Journal of Solar Energy Research 21 (2017) 43-47

Journal of Solar Energy Research (JSER)

Journal homepage: www.jser.ut.ac.ir

Modeling and Experimental Investigation a Solar Tray Dryer with Indirect Forced Convection using Phase Change Materials

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ARTICLE INFO

Received: 19 October 2016
Received in revised form: 29 January 2017
Accepted: 30 January 2017

Keywords:
Solar energy; Solar tray dryer; Collector; Energy storage

ABSTRACT

Solar energy is rapidly gaining attention in different industries, especially agricultural industries. Application of this clean energy in drying industry resulted in many investigations in academia. Dryers with energy storage can reduce thermal fluctuations of solar irradiations and also enhance drying efficiency of agricultural products. In this study, paraffin phase change material has been used as energy storage and the performance of a solar tray dryer with indirect forced convection has been investigated. The mathematical model of the energy balance for the process has been derived. The effect of parameters namely inlet air velocity and collector surface area on the final moisture content of samples and air outlet temperature have been studied. Air inlet temperature has been tested at two levels of 1 and 3m/s using a collector surface area of $2m^2$ with and without energy storage. The integration of energy storage enhances the efficiency by 37% and reduces the outlet moisture content. Lower inlet air velocity and larger collector surface area results in lower final moisture content of samples. On the other hand, for higher ambient temperature even higher inlet air velocity can result in lower moisture content of products. Comparison of experimental data with simulation results shows correlation coefficient of 96.27.

1. Introduction

Rapid utilization of non-renewable energy resources as well as their pollution consequences resulted in growing environmental destruction. Nowadays, the fundamental challenge for researchers is to exploit and optimize clean energy sources. Solar energy is the cheapest available energy source for several applications, especially agricultural and dryer industries [1]. Due to the intermittency of solar energy in a 24 hour period, storage of excessive available diurnal energy for exploitation during night-time not only shortens the drying period and consequently increases dryer’s annual capacity, but also dramatically decreases its operational costs[2]. Thermal energy storage is known to be a key technology to tackle energy supply and demand mismatch. Thermal energy can be stored sensibly, latently and chemically (using a reversible chemical reaction). However, latent thermal energy storage using phase change materials (PCMs) is the most effective one. The reason is due to the high energy storage capacity as well as almost constant temperature in the long period of energy storage [3]. Among available PCMs, polyethylene glycol received considerable attention. Suitable thermophysical properties such as desirable phase change temperature, high latent heat capacity, congruent melting, non-toxicity, lack of supercooling, low vapour pressure, low volume change during solid-liquid phase change process and also high thermal and chemical stability resulted in the high interest [4]. In 2010, KenisarinandMurat comprehensively investigated materials which could be potentially used as PCMs for a temperature range of 120 to 1000°C. It is obvious that no material can simultaneously satisfy all the desirable requirements of a suitable PCM; therefore, selection of a PCM for a certain application requires careful consideration of the properties of several materials. Design and determination of operational details for a latent thermal energy storage system depends upon the physicochemical properties of the PCM such as energy storage density to volume ratio [5]. Devahastin and Saovakhon(2006) investigated the possibility of thermal energy storage in solid paraffin as a PCM. Paraffin was used to store solar energy during drying and released energy when solar energy was not sufficient or not available where the effect of PCM integration on the drying kinetics of sweet potato was investigated. Heat transfer characteristics, temperature profiles as well as the effect of inlet air temperature and velocity on charging and discharging periods were studied [6]. Solar dryer are among those solar systems with great potential of PCM integration. In solar dryers, PCM integration is due to solar energy storage and continuous solar drying in the hours with no sun availability. Numerous studies have been conducted using these systems for various drying materials [7-10]. Chen et al. developed a theoretical transient model to investigate the novel concept of solar dryer with absorbing flat reverse collector with thermal storage and natural air convection. The efficiency of the packed bed system was investigated for onion drying of its trays. It was shown that sample temperature depends upon air flow channel width and packed bed height. Thermal energy storage is effective during non-irradiation hours by greatly decreasing drying temperature fluctuation [11, 12]. The developed mathematical model is suitable for evaluating the performance of absorbing reverse collector with thermal storage in solar convective drying. The model is also suitable for predicting sample temperature, moisture content and sample drying rate. The drying process in solar systems is greatly complicated due to the simultaneous heat and mass transfer. The sample properties and PCM behaviour is greatly effective on the analysis. Moreover, PCM integration in solar drying systems significantly enhances energetic and exegetic efficiencies of the system [13, 14].

