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Performance evaluation of an enhanced fruit solar dryer using concentrating panels

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ABSTRACT

Concentrating solar panels (CSP) improve the process of solar drying Roma tomatoes. This paper presents a performance comparison between two mixed-mode solar dryers. The dryers were identically constructed, however one of the dryers utilized mobile and easily adjustable flat concentrating solar panels to maximize incident solar energy on the dryer. Temperatures inside the dryer that utilized the concentrating solar panels were approx. 10 °C higher than those in the normal dryer during the majority of a sunny day testing period. This increase in temperature led to shorter Roma tomato drying times in the dryer with CSP. The concentrating solar panels showed a considerable increase in drying rate on sunny days, with a 27% decrease in total drying time as compared to the normal dryer to reach the target dimensionless moisture content of 0.2. A less significant increase in drying capacity was achieved when the dryer was tested in simulated cloudy conditions. The faster drying rate achieved in the dryer utilizing solar concentrators, under both sunny and simulated cloudy conditions, demonstrates the ability to dry produce to an acceptable moisture content in a reasonable time, with the objective of reducing postharvest loss and preventing spoilage.

Introduction

Based upon a recent study of postharvest losses in both industrialized and developing nations, farmers are estimated to lose over 40% of the value of their produce before it reaches the final consumer (Gustavsson et al., 2011). During the peak harvest period there is often a significant overabundance of produce. This surplus cannot be stored for long periods and ultimately goes to waste. Therefore, there is a need to inexpensively preserve produce postharvest. Among the various methods of produce preservation available, solar drying has commonly been accepted as the simplest and least expensive technique and is a resource that is underutilized in many areas.

The practice of solar drying dates back to the beginning of civilization. The approaches used then were simple and often rudimentary but were effective nonetheless (Mwithiga and Kigo, 2006). Traditional solar drying, which has been carried out on the bare ground in open air, is the most widely used method of drying in developing nations because it is simple and inexpensive (Bolaji and Olalusi, 2008). However, there are numerous disadvantages to this method. This drying process exposes the product to unpredictable weather, dust, potentially damaging UV radiation, and infestation by insects (Madhlopa et al., 2002).

Many modifications have been attempted to eliminate the issues with traditional drying in such areas. However, past efforts to establish solar drying for produce remain either costly and complicated or are not easily maintained and operated by rural farmers with locally available materials and skill (Das and Kumar, 1989). Solar dryers have been reported to improve the taste, nutrition, and final value of produce compared to traditional drying but at the cost of greater initial capital investment and the requirement for extensive training.

Enclosed cabinet style solar dryers have the potential to produce high quality dried products and can help avoid the problem of contamination (Gregoire, 1984). There are some relatively inexpensive and productive dryer designs that are operated with a 120 V A.C. electric powered fan. These can dry fruits and vegetables in just hours, unlike direct drying which can take days (Blair et al., 2007). Unfortunately these designs require a reliable electricity source which is unavailable in many countries where this technology is in high demand.

Most solar dryer designs fall into three main types: direct, indirect and mixed-mode (Simate, 2001). In a direct solar dryer, the product absorbs solar energy that enters through a transparent cover. Direct solar radiation dries the produce while the drying chamber protects

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the produce from environmental elements (Simate, 2001). Indirect dryers have a separate compartment called the collector, in which the air from the outside passes through and is heated before entering the drying chamber containing the produce. The hot air flow provides the necessary heat to help evaporate moisture from the produce as well as carry the evaporated moisture out of the dryer (Simate, 2001).

A mixed-mode dryer combines the features of the direct mode and indirect mode dryers. The produce is dried concurrently by both direct radiation and by natural convection from the collector heating the entering air. The mixed-mode dryer has been found to be the most effective in terms of the time it takes to dry the produce (Simate, 2001).

It is important for a solar dryer to be operational in partially cloudy, hazy and sunny environments. Increasing the collector area increases the area available for insolation and thus reduces the drying time. However, increased collector area subsequently leads to increased capital cost and more space required for a larger solar dryer. To solve this problem, reflective solar panels may be used to inexpensively increase the heat output of the collectors used for indirect dryers. They can focus additional radiation into the drying chamber and allow dryers to operate in low insolation environments.

There have been solar dryers that have used solar reflection as a means to increase solar radiation on the drying surface, but the reflectors in these cases have been attached to the dryer itself and not separate entities (Wagner et al., 1984). The objective of this study is to improve upon the existing methods of solar drying by using flat panel solar concentrators in concert with a mixed-mode dryer to determine if there is an improvement in the drying performance of tomatoes.

The reflectors in this study are separate from the dryer and therefore they may be moved to different locations and orientations around the dryer to maximize the amount of insolation striking the collector and the fruit directly. This is advantageous due to changes in the position of the sun throughout the year and during any particular day. Two identical dryers were built, one dryer with two flat concentrating solar panels (CSP) and the other without reflectors (control). The dryer, as well as the solar panels, can be easily constructed with locally available materials and technology. The dryer was tested under both sunny and simulated, partially cloudy conditions. While food quality is a critically important parameter to include, this study describes a performance evaluation of the dryer and concentrator alone, while future studies will include food quality assessment.

