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A greenhouse type solar dryer for small-scale dried food industries: Development and dissemination

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Abstract
In this study, a greenhouse type solar dryer for small-scale dried food industries was developed and disseminated. The dryer consists of a parabolic roof structure covered with polycarbonate sheets on a concrete floor. The system is 8.0m in width, 20.0m in length and 3.5m in height, with a loading capacity about 1,000kg of fruits or vegetables. To ensure continuous drying operation, a 100kW-LPG gas burner was incorporated to supply hot air to the dryer during cloudy or rainy days. Nine 15-W DC fans powered by three 50-W PV modules were used to ventilate the dryer. This dryer was installed for a small-scale food industry at Nakhon Pathom in Thailand to produce osmotically dehydrated tomato. To investigate its performance, the dryer was used to dry 3 batches of osmotically dehydrated tomato. Results obtained from these experiments showed that drying air temperatures in the dryer varied from 35°C to 65°C. In addition, the drying time for these products was 2-3 days shorter than that of the natural sun drying and good quality dried products were obtained. A system of differential equations describing heat and moisture transfers during drying of osmotically dehydrated tomato was also developed. The simulated results agreed well with the experimental data. For dissemination purpose, other two units of this type of dryer were constructed and tested at two locations in Thailand and satisfactory results were obtained.

Keywords: Solar energy; Solar drying; Osmotically dehydrated tomato; Dried food industries; Greenhouse solar dryer.

1. Introduction

Small-scale dried food industries are growing very fast in Southeast Asia, especially in Thailand. Situated in favorable climate conditions, Southeast Asian countries produce annually huge amounts of tropical fruits and vegetables. Drying is a major post-harvest processing of these food products. To respond to the demand of dried food from both domestic and international markets, a number of small-scaled dried food industries have been developed in Southeast Asia. In Thailand, some of these industries are established as community enterprises which are operated by villagers. To dry their products in commercial scale, most community enterprises use cabinet tray dryers heated by using liquefied petroleum gas (LPG) burners. In some cases, the drying starts with the open-sun drying and continues with a cabinet tray dryer using an LPG burner.

In the last few years, the price of LPG has substantially increased, thus increasing the drying cost. As Thailand is located in the tropical zone which receives abundant solar radiation, the country has tremendous potentials for solar drying of fruits and vegetables [1, 2].

In the last 40 years many types of solar dryers have been developed in various countries [3-24]. Many studies on natural convection solar drying of agricultural products have been reported [3-6]. However, the success achieved by natural convection solar dryers has been limited due to low buoyancy induced air flow. This has prompted researchers to develop forced convection solar dryer. Also many studies have been reported on forced convection solar dryers [7-14]. The intensive literature reviews on solar dryers can be found in [25, 26]. From this reviews, it is noticed that most solar dryers have as small loading capacity and cannot function properly during cloudy or raining periods. Consequently, it is not appropriate to use such dryers for the small-scale food industries in Thailand.

In general, small-scale food industries in Thailand require a solar dryer which could be used to dry 1,000-2,000 kg of fruits or vegetables per batch. As Thailand is situated in the tropics, the rainy season lasts approximately six months. Apart from high loading capacity, the dryer has to be equipped with an auxiliary heater to ensure continuous drying operation during the rainy season. To meet this requirement, we have developed a greenhouse type solar dryer for drying fruits and vegetables in small-scale food industries in Thailand. The dryer has a loading capacity of 1000 kg for fruits or vegetables. To ensure the continuous drying operation during cloudy or rainy periods, an auxiliary heater using LPG burner as heat source was equipped. The technical and economic performance of this dryer for drying osmotically dehydrated tomato in a commercial scale were presented in this paper.

2. Materials and methods

2.1 Experimental study

2.1.1 Experimental set up

The greenhouse type solar dryer was installed at a small-scale food industry in Nakhon Pathom (13.96°N, 100.10°E), Thailand. The dryer consists of a parabolic roof structure made from polycarbonate sheets on a concrete floor. The system has a width of 8.0 m, length of 20.0 m and height 3.5 m with a loading capacity of about 1,000 kg of fruits or vegetables. Nine DC fans operated by three 50-Watt solar cell modules were installed in the wall opposite to the air inlet to ventilate the dryer. An 100 kW LPG-burner was installed in a housing at the rear side of the dryer to heat drying air which was guided through the air ducts inside the dryer. The burner was equipped with a thermostat to control the drying air temperature. This type of burner is widely used in longan dryer in northern Thailand. A pictorial view of the dryer developed in this study is shown in Figure 1.

Figure 1. Pictorial view of the large-scale solar greenhouse dryer with LPG burner

Solar radiation passing through the polycarbonate roof heats the air and the products inside the dryer as well as the concrete floor. Ambient air is drawn in through a small opening at the bottom of the front side of the dryer and is heated by the floor and the products exposed to solar radiation. The heated air, while passing through and over the products absorbs moisture from the products. Direct exposure to solar radiation of the products and the heated drying air enhance the drying rate of the products. Most air is sucked from the dryer by nine PV-fans at the top of the rear side of the dryer. In case of rain and cloudy day, LPG burner is manually started and the AC fan of the burner blow hot air from the burner through the air guide in to the dryer. A pictorial view of the burner and air guides is shown in Figure 2.