In this study, a mathematical model is developed to investigate the performance of a PCM in a solar dryer. Experimental and theoretical investigation of efficiency as well as the performance of a solar tray dryer with solar energy storage in a PCM is conducted. Furthermore, the effect of thermal energy storage on effective parameters such as outlet air moisture content and temperature is also studied.

2. Materials and Methods

The selected drying material in this study was banana. To prepare samples, first, bananas were peeled and from each sample 6 pieces were selected with identical dimensions. In each experiment, 50 grams of samples were weighed and then put in the baskets. Thereafter, the baskets containing samples were transferred inside the drying chamber through the mounted hatches on the dryer's door. To determine product weight, a digital scale (model APX-153 manufactured by Denver Instrument Co., Colorado, United States) with 0.001 gram accuracy was used. Ambient air temperature was measured by means of a digital thermometer (model P300w temp manufactured by Dostmann, Germany) with 0.1°C accuracy was used. In order to measure air velocity, an anemometer (model Testo 425 manufactured by Testo Co., England) was used with an accuracy of 0.01 m/s. An air temperature measurement device with a data acquisition system linked with temperature sensors was used to measure temperature at different points of the system including inside chamber, collector and ambient. Data acquisition time interval was first set at 30 minutes which was then gradually increased by decreasing drying rate. After conducting experiments, experimental data were plotted as drying kinetic curves. The thermophysicalproperties of the PCM are shown in Table 1.

Table 1. Thermophysical properties of paraffin

Property	Unit	Value
Melting point	°C	60
Solid density	kg/m^3	910
Liquid density	kg/m^3	820
Solid conductivity	W/m.K	0.24
Liquid conductivity	W/m.K	0.22
Solid specific thermal capacity	J/kg.K	2,000
Liquid specific thermal capacity	J/kg.K	2,150
Latent heat	J/kg	190,000

2.1. Solar dryer

Figure 1 shows a picture of the experimental setup. The system consisted of a drying chamber, two flat type solar collectors and the thermocouples. Inside the dryer, two trays were used simultaneously and air was circulated by means of a blower. The blower was mounted at the entrance of the first collector. Three small baskets were considered to put samples on each tray. The four legs of the dryer are equipped with wheels in order to enable orientation change of collectors towards a proper solar angle to absorb maximum solar irradiation. Drying experiments were conducted for either with or without the PCM. In the experiments with the PCM, 65.6kg of paraffin was used as thermal storage. An exhaust fan was mounted at the bottom of the dryer to transfer the heated air inside the collector (by greenhouse effect) to the chamber. Each drying sample was put on a container to facilitate the weighing process. Galvanized containers with 0.9mm thickness was used for PCM whose dimensions were 100cm (L) × 20cm (W) × 4cm (H). Ten containers were manufactured and mounted at the bottom of Collector 1. The distance between the top of the containers and the glass (Collector 1) was 16cm through which the air was blown. Figure 1 shows the arrangement of the containers.

Figure 1. The presentation of the solar dryer and thermal energy storage containers

2.2. Modelling Assumptions

The simplifying assumptions for the model include:

- Air moisture content distribution only exists along air flow direction and is constant between two trays

- Air is considered as an ideal gas
- Pressure loss inside the drying chamber is negligible
- Temperature distribution inside the drying sample is negligible
- Conduction along air flow direction is negligible as compared to the fluid bulk convection
- Works by external forces (such as gravitational force) and molecular mechanism (such as viscous forces) are negligible

2.3. Experimental Procedure

Experiments were conducted in summer 2014. One of the objectives of this study was to investigate the effect of inlet air velocity on drying performance in a three-day period. Table 2 shows the selected values for the modeling parameters. During the experiments, the absolute moisture content of the drying air was measured and recorded using a 2m^2 collector area.

