits by drying kinetics. J Food Eng 1999;39:337–44.
[34] Midilli A, Kucuk H, Yapar Z. A new model for single layer drying. Dry Technol 2002;20:1503–13.
[35] Wang CY, Singh RP. A single layer drying equation for rough rice. ASAE; 1978. Paper no:78–3001.
[36] Brady LP. Drying fruits. University of Arkansas Cooperative Extension Service Fact Sheet; 2001.
[37] International Standard ISO 7701. Dried apples-Specification and test methods. second ed. 1994. Switzerland.