Figure 2. A pictorial view of the burner (a) and air guides (b)

2.1.2 Experimental procedure

The dryer installed for a small-scale food industry in Nakhon Pathom was used to produce osmotically dehydrated tomato. For the production of osmotically dehydrated tomato, small tomato (diameter of 1.5 cm) was used in this study and these were collected from local farmers. Fresh whole tomato was blanched in boiling water for about 5 minutes. After blanching, the tomato were soaked in sugar solution (40% of sugar) for 72 hours and next these products were dried in the greenhouse dryer. In this study 1,000 kg of osmotically dehydrated tomato was dried in the solar greenhouse dryer to demonstrate its potentials for drying. A total of three full scale experimental runs were conducted during the period of October-December, 2009.

Solar radiation was measured by a pyranometer (Kipp & Zonen model CM 11, accuracy ± 0.5%) placed on the roof of the dryer. Thermocouples (type K) used to measure air temperatures in the dryer were tested by measuring the boiling and freezing temperatures of water to determine the accuracy (± 2%). Thermocouple positions for temperature measurement are shown in Figure 3. A hot wire anemometer (Airflow, model TA5, accuracy ± 2%) was used to monitor the air velocity inside the dryer. The anemometer was also used to monitor the ambient wind speed. The relative humidity of ambient air and drying air were periodically measured by hygrometers (Electronik, model EE23, accuracy ± 2%). Voltage signals from the pyranometer, hygrometers and thermocouples were recorded every 10 minutes by a multi-channel data logger (Yokogawa, model DC100). The air speed at the inlet and outlet of the dryer were recorded during the drying experiments. Before the installations, the pyranometer was calibrated against a pyranometer recently calibrated by the manufacturer. The hygrometers were calibrated using standard saturated salt solutions.

For each drying test, 1000 kg of osmotically dehydrated tomato was used. The tomato was placed in the product trays in a thin layer (Figure 4). The experiments were started at 8.00 am and continued till 6.00 pm. The drying was continued on subsequent days until the desired moisture content (about 17% wb). The final moisture content corresponds to the moisture content of high quality dried products available from local markets. Product samples were placed in the dryer at various positions (Figure 3) and were weighed periodically at three-hour intervals using a digital balance (Kern, model 474-42, accuracy ± 0.1 g). Also, about 100 g of the product was weighed from the dryer at three hour intervals and the moisture contents of the products inside the dryer were compared against the control samples (open-air sun dried).

The moisture content during drying was estimated from the weight of the product samples and the estimated dried solid mass of the samples. At the end of the experimental drying run, the exact dry solid mass of the product samples was determined by the oven method (103°C for 24 hours, accuracy ± 0.5%).