$$Acc = Input - Output \tag{1}$$

$$\frac{d\left(\rho V\left[C_{pm}\left(T_{g,in}-T_{o}\right)+\lambda \mathrm{H}\right]\right)}{dt} = \left(\dot{G}_{s_{ch,k}} H_{ch}\Big|_{1} - \dot{G}_{s_{ch,k}} H_{ch}\Big|_{2}\right) + nA_{p} h_{c,ch-p}\left(T_{g,out}-T_{p,i}\right) \tag{2}$$

Table 2. Constants used in the chamber modeling

Constant	Value
n	9
m	3
$M_w\,(kg/kmol)$	0.018
$A_P\,(m^2)$	9.1483×10^{-5}
$V_p\,(m^3)$	5.5418×10^{-8}
$V_k\,(m^3)$	1.332×10^{-4}
$A_k\,(m^2)$	0.0285
$A_T\,(m^2)$	1.08
$c_a(J/kg\,K)$	1,005
$c_{A\upsilon}(J/kg\,K)$	1,851
$c_p(J/kg\,K)$	3,810
$c_w(J/kg\,K)$	4,187
$h_{fg_0}(J/kg)$	2,257,000
$T_0(K)$	298
$m_s\,(kg)$	0.0052

3. Results and Discussion

In this section, first the mathematical model is presented and then the experimental results are analyzed. It should be noted that to prevent systematic bias, the experiments were conducted randomly. Moreover, each experiment was replicated three times and the averages of the replication results are reported.

3.1. Energy and Mass Balance Equations

In this section,energy and mass balance equations are developed for air and the drying sample.

3.1.1. Energy Balance for Air in the Drying Chamber

Each tray is considered as a fully mixed system where heat and mass transfer occur. Therefore, energy conservation equation for air flow over each tray is:

Enthalpy of air per unit dry air mass is calculated as

$$H_{ch,in} = C_{pm}\left(T_{g,in}-T_{0}\right)+h_{fg}\mathrm{H}_{in} \tag{3}$$

$$H_{ch,out} = C_{pm}\left(T_{g,out}-T_{0}\right)+h_{fg}\mathrm{H}_{out} \tag{4}$$

Substituting Equations (3) and (4) in Equation (2) gives:

$$\rho V C_{p}\frac{dT_{g,out}}{dt} = \dot{G}_{s_{ch,k}}\left[C_{pm}\left(T_{g,in}-T_{g,out}\right)\right] - nA_{p}h_{c,ch-p}\left(T_{g,out}-T_{p,i}\right) \tag{5}$$

$$\left(\dot{m}V_{K}-nV_{p}\right)\rho_{ch}C_{p}\frac{dT_{g,out}}{dt} = \dot{G}_{s_{ch,k}}\left[C_{pm}\left(T_{g,in}-T_{g,out}\right)\right] - nA_{p}h_{c,ch-p}\left(T_{g,out}-T_{p,i}\right) \tag{6}$$

3.1.2. Mass Balance for Air Moisture Content inside the Chamber

The moisture content of the air varies due to the evaporation from drying samples. Based on mass conservation equation for the moisture content over each tray:

$$\frac{\left(\dot{m}V_{K}-nV_{p}\right)}{1+\mathrm{H}}\frac{\partial \mathrm{H}_{ch}}{\partial t} = \left(\dot{G}_{s_{ch,k}}\mathrm{H}_{1}-\dot{G}_{s_{ch,k}}\mathrm{H}_{2}\right)+nA_{p}N_{w}M_{w} \tag{7}$$

3.1.3. Energy Balance for Drying Sample

The energy of the samples on each tray are affected by convection from hot air as well as its consequent water evaporation. Therefore, energy conservation equation yields:

$$\frac{dU_{p,i}}{dt} = -h_{c,ch-p}\left(T_{p,i}-T_{ch,i}\right)nA_{p} - nA_{p}N_{w,i}M_{w}h_{fg} \tag{8}$$

The internal energy of the sample per unit dry mass is:

$$U_{p} = \left(C_{p}+C_{w}X\right)\left(T_{p}-T_{0}\right) \tag{9}$$

Substitution of Equation (9) in Equation (8) gives:

$$m_{s}\left(C_{p}+C_{w}X_{i}\right)\frac{dT_{p,i}}{dt} = A_{p}\left[-h_{c,ch-p}\left(T_{p,i}-T_{ch,i}\right)-N_{w,i}M_{w}h_{fg}\right] \tag{10}$$

Where$m_s$is the mass of the dried solid in each drying sample.