Basic theory of operation

The main goal of solar drying is to remove moisture from the fruit or vegetable to a level that will prevent microbial growth (≤20% wet bulb in this study) while maintaining acceptable quality of the product. The drying rate of produce is dependent upon the rate at which the moisture content is evaporated from the surface of the tomatoes and how quickly the moist air is removed from the area adjacent to the surface of the tomatoes (Joshi et al., 2004). The drying rate also depends on the rate of mass transfer of moisture from the interior of the produce to the surface of the produce. During drying, the produce structural changes cause a reduction in moisture transport inside the produce.

The mixed-mode dryers are composed of three main parts. The solar collector where the air is heated by the radiation emitted by the solar absorber, the drying chamber where the produce is exposed to the hot air from the collector and the direct radiation, and the outlet chimney which aides the exhaust of moist air while utilizing a buoyancy effect (Vlachos et al., 2002).

The latent heat of vaporization required to remove moisture from the produce is provided by the hot air flowing through the dryer and by the direct radiation striking the tomatoes in the drying chamber. The air flow in the dryer is responsible for carrying away the evaporated moisture from the produce (Das and Kumar, 1989). The moisture leaving the produce is equal to the moisture entering the air stream by convection (Simate, 2001):

$$\rho_f \Delta M/\Delta t = -G\ \Delta H/\Delta x$$

where ρ_f = density of the dry matter of the food (kg/m^3), M = moisture content (d.b.), t = time (h), G = air flux (kg/m^{2}hr), H = humidity (kg/kg) and x = depth of the bulk (m).

The air flow through the dryer is an important factor in the drying process and is responsible for moisture transport by enhancing convective transfer of water vapor from the tomato to the dry surrounding air. The moist air located just above the tomatoes is carried away by the air flow (Brown, 2000).

Humidity and temperature determine the dryness or drying power of the atmosphere (Brown, 2000). However, temperature and relative humidity by themselves can be poor predictors of dryer success. The vapor pressure deficit (VPD) is often a more important variable in modeling the drying process because it combines both relative humidity and temperature into a single number (Eaton and Kells, 2009).

Vapor pressure deficit is the difference between the current amount of moisture in the air and the amount of moisture the air can hold when it is fully saturated (Prenger and Ling, 2010). It quantifies how close the dryer air is to saturation. The VPD calculation is more appropriate to report over the relative humidity measurement because the VPD measurement includes the relative humidity measurement as well as the temperature measurement. This is important because the temperature has an effect on the moisture holding ability of the air, which approximately doubles with every 10 °C increase in temperature (Prenger and Ling, 2010). The drying process within the constructed dryers is an extremely complex heat and mass transfer process that depends on insolation level, air temperature, air humidity and the air flow rate through the dryer. In addition, the specific drying properties of a product of interest affect the drying process as well.

The concentrating solar panels can be used to increase the VPD within the CSP dryer. The panels are capable of reflecting further insolation onto the absorbers that would otherwise not be utilized by the dryer. The extra incident radiation is absorbed by the solar collector in a mixed mode dryer leading to an increase in dryer temperature and therefore an increase in the VPD.

These highly variable environmental conditions make the characterization of the drying process difficult because parameters such as air temperature and airflow are constantly varying. Therefore, this study does not attempt to derive a drying model for the particular dryer design. The study experimentally compares the differences in dryer performance between the CSP and the control designs.

Materials and methods

Construction of the solar dryer with concentrating panels

The mixed-mode solar dryer and the concentrating solar panels used in this study are shown in Fig. 1. The reflective panels were constructed from 32″ × 48″ (0.8 m × 1.2 m) wooden A frame planks. The panels are easily moveable and have an adjustable tilt angle in order to get maximum radiation reflection into the collector area. Aluminized Mylar sheeting is used as the reflective material and this was stapled onto the wooden panels. This material can easily be replaced by less expensive aluminum foil, or even reflective spray paint, in developing countries. A previous report showed that solar energy received by a small-scale solar dryer using aluminum foil as a reflective material shows no significant difference when compared to aluminized Mylar (Wagner et al., 1984).

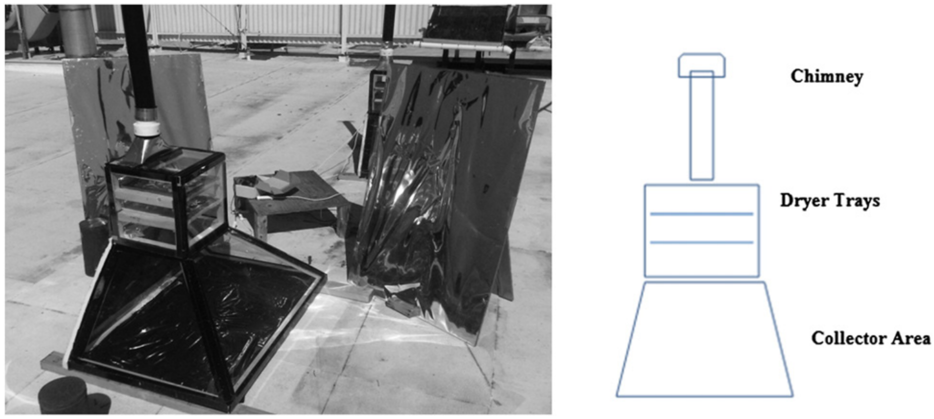

Fig. 1. Solar dryer and two concentrating solar reflection panels used in drying experiments. The data logging instrumentation for the sensors is located on the low table.