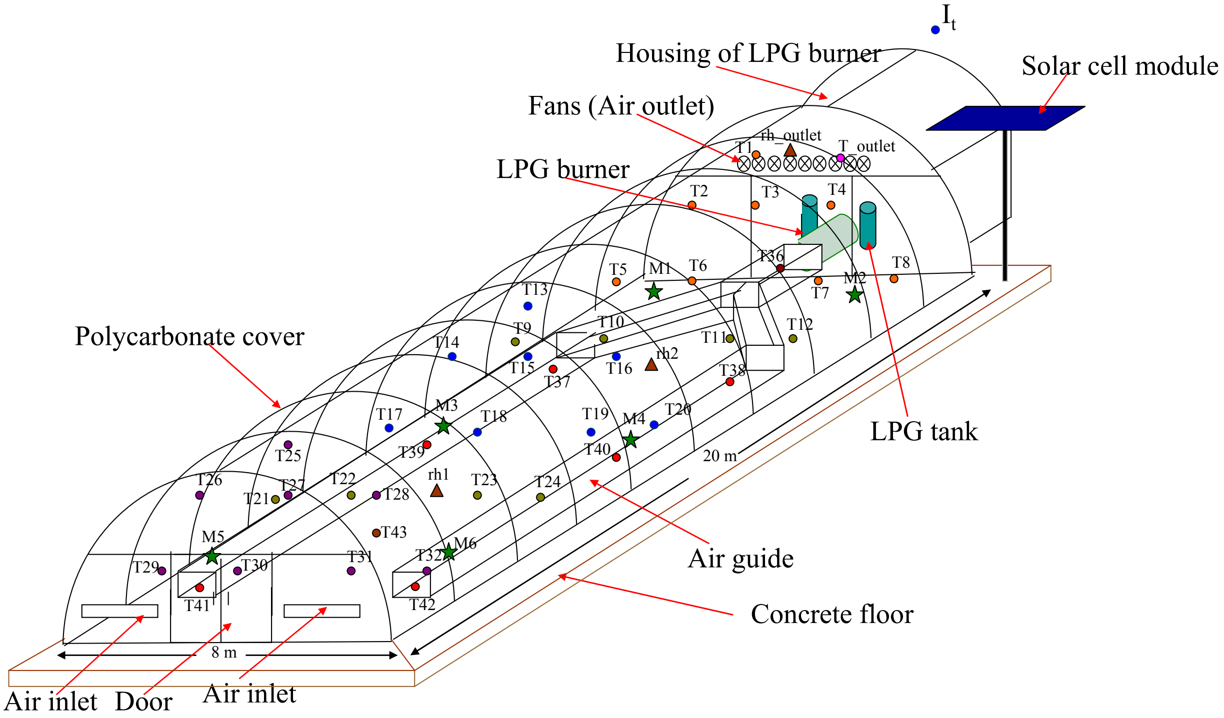

Figure 3. The dimension and the positions of the thermocouples (T), hygrometers (rh), product samples for weights (M) and solar radiation (I_t)

Figure 4. Pictorial view of the tomato in the greenhouse dryer

2.2 Mathematical modeling

The assumptions in developing the mathematical model for the solar greenhouse dryer are i) no stratification of the air inside the dryer, ii) drying computation is based on a thin layer drying model, and iii) specific heat of air, cover and product are constant.

Schematic diagram of energy transfers inside the solar greenhouse dryer is shown in Figure 5 and the following heat and mass balances are formulated:

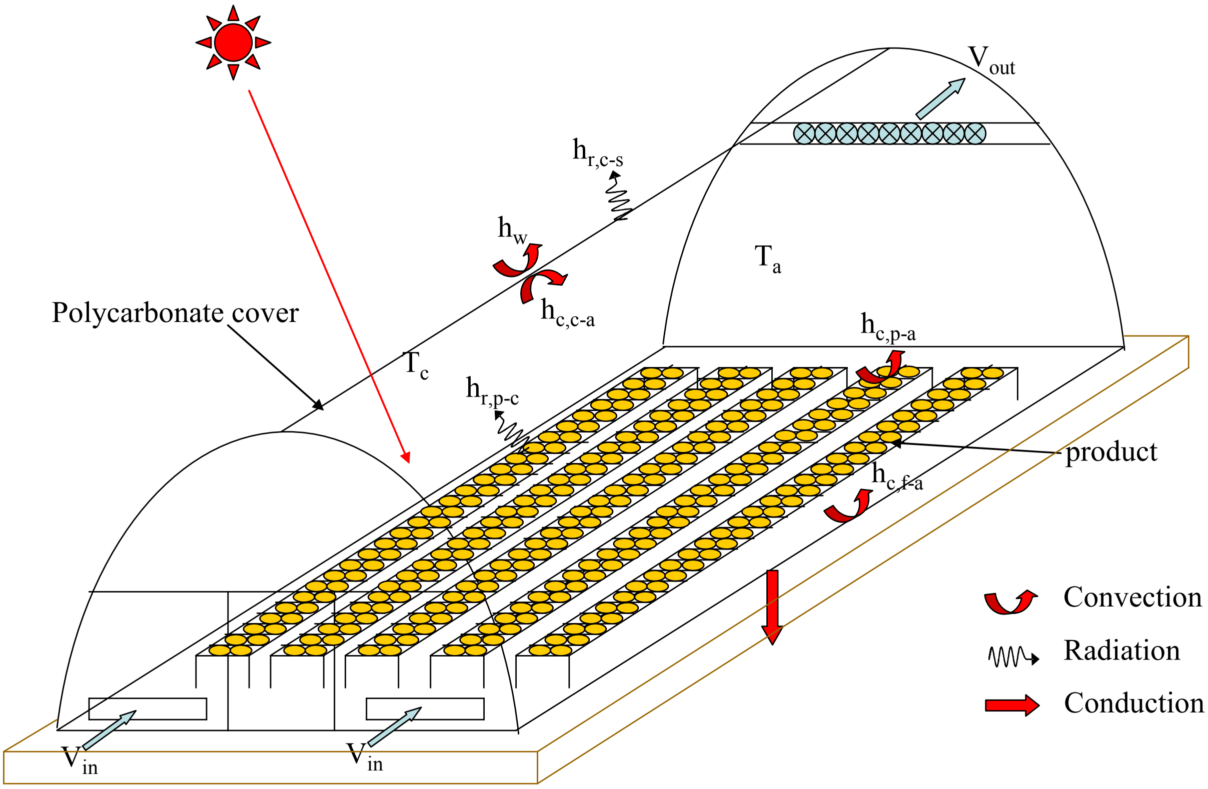

Figure 5. Schematic diagram of energy transfers inside the solar greenhouse dryer

2.2.1 Energy balance of the cover

The balance of energy on the cover is considered as follows: Rate of accumulation of thermal energy in the cover = Rate of thermal energy transfer between the air inside the dryer and the cover due to convection + Rate of thermal energy transfer between the sky and the cover due to radiation + Rate of thermal energy transfer between the cover and ambient air due to convection + Rate of thermal energy transfer between the product and the cover due to radiation + Rate of solar radiation absorbed by the cover.