3.1.4. Mass Balance for Moisture Content in Drying Sample

For the drying sample, mass balance gives:

$$m_s\frac{dX_i}{dt}=-N_{w,i}M_wA_p \qquad (11)$$

Molar moisture content flux is given by:

$$N_w=-\frac{m_s}{A_pM_w}\frac{dX}{dt} \qquad (12)$$

Convective heat transfer coefficient between air and sample is:

$$h_{c,ch-p}=172.5\dot{m}_{ch,k}^{0.5} \qquad (13)$$

Latent heat of evaporation was calculated by:

$$h_{fg}=4.186\times10^3\left(597-0.56T_p\right) \qquad (14)$$

Moreover, air flow density inside the chamber is:

$$\rho_{ch}=1.1774-0.00359\left(T_f-27\right) \qquad (15)$$

The kinetic equation used in the model was obtained by means of curve fitting over experimental data:

$$\frac{dX}{dt}=a_1T_{ch}^{a_2}X^{a_3} \qquad (16)$$

Where T is temperature in °C, X is moisture content on dry basis and a_i are kinetic constants. Equation (16) was used to predict evaporation flux in Equation (10). Based on the fitting results for different velocities, kinetic model constants were calculated which are tabulate in Table 3.

Table 3. Kinetic model constants

CONSTANT	VALUE
a_1	3.5×10^{-7}
a_2	2.913
a_3	2.77

The obtained model was evaluated using analysis of variance (ANOVA) based on correlation coefficient (R^2) which was calculated to be 96.27%.

3.2. Effect of Air Velocity using One Collector without PCM

In this mode, solar irradiation was prevented on the dryer by means of covering the dryer glass. In other words, drying air was heated only in Collector 1. Figure 2 shows the effect of air inlet velocity on moisture content variations versus time. As it is shown, lower air velocities resulted in lower instantaneous and final moisture content.

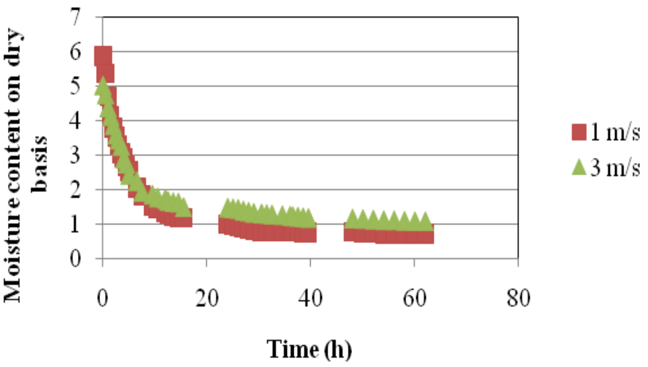

Figure 2. Moisture content variation without PCM for air inlet velocities of 1 and 3m/s

When air velocity was low, air temperature raised higher in Collector 1; therefore, the drying chamber was hotter and consequently the drying rate was higher resulting in lower sample moisture content. In other words, air velocity raise did not affect the drying rate since it reduced external mass transfer resistance while the drying process of banana is controlled by molecular diffusion inside the sample. On the other hand, increasing air temperature increased the drying sample temperature which in turn increased molecular diffusion coefficient of sample resulting in higher drying rate.

Figure 3 shows the variations of ambient temperature and collector outlet temperature during the drying process. Based on the figure, maximum collector outlet temperature was 52°C.

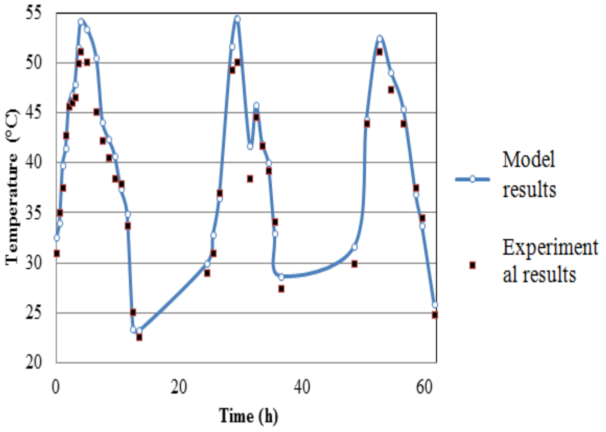

Figure 3. Comparison of collector outlet temperature and ambient temperature without PCM with modeling results for air velocity of 1m/s