The dryer consists of two main sections: the drying chamber, and the solar radiation collector. Within the drying chamber are two sections that allow two trays to be set in place, one above the other. The trays were constructed from 1″×2″ (2.5 cm×5.0 cm) furring strips and food grade plastic screen was stapled to the frame of the trays. The frame was constructed from 1″×2″ (2.5 cm×5.0 cm) furring strips and 2″×4″ (2.5 cm×10.0 cm) wood. Foam board insulation 1.5″ (3.75 cm) thick was used to insulate the bottom and back side of the dryer and 10′×25′ (3.0 m×7.5 m) black polyethylene film was attached to the bottom insulation, where it served as the absorber material. Transparent polycarbonate with a 90% transmittance of near infrared and visible wavelengths was used as the glazing material for the collector area and was responsible for filtering UV radiation, which may cause degradation of vitamins, color and flavor in tomatoes. The faces of the dryer chamber also used the polycarbonate glazing material. The polycarbonate sheets were fixed to the dryer frame with industrial strength Velcro and can be easily removed for tray loading as well as for maintenance purposes.

The collector chamber is pyramidal in shape to allow a large surface area for the black polyethylene absorber. Each face of the chamber was inclined to approximately 45°. A black PVC pipe, 3″ (7.5 cm) in diameter and 2′ (0.6 m) in length, was attached to the drying chamber to serve as an air outlet and a stack. The chimney has a bent piece of polycarbonate attached to the top to serve as a rain blocker. The inlet was installed on the bottom back of the dryer and aluminum mesh covered the inlet to prevent rodents from entering.

In order to simulate cloudy conditions, the entire dryer was covered with sun screen fabric or 100% natural burlap. According to the manufacturer, the sun screen fabric allowed 25 to 30 percent of solar radiation in the visible and infrared wavelengths to be incident upon the dryers and blocked 81–87% of the ultraviolet radiation. The 100% natural burlap fabric blocked less radiation compared with the sun screen fabric. The burlap did not have a listed sun protection amount but we estimated that about 50% of the solar radiation was allowed to pass through the mesh, based on a visual estimate of porosity and experimental insolation data.

Tomatoes

Processing tomatoes were obtained from growers working in collaboration with the University of California Davis, and hand-harvested at peak maturity. Fruit were sorted to remove defects, washed and then sliced with clean knives into approximately 5 mm thick slices. They were placed on tared drying trays and then weighed once an hour during the daylight hours to determine drying rate.

Solar dryer performance evaluation

Measurements of solar radiation, temperature, humidity, air speed inside the dryer and tomato weight loss data were used to compare the effectiveness of the two dryers. Vapor pressure deficit for each relative humidity and temperature measurement in the dryers was calculated using the saturated vapor pressure and the vapor pressure within the area of interest as follows (Eaton and Kells, 2009):

The saturated vapor pressure using the measured temperature (t), in °C was

$$P_w = 6.1121e^{\left(\frac{17.502t}{(240.97+t)}\right)}$$

The vapor pressure, in mbar within the area of interest (P_v), based on the measured relative humidity (% RH) was

$$P_v = P_w \times RH/100$$

Lastly, the vapor pressure deficit (VPD) was

$$VPD = P_w - P_v$$

The amount of heat required to dry the tomatoes is calculated in units called degree-days (°D). Often referred to as heat units, degree-days are the integrated product of time and temperature above a certain temperature threshold for each day (The Regents of the University of California, 2010). In this study a degree-day was defined as one day with the temperature above a threshold of 18 °C by 0.55 °C. Degree-days were calculated for each trial using the trapezoidal rule for integration over a drying period.

Dimensionless moisture content during a drying period was obtained for all experimental trials and determined by the following equation:

$$Moisture\ Ratio = \frac{M - M_e}{M_i - M_e}$$

Where M = moisture content (dry basis) at some time, M_e = the equilibrium moisture content (dry basis), and M_i = initial moisture content (dry basis).

Other factors including solar insolation were also obtained.