The energy balance of the polycarbonate cover gives:

$$m_c C_{pc} \frac{dT_c}{dt} = A_c h_{c,c-a}(T_a - T_c) + A_c h_{r,c-s}(T_s - T_c) + A_c h_w(T_{am} - T_c) + A_p h_{r,p-c}(T_p - T_c) + A_c \alpha_c I_t \quad (1)$$

2.2.2 Energy balance of the air inside the dryer

This energy balance can be written as: Rate of accumulation of thermal energy in the air inside the dryer = Rate of thermal energy transfer between the product and the air due to convection + Rate of thermal energy transfer between the floor and the air due to convection + Rate of thermal energy gain of the air from the product due to sensible heat transfer from the product to the air + Rate of thermal energy gained in the air chamber due to inflow and outflow of the air in the chamber + Rate of over all heat loss from the air in the dryer to the ambient air + Rate of energy absorbed by the air inside dryer from solar radiation.

The energy balance in the air inside the greenhouse chamber gives:

$$m_a C_{pa}\frac{dT_a}{dt} = A_p h_{c,p-a}(T_p - T_a) + A_f h_{c,f-a}(T_f - T_a) + D_p A_p C_{pv}\rho_p (T_p - T_a)\frac{dM_p}{dt} \\ + (\rho_a V_{out} C_{pa} T_{out} - \rho_a V_{in} C_{pa} T_{in}) + U_c A_c (T_{am} - T_a) + [(1-F_p)(1-\alpha_f) + (1-\alpha_p)F_p] I_t A_c \tau_c \qquad (2)$$

2.2.3 Energy balance of the product

Rate of accumulation of thermal energy in the product = Rate of thermal energy transfer between air and product due to convection + Rate of thermal energy transfer between cover and product due to radiation + Rate of thermal energy lost from the product due to sensible and latent heat loss from the product + Rate of solar energy absorbed by the product.

The energy balance on the product gives:

$$m_p(C_{pg} + C_{pl}M_p)\frac{dT_p}{dt} = A_p h_{c,p-a}(T_a - T_p) + A_p h_{r,p-c}(T_c - T_p) \\ + D_p A_p \rho_p [L_p + C_{pv}(T_a - T_p)]\frac{dM_p}{dt} + F_p \alpha_p I_t A_c \tau_c \qquad (3)$$

2.2.4 Energy balances on the concrete floor

Rate of accumulation of thermal energy in the floor = Rate of convection heat transfer between air in the dryer and the floor + Rate of conduction heat transfer between the floor and the ground + Rate of solar radiation absorption on the floor.

$$m_f C_{pf}\frac{dT_f}{dt} = A_f h_{c,f-a}(T_a - T_f) + A_f h_{D,f-g}(T_g - T_f) + (1 - F_p)\alpha_f I_t A_f \tau_c \qquad (4)$$

2.2.5 Mass balance equation

The accumulation rate of moisture in the air inside dryer = Rate of moisture inflow into the dryer due to entry of ambient air – Rate of moisture outflow from the dryer due to exit of air from the dryer + Rate of moisture removed from the product inside the dryer. The mass balance inside dryer chamber gives:

$$\rho_a V\frac{dH}{dt} = A_{in}\rho_a H_{in} v_{in} - A_{out}\rho_a H_{out} v_{out} + D_p A_p \rho_d \frac{dM_p}{dt} \qquad (5)$$

2.2.6 Heat transfer and heat loss coefficients

Radiative heat transfer coefficient from the cover to the sky $(h_{r,c-s})$ is calculated as [27]:

$$h_{r,c-s} = \varepsilon_c \sigma (T_c^2 + T_s^2)(T_c + T_s) \qquad (6)$$

Radiative heat transfer coefficient between the product and the cover $(h_{r,p-c})$ is computed as [27]:

$$h_{r,p-c} = \varepsilon_p \sigma (T_p^2 + T_c^2)(T_p + T_c) \qquad (7)$$

Convective heat transfer coefficient from the cover to ambient due to wind (h_w) is computed as [28]:

$$h_w = 2.8 + 3.0 V_w \qquad (8)$$

Convective heat transfer coefficient inside the solar greenhouse dryer for either the cover or product and floor (h_c) is computed from the following relationship:

$$h_{c,f-a} = h_{c,c-a} = h_{c,p-a} = h_c = \frac{Nu\,k}{D_h} \qquad (9)$$

Nusselt number, (Nu) is computed from the Reynolds number (Re) by using the following relationship [29]:

$$\mathrm{Nu} = 0.0158\,\mathrm{Re}^{0.8} \tag{10}$$

The overall heat loss coefficient from the greenhouse cover (U_c) is computed from the following relation:

$$U_c = \frac{k_c}{\delta_c} \tag{11}$$

2.2.7 Thin layer drying equation

We conducted thin layer experiments in a laboratory dryer under controlled conditions of temperature and relative humidity and the following thin layer drying equation was developed for thin layer drying of osmotic treated tomato:

$$\frac{M - M_e}{M_o - M_e} = \exp(-At^B) \tag{12}$$

where M (decimal, db) is the product moisture content at time t (hour), M_0 (decimal, db) is initial moisture content, M_e (decimal, db) is the equilibrium moisture content. The drying parameters A and B are given as:

$$A=-0.276079+0.00723T+0.001594rh-0.000099Trh+0.000041rh^2 \tag{13}$$

$$B=1.511073-0.042305T+0.134277rh-0.0020655Trh+0.000533T^2-0.001355rh^2 \tag{14}$$

where T is temperature (°C) and rh is relative humidity (%)

We also conducted experiments to determine the equilibrium moisture content of the osmotically dehydrated tomato under controlled conditions of temperature and relative humidity. The result is written as:

$$a_w = \frac{1}{1+\left[\frac{51.50883-0.41666T}{M_e}\right]^{1.74215}} \tag{15}$$

where T is temperature (°C) and a_w is water activity (decimal). The water activity is equal to the relative humidity in percent divided by 100.

2.2.8 Solution procedure

The system of Eqs. (1–5) are solved numerically using the finite difference technique. The time interval should be small enough for the air conditions to be constant, but for the economy of computing, a compromise between the computing time and accuracy must be considered. On the basis of the drying air temperature and relative humidity inside the drying chamber, the drying parameters A and B and the equilibrium moisture content (M_e) of the product are computed. Using the A, B and M_e values, the change in moisture content of the product, ΔM for a time interval, Δt are calculated using Eq. (12). Next, the system of equations consisting of Eqs. (1), (2), (3) and (4) are expressed in the following form for the interval Δt.

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix} \begin{vmatrix} T_c \\ T_a \\ T_p \\ T_f \end{vmatrix} = \begin{vmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \end{vmatrix} \tag{16}$$

This system of equations is a set of implicit calculations for the time interval Δt. These are solved by the Gauss–Jordan elimination method using the recorded values for the drying air temperature and relative humidity, the change in moisture content of the product (ΔM) for the given time interval. The process is repeated until the final time is reached. The numerical solution was programmed in Compaq Visual FORTRAN version 6.5.

2.3 Colour measurement of dried tomato

The colour of dried osmotically dehydrated tomato samples was measured by a chromometer (CR-400, Minolta Co., Ltd., Japan) in Commission Internationale l'Eclairage (CIE) chromaticity coordinates. L*, a* and b* represent black to white (0–100), green to red (−60 to +60) and from blue to yellow (−60 to +60) colours, respectively. Out of five available colour systems, the L*a*b* [30, 31] and L*C*h [32] systems were selected because these are the most-used systems for evaluation of the colour of dried food materials. The instrument was standardised each time with a white ceramic plate. Three readings were taken at each place on the surface of samples and then the mean values of L*, a* and b* were averaged. The different colour parameters were calculated using the following equations [33].
Hue angle (h) indicating colour combination (i.e. browning) is defined as:

$$h = \begin{cases} \tan^{-1}(b^*/a^*) & (\text{when } a^* > 0) \\ 180° + \tan^{-1}(b^*/a^*) & (\text{when } a^* < 0) \end{cases} \tag{17}$$

Chroma (C*) indicating colour intensity or saturation is defined as:

$$C^* = (a^{*2} + b^{*2})^{1/2} \tag{18}$$

and the total colour change (ΔE) is defined as:

$$\Delta E = \sqrt{(L^* - L^*_{ref})^2 + (a^* - a^*_{ref})^2 + (b^* - b^*_{ref})^2} \tag{19}$$

2.4 Economic analysis

The total capital cost for the solar dryer (C_T) is given by the following equation:

$$C_T = C_m + C_l \tag{20}$$

where C_m is the material cost of the dryer and C_l is the labor cost for the construction.
The annual cost calculation method proposed by Audsley and Wheeler [34] yields:

$$C_{annual} = \left[C_T + \sum_{i=1}^{N} (C_{maint,i} + C_{op,i})\omega^i \right] \left[\frac{\omega - 1}{\omega(\omega^N - 1)} \right] \tag{21}$$

where C_{annual} is the annual cost of the system. $C_{maint,i}$ and $C_{op,i}$ are the maintenance cost and the operating cost at the year i respectively. ω is expressed as

$$\omega = (100 + i_{in})/(100 + i_f) \tag{22}$$

where i_{in} and i_f are the interest rate and the inflation rate in percent, respectively.
The operating cost consists C_{op} of the gas consumption cost, electricity consumption cost and the labour cost for operating the dryer. This cost can be written as follows;

$$C_{op} = C_{gas} + C_{electric} + C_{labour,op} \tag{23}$$

The maintenance cost of the first year was assumed to be 1% of the capital cost. Where C_{gas} is the cost of LPG gas, $C_{electric}$ is the cost of electricity required by the LPG burner, $C_{labour,op}$ is labour cost for operating the dryer.
The annual cost per unit of dried product is called the drying cost (Z, USD/kg). It can be written as

$$Z=\frac{C_{annual}}{M_{dry}} \tag{24}$$

where M_{dry} is the dried product obtained from this dryer per year.