3.3. Effect of Air Velocity using One Collector with PCM

Figure 4 shows the effect of air inlet velocity on moisture content variation versus time with PCM integration. According to the figure, lower air velocity resulted in faster sample moisture content reduction. The experiments without PCM (see Figure 2) were conducted in the hottest months of the year (July and August), while those with PCM were carried out in fall. Comparing Figure 2 with Figure 4 it is clear that the amounts of moisture content reduction in Figure 4 (with PCM) were 0.58 and 0.61 on dry basis, while the same amounts for Figure 2 (without PCM) were 0.39

and 0.29 on dry basis, respectively. This confirms the benefit of thermal energy storage. It is worth pointing out that the experiments with PCM were conducted in colder ambient temperature (about 14°C colder); nevertheless, the drying rate is almost the same as that of those experiments without PCM in hot ambient temperatures (in July and August). This comparison enlightens the evaluation of thermal energy storage.

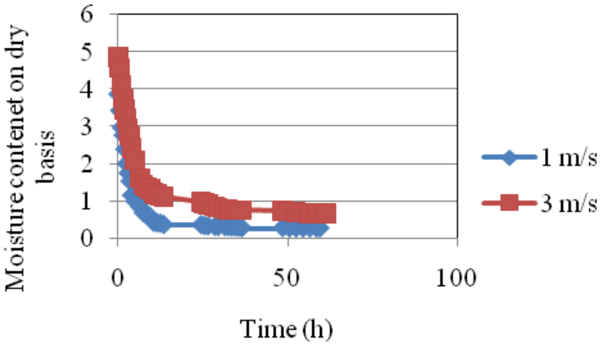

Figure 4. Moisture content variation with PCM for air inlet velocities of 1 and 3m/s

Figure 5 shows that maximum and minimum ambient temperatures were 29 and 16.4°C, respectively and collector outlet temperature was 46°C. On the other hand, in Figure 6 maximum and minimum ambient temperatures were 27.6 and 17.8°C, respectively and collector outlet temperature was 36°C. Therefore, higher air velocity reduced collector outlet temperature in Figure 6. It is obvious that lower air velocity gave higher collector outlet temperature and moisture content reduction was faster.

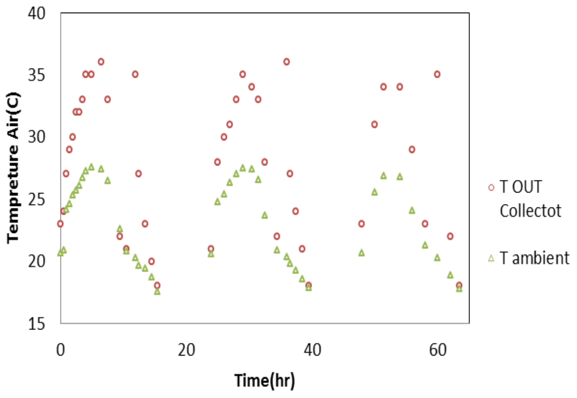

Figure 6. Collector outlet temperature and ambient temperature variation with PCM for air velocity of 3m/s

4. Conclusions

Solar dryers are considered as suitable options to exploit the cheap solar energy source. Several scenarios are developed to optimize utilization of this technology. Integration of thermal energy storage prevents the effect of temperature fluctuations by solar irradiation and increases drying efficiency during energy release period. In this study, the drying process of banana samples was investigated using indirect forced convection solar dryer using paraffin as PCM. The effects of three parameters were studied which were air inlet velocity, presence/lack of PCM, and collector surface area. Mathematical modelling of the process was derived by energy conservation equations together with kinetic equations from experimental analysis with correlation coefficient of 96.27%. Air inlet velocity was investigated for two levels of 1 and 3m/s. According to the results, lower air velocity resulted in lower sample moisture content. Furthermore, the results indicated that PCM integration resulted in lower moisture content than the case without PCM. Comparing air outlet moisture content, integration of PCM reduced the outlet moisture content efficiency by 37% which can greatly shorten the required drying period and provide economic advantages.

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