Experiment

Testing was performed from September through November 2010 at the University of California, Davis (38° 32' 42″ N/121° 44' 21″ W). Each test was conducted for a one to three day period, depending

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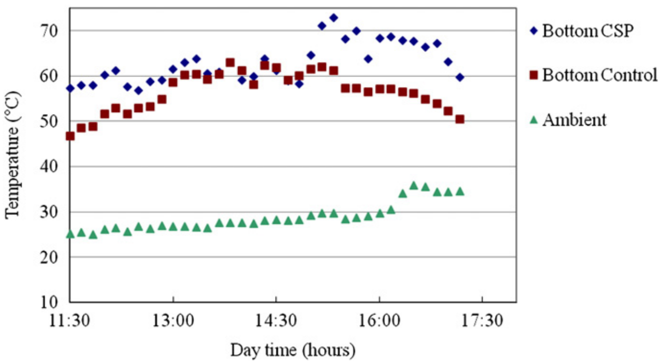

Fig. 2. Change in temperature versus time of the CSP dryer, control dryer, and the ambient environment at various times during a sunny day trial (9/20/10).

on the time required to remove an acceptable amount of moisture from the samples. Testing was done simultaneously on a CSP dryer with concentrating panels and a control dryer without panels. The concentrating panels provide varying amounts of radiant energy based on cloud cover so tests were carried out both on sunny and on simulated cloudy days.

During the testing period, the air temperatures and relative humidity at the bottom tray, top tray and ambient were measured by 12-bit Temperature/RH Smart Sensors (Temp accuracy: ±0.21 °C and RH accuracy: ±2.5%) at regular intervals during the day. The solar radiation was measured by a Silicon Pyranometer Sensor (accuracy: Typically within ± 10 W/m^2). The sensors were read at regular intervals by using a data logger and entered into a spreadsheet for analysis. Air speed in the stack was measured with a handheld anemometer during sunny conditions. An air velocity sensor was purchased later and used during simulated cloudy condition testing. The air velocity sensor was placed at the center axis of each stack to estimate and compare the CSP dryer and Control dryer air flow rates.

The dryer trays were designed to hold tomato slices of approximately 5 mm thickness. Each tray held 12 slices for the drying process. A scale was used to weigh the trays. Knowledge of the weight loss enabled a direct comparison of drying performance of the dryers.

The two dryers were set up identically and were exposed to the same weather conditions and direct solar radiation, the only difference being the addition of the reflectors for the CSP dryer. After each weight measurement was taken, approximately every hour during the day, the reflectors were adjusted to track the sun with the goal of reflecting a maximum amount of insolation on the collector and drying chamber.

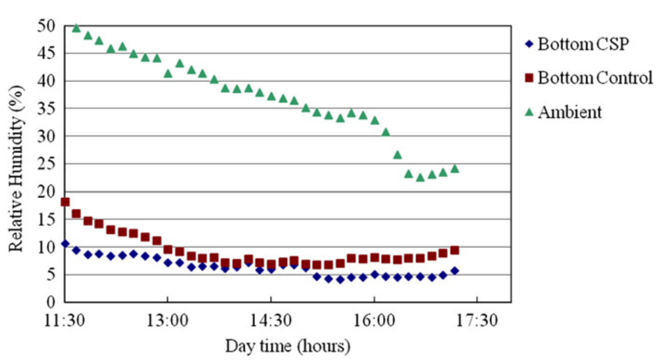

Fig. 3. Change in relative humidity of the CSP dryer, control dryer, and ambient at various times during the day (9/20/10).

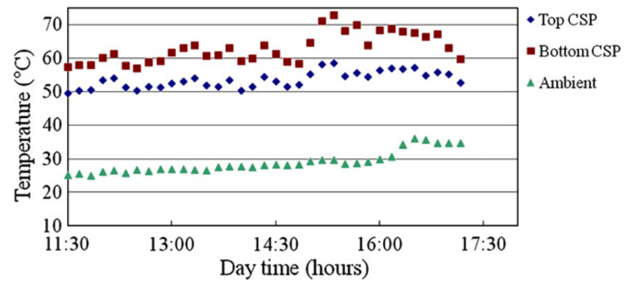

Fig. 4. Temperatures versus time at different locations within the CSP dryer (9/20/10).

Results and discussion

Dryer performance on sunny days

Figs. 2, 3, 4 and 5 represent the temperature, relative humidity, vapor pressure deficit and dimensionless moisture content changes during a typical sunny day drying trial carried out on Sept. 20, 2010. This trial is representative of the multiple tests done during sunny conditions.

Fig. 2 shows the change in the ambient air, CSP dryer and the control solar dryer temperatures over the period of the drying trial. The ambient temperature remains much lower than that in either the CSP or the control dryers. The CSP dryer temperature is much higher than the control dryer during the majority of the drying process. Fig. 3 shows changes in the relative humidity versus time for the CSP dryer, control dryer and ambient air. Relative humidity in the CSP dryer is consistently lower than both the control dryer and the ambient air relative humidity values. These graphs all illustrate the temperatures of the bottom tray location of the dryers.