$$\text{Payback period} = \frac{C_T}{M_{dry}\,P_d - M_f\,P_f - M_{dry}Z} \tag{25}$$

where M_{dry} is annual production of dry product (kg), M_f is the amount of fresh product per year (kg), P_d is the price of the dry product (USD/kg) and P_f is the price of the fresh product (USD/kg).

3. Results and discussion

3.1 Experimental results

Figure 6 shows the variations of solar radiation during the typical experimental runs of solar drying of osmotically dehydrated tomato in the solar greenhouse dryer. During the drying of osmotically dehydrated tomato, solar radiation increased sharply from 8 am to noon but it considerably decreased in the afternoon. There was also a slight random fluctuation in solar radiation. However, the overall cyclic patterns of the solar radiation were similar except the forth day of solar drying of osmotically dehydrated tomato due to rain and the LPG burner was used.

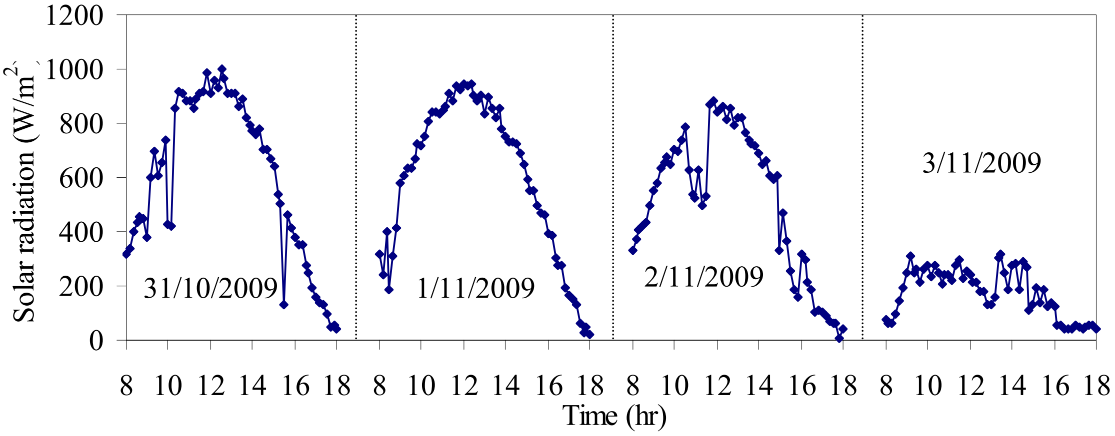

Figure 6. Variations of solar radiation with time of the day for a typical experimental run during drying of osmotically dehydrated tomato

Figure 7 shows the comparison of air temperatures at three different locations inside the dryer and the ambient air temperature for typical experimental runs of solar drying of osmotically dehydrated tomato. The patterns of temperature changes in different positions were comparable for all locations.

Temperatures in different positions at these three locations vary within a narrow band. In addition, temperatures at each of the locations differed significantly from the ambient air temperature.

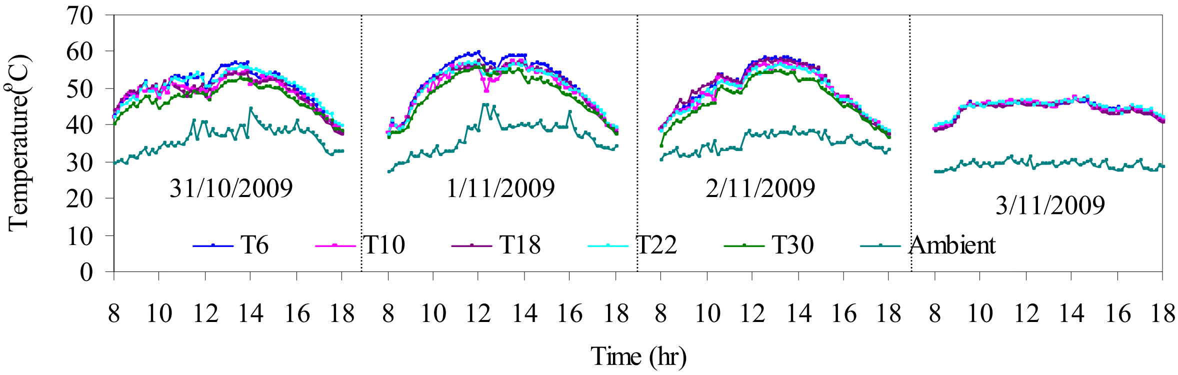

Figure 7. Variations of ambient temperature and the temperatures at different positions inside the greenhouse solar dryer for a typical experimental run during drying of osmotically dehydrated tomato