To obtain uniform drying, which is necessary to achieve a consistent product, it is important to look at the differences in parameters at different tray heights (top and bottom) in the dryer (Prasad et al., 2006). In some of the drying trials, it was necessary to switch tray locations every hour during the drying process as a result of the different temperatures achieved at different locations in the dryer. In one representative trial (Fig. 4), the maximum temperature reached on the top tray was measured as 59 °C while the maximum temperature in the bottom tray was about 72 °C. The graphs show the temperature in the CSP dryer is higher than the control dryer. The vapor pressure deficit is also significantly higher than the control dryer at most points during the drying process, supporting the hypothesis that the concentrated solar dryer has a higher drying capacity. This can also be seen in Fig. 5.

The air flow due to the buoyancy effect is directly related to the difference in air temperature of the ambient air and the air inside air. The airflow due to buoyancy is induced due to variation of the air density which is air temperature and concentration dependent

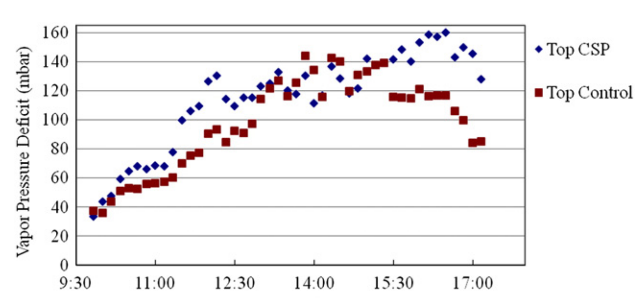

Fig. 5. Vapor pressure deficit versus time for each dryer on a representative sunny day (9/20/10).

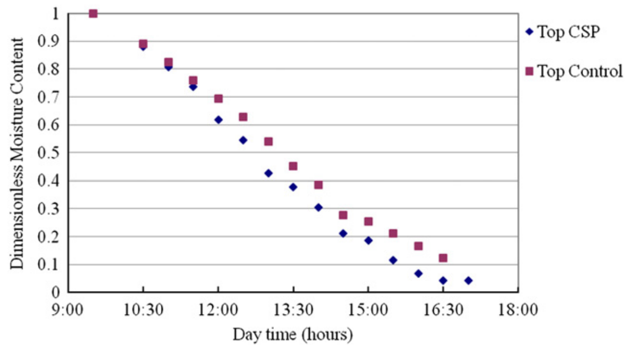

Fig. 6. Dimensionless moisture versus time for each dryer on a completely a sunny day trial.

(Oberbeck-Boussinesq approximation). On a particular test day, the average volumetric flow rate of air through the CSP dryer chimney was 0.0157 m^3/s compared to 0.0133 m^3/s in the control dryer, supporting the evaporative effects due to buoyancy of the temperature differences in each dryer.

The parameters affecting the drying process help explain why the final moisture content of the tomatoes of <20% was reached faster in the CSP dryer compared with the control dryer. The increased vapor pressure deficit ultimately led to an increased drying capacity. Fig. 6 shows the dimensionless moisture content of the tomatoes during the drying process on a representative sunny day and it clearly shows the moisture content falling faster in the CSP dryer.

Dryer performance in simulated cloudy conditions

Fig. 7 shows the effect of the burlap shading acting as simulated cloud cover over the dryers. It shows the measured reading of the pyranometer under the simulated shading versus the CIMIS solar insolation data for Davis, CA. The insolation was reduced from 505 to 310 W/m^2.

Figs. 8 and 9 show the temperature and relative humidity values for each dryer in simulated overcast conditions. Ambient temperature and insolation during this trial is lower than the sunny day trials. Therefore, the drying time was longer and the trial was conducted in three days to reach acceptable moisture content. The three day trial showed that the temperature of the CSP dryer was higher than the control dryer (Fig. 8), while relative humidity (Fig. 9) was similar.

Vapor pressure deficit is plotted in Fig. 10. It can be seen that the VPD in the CSP dryer is consistently higher than the VPD in the control dryer. Overnight, when there is no solar radiation present, the vapor pressure deficits in each dryer becomes approximately equal.

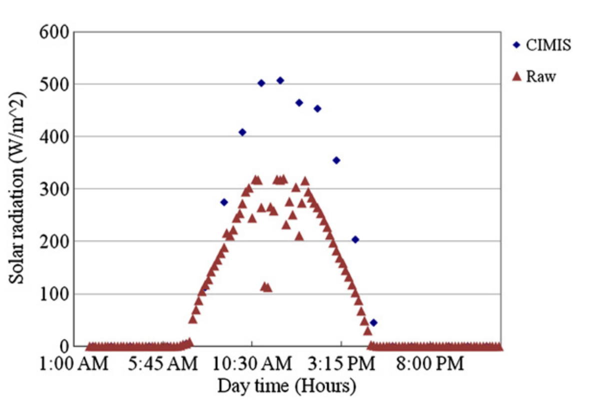

Fig. 7. Effect of the burlap shading on the insolation. CIMIS is the direct insolation and "Raw" is the insolation measured under the burlap.

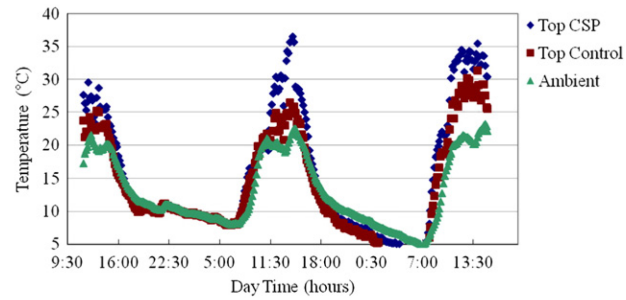

Fig. 8. Temperature in the dryers using the burlap shading for a three day period.

Therefore, the increase in VPD can be attributed to the increase in solar radiation from the reflective panels. The higher vapor pressure deficit in the CSP dryer leads to the moisture content calculations in Fig. 11. The use of reflectors clearly increases the amount of incident radiation on the dryer and subsequently increases the vapor pressure deficit which in turn has a positive effect on the drying rate of the tomatoes in the dryer.

Dryer performance in simulated cloudy conditions using the sun screen fabric

Figs. 12 and 13 show the temperature and relative humidity values for each dryer respectively in simulated conditions using the sun screen fabric. The two day trial showed that the temperature and relative humidity of the CSP dryer were not consistently higher than the control dryer and there ceases to be a significant advantage of using the reflectors when at insolation levels that are near 75% of clear sky levels.

The vapor pressure deficit is not significantly higher than the control dryer values, Fig. 14. The slightly higher vapor pressure deficit in the CSP dryer leads to the moisture content calculations in Fig. 15. While the use of reflectors clearly increases the amount of incident radiation on the dryer and subsequently increases the vapor pressure

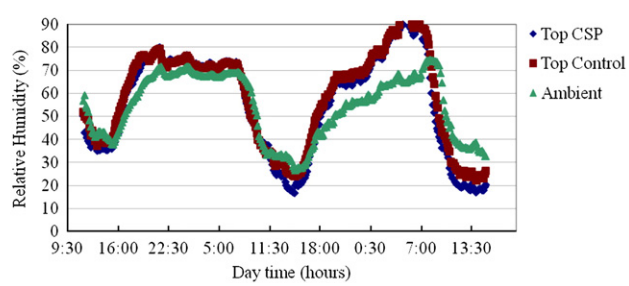

Fig. 9. Relative humidity for a two day period in the dryers using burlap to simulate cloudy conditions.

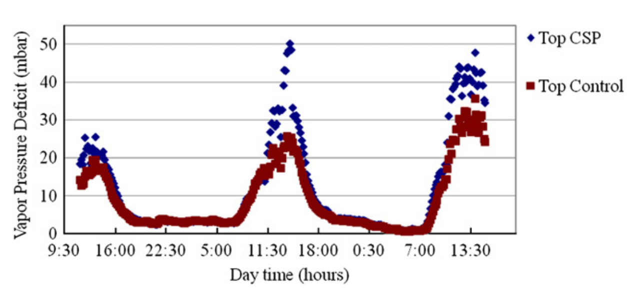

Fig. 10. Vapor pressure deficit for a three day period in each dryer using the burlap for simulated cloudy conditions.

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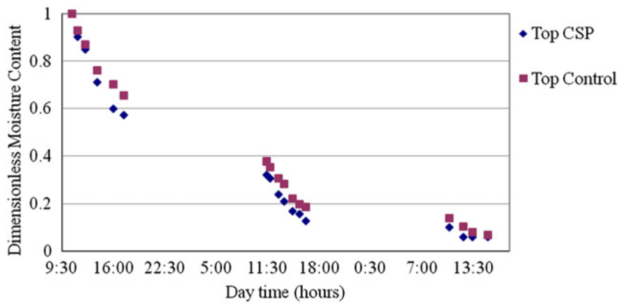

Fig. 11. Moisture level of tomatoes in a trial using the burlap shading.

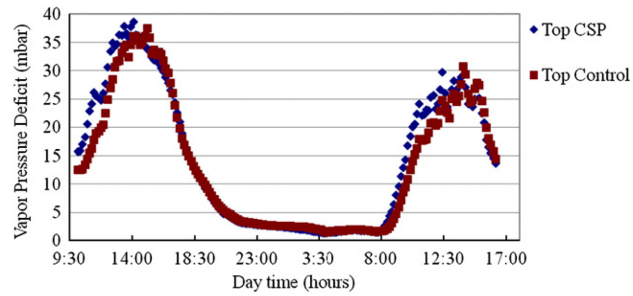

Fig. 14. Vapor pressure deficit in each dryer during a sun screen simulated trial for a two day period.

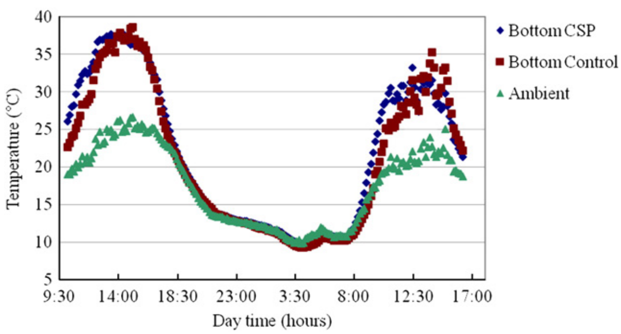

Fig. 12. Temperatures over a two day period in each dryer using the sun screen fabric.

deficit, the high amount of radiation blocked by the sun screen fabric exhibits a negligible advantage. Parabolic reflectors should be more efficient in focusing the solar radiation on the drying platform and this will be our future studies.