Figure 8 shows relative humidity inside the dryers for typical experimental runs during solar drying of osmotically dehydrated tomato. Relative humidity decreases with time inside the dryer during the first half of the day. This is caused by decreasing relative humidity of the ambient air and increased water holding capacity of the drying air due to temperature increase, whereas the opposite is true for the latter half of the day. The relative humidity of the air inside the dryers is always lower than that of the ambient air and the lowest relative humidity is in the middle of the day which persists for about 5 hours. Thus, the time of day with the most potential for solar dying is between 8:00 and 16:00. Furthermore, the air leaving the dryer has lower relative humidity than that of the ambient air, which indicates the exhaust air from the dryer, still has drying potential.

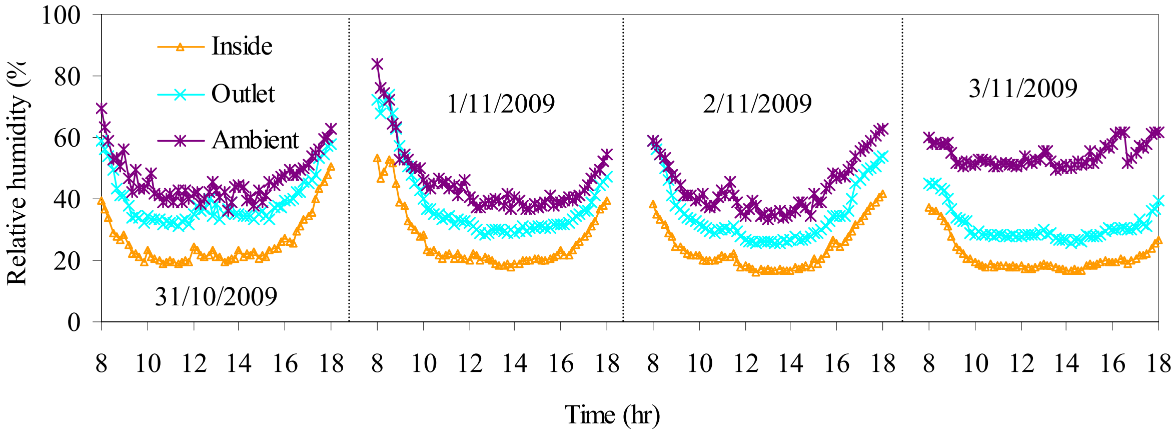

Figure 8. Variations of ambient relative humidity and relative humidity inside the greenhouse dryer with time of the day for a typical experimental run during drying of osmotically dehydrated tomato

Figure 9 shows the variations in moisture content of osmotically dehydrated tomato samples at different positions in the dryer for typical experimental runs compared to the control samples dried in the open-air sun drying. The moisture content of osmotically dehydrated tomato in the solar dryer was reduced from an initial value of 54 % (wb) to a final value of 17 % (wb) within 4 days whereas the moisture content of the sun-dried samples was reduced to 29 % (wb) within the same period. Thus, drying in the solar greenhouse dryer results in a reduced drying time.

Statistical analysis shows that there is no significant difference in solar drying of osmotically dehydrated tomato in the different positions inside the solar greenhouse dryers. However, there was a significant difference between solar-dried and sun-dried osmotically dehydrated tomato product at a significance level of 1%.

During the experiments when there was a rain, the LPG burner was used. The consumption of LPG during the experiments is shown in Table 1.

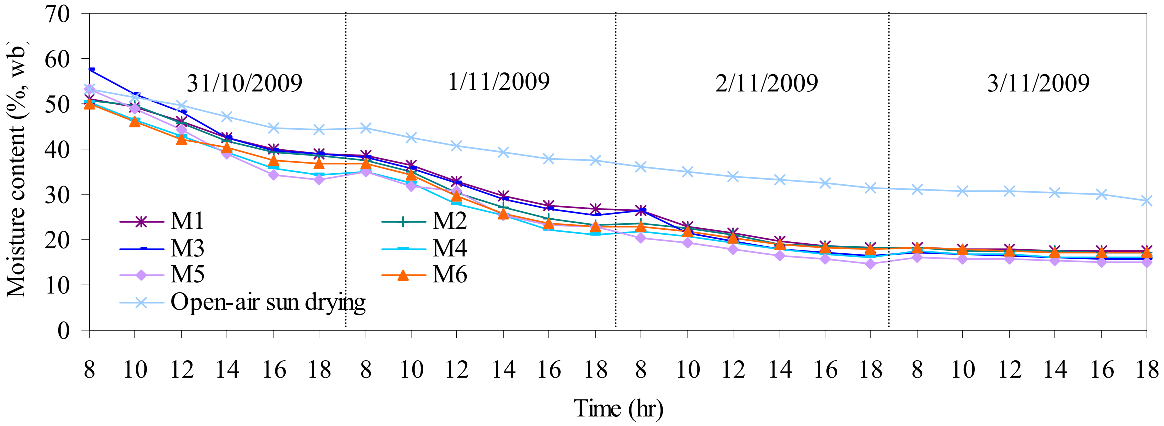

Figure 9. Comparison of the moisture contents of osmotically dehydrated tomato at different positions inside the greenhouse dryer with those obtained by the open-air sun drying method