For a typical sunny day drying trial, burlap drying trial, and sun screen trial the total degree days calculated are shown in Table 1. Total amount of degree days in the CSP dryer is greater than the control dryer in every experiment with the difference being less pronounced with increased shading.

Overall drying performance

Table 1 provides an overview of the overall drying performance of the dryer with CSP as compared to a normal mixed-mode dryer. The final dimensionless moisture content when using the concentrating solar panels is lower than that for the control dryer for each trial. A target 0.2 dimensionless moisture content was achieved in a shorter time in the dryer utilizing CSP as compared to the control dryer. The calculated percent decrease in drying time for each trial was also determined. There was an average of 27.0% decrease in total drying time required when the CSP was used for two sunny day trials.

In the sun screen trial, there was an 7.4% decrease in total drying time. The burlap trials were less successful, use of the CSP achieved only a 3.1% average decrease in total drying time. This relatively low increase in performance was also affected by the ambient temperature and thus the ambient degree days were too low for a significant increase in drying ability. During one sunny day experiment on September 23, 2010 and also during the sun screen experiment the target dimensionless moisture content was not quite reached (Table 1). In these cases, the data was linearly extrapolated to estimate the drying time.

The results obtained from the experiments mentioned in this paper cannot be numerically compared to the results of other reflector experiments in the literature due to the differences in dryer design and the variability of external conditions which affect the drying process. A direct comparison between modular reflectors and immobile reflectors needs to be evaluated to determine if there is a difference in performance.

Several researchers have investigated the drying improvement of mixed-mode solar dryers. Mixed-mode dryers with solar reflectors have previously been studied and compared to mixed-mode dryers without reflectors. A group from Appalachian State University has investigated different reflector strategies using hinged reflectors attached to the dryer. This technique allowed them to move the reflectors to optimal positions throughout the day. The main problem with their method is that if the dryer could not track the sun, one of the reflectors would shade the collector in the morning and the other in the afternoon. Their tests determined that the reflectors did indeed increase the temperature inside of the dryer significantly (Scanlin et al., 2010). Unfortunately, they did not investigate the actual effect on drying time.

Wagner et al. previously investigated a solar dryer used for mangoes that included a parabolic trough reflector as an integral part of the design. Evaluations made on the solar dryer modules indicated that they could be used to increase drying capacity. The reflector was built into the design and not movable (Simate, 2001).

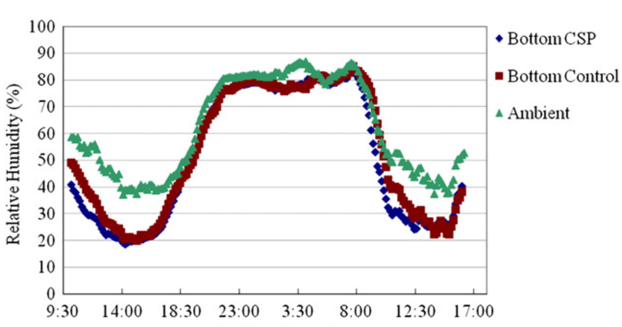

Fig. 13. Relative humidity in each dryer during a sun screen simulated trial.

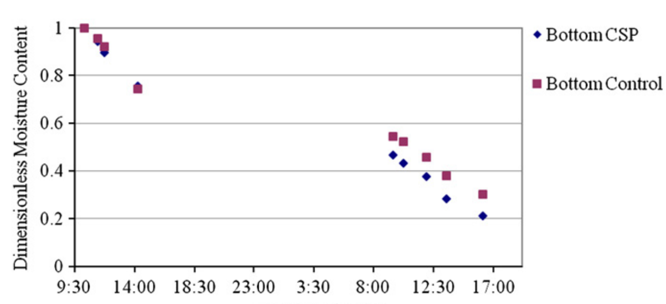

Fig. 15. Dimensionless moisture content during a simulated trial using the sun screen fabric for a two day period.

Table 1
Dryer performance comparison under sunny conditions, both uncovered and covered with burlap and/or sun screen to simulate hazy conditions.

Date	Ambient conditions	Shading conditions	Final dimensionless moisture		Degree days (°F* days)			Time to 0.2 MC (hours and minutes)		Difference between CSP and control drying times (hours and minutes)	(Average) drying time difference (hours)	(Average) percent decrease in drying time
			Control	CSP	Control	CSP	Ambient	Control	CSP	Control - CSP		
9/20	Sunny	Uncovered	0.08	0.06	16.30	17.90	5.00	6:07	5:13	0:54	1.80	27.0%
9/23	Sunny	Uncovered	0.26	0.09	14.60	17.40	4.85	0.30	4:30	2:42		
11/10 to 11/12	Sunny	Burlap	0.09	0.06	1.21	2.17	0.42	28:40	27:05	1:35	0.85	3.1%
11/16 to 11/18	Sunny	Burlap	0.07	0.04	3.67	4.11	5.27	25:56	25:49	0:07		
10/20 to 10/21	Sunny	Sun Screen	0.30	0.20	6.42	7.24	3.05	32:33	30:08	2:25	2.42	7.4%

Conclusions

This study reveals the effects of adding mobile concentrating solar panels to a mixed-mode solar dryer. The measured temperature and relative humidity inside the CSP dryer was noticeably higher than that of a normal mixed-mode dryer of identical design. The increased temperature and relative humidity led to an increased vapor pressure deficit which is an established indicator of the ability to evaporate. Drying time of tomatoes was reduced when using the concentrating solar panels as compared to not using the concentrating solar panels, which is indicated by the percent decrease in drying times for the experiments listed in Table 1. The use of mobile concentrating solar panels with mixed-mode dryers ensures a faster drying rate and it therefore reduces the chance of spoilage.

It has been shown that the concentrating solar panels used in this study increase the effectiveness of a particular mixed-mode solar dryer. Therefore, further studies and modifications to the design of concentrated solar drying using separate reflectors needs to be done to improve performance significantly. Parabolic reflectors are being investigated as a means to increase the drying rate of tomatoes in cloudy conditions. It will also be important in the future to look at important quality measures of the fruit to determine if the concentrated solar drying process leads to an acceptable final product such as: moisture content, water activity, rehydration ratio, lycopene content (for tomatoes), vitamin C concentration, color, firmness, pH level, and sugar concentration. The use of mobile concentrating solar panels exhibits a positive effect on the drying process and is a method that can potentially help farmers dry their crops quickly in developing countries.

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References

Blair R, Calota G, Crossman A, Drake F, O'Keefe K. Design of a Solar Powered Fruit and Vegetable Dryer. http://hdl.handle.net/2047/d10011730 2007. [accessed 01.11].

Bolaji BO, Olalusi AP. Performance evaluation of a mixed-mode solar dryer. AU J Technol 2008;11(4):225–31.

Brown P. Basics of evaporation and evapotranspiration. The University of Arizona Cooperative Extension; 2000 http://ag.arizona.edu/pubs/water/az1194.pd [accessed 01.11].

Das S, Kumar Y. Design and performance of a solar dryer with vertical collector chimney suitable for rural application. Energy Convers Manag 1989;29(2):129–35.

Eaton M, Kells SA. Use of vapor pressure deficit to predict humidity and temperature effects on the mortality of mold mites, *Tyrophagus putrescentiae*. Exp Appl Acarol 2009;47(3):201–13.

Gregoire RG. Understanding Solar Food Dryers. Arlington, VA: Peace Corps, Volunteers in Technical Service; 1984.

Gustavsson J, Cederberg C, Sonesson U, van Otterdijk R, Meybeck A. Global Food Losses and Food Waste. Food and Agricultural Organization; 2011 http://www.fao.org/fileadmin/user_upload/ags/publications/GFL_web.pdf [accessed 02.11].

Joshi C, Gewali M, Bhandari R. Performance of solar drying systems: a case study of Nepal. Inst Eng (India) 2004;85:53–7.

Madhlopa A, Jones SA, Kalenga SJD. A solar air heater with composite–absorber systems for food dehydration. Renew Energy 2002;27:27–37.

Mwithiga G, Kigo S. Performance of a solar dryer with limited sun tracking capability. J Food Eng 2006;74(2):247–52.

Prasad J, Vijay VK, Tiwari GN, Sorayan VPS. Study on performance evaluation of hybrid drier for turmeric (Curcuma longa L.) drying at village scale. J Food Eng 2006;75(4):497–502.

Prenger JJ, Ling PP. Greenhouse Condensation Control: VPD, AEX-804-01. Ohioline. http://ohioline.osu.edu/aex-fact/0804.html 2010. [accessed 01.11].

Scanlin D, Renner M, Domermuth D, Moody H. Improving Solar Food Dryers. Home Power, Feb. 1999. http://www.at.appstate.edu/documents/HP%20Improving%20Solar%20Food%20Dryers.pdf 2010. [accessed 01.11].

Simate I. Simulation of the mixed-mode natural-convection solar drying of maize. Drying Technol 2001;19(6):1137–55.

The Regents of the University of California. How to Manage Pests Degree-Days. UC IPM Online. http://www.ipm.ucdavis.edu/WEATHER/ddconcepts.html 2010. [accessed 01.11].

Vlachos NA, Karapantsios TD, Balouktsis AI, Chassapis D. Design And Testing Of A New Solar Tray Dryer. Drying Technol 2002;20(6):1243–71.

Wagner C, Coleman R, Berry R. Modular Solar Food Dryers for Farm Use. Energy Agric 1984;3:121–7.