Table 1. LPG and electricity consumption for the burner

No. of experiment	Period	LPG consumption (kg)	Electricity consumption (kWh)
1	12 October – 15 October, 2009	13	6.0
2	19 October – 22 October, 2009	30	8.5
3	31 October – 3 November, 2009	25	7.0

3.2 Simulated results

Figure 10 shows typical comparisons between the predicted and experimental temperature values for solar drying of osmotically dehydrated tomato. Predicted temperature shows plausible behaviour and the agreement between the predicted and observed values is good.

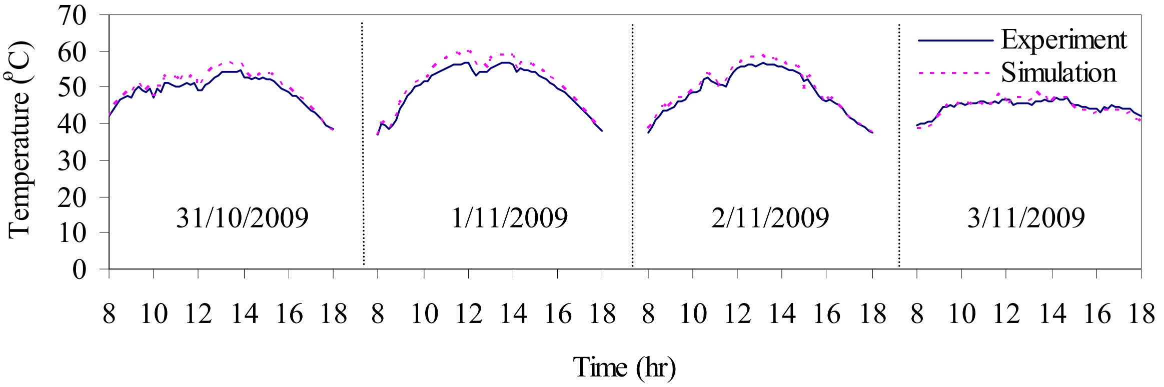

Figure 10. Comparison of the simulated and observed temperatures inside the greenhouse dryer during drying of osmotically dehydrated tomato for a typical experimental run

Figure 11 shows comparisons of the predicted and observed moisture contents of osmotically dehydrated tomato inside the dryer. The model predicts well the moisture content changes of osmotically dehydrated tomato during drying. The model predictions for drying of osmotically dehydrated tomato were evaluated on the basis of root mean square difference (RMSD). RMSD of the prediction of the temperatures inside the dryer were 3.4%. This study indicates that the model can predict the temperatures with a reasonable accuracy. RMSD of the predictions of moisture contents of osmotically dehydrated tomato was 7%. Thus, the model predictions are reasonably accurate. Furthermore, predictions are also within the acceptable limit (10%) [35].

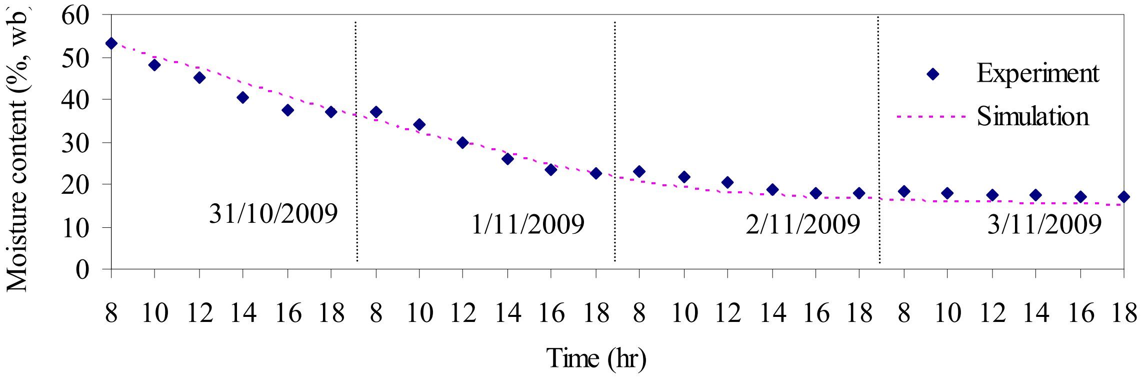

Figure 11. Comparison of the simulated and observed moisture content during drying of osmotically dehydrated tomato for a typical experimental run

3.3 Colour change

The colour of fresh and dried osmotically dehydrated tomato was measured using chromometer (CR-400, Minolta Co. Ltd, Japan) and results are shown in Table 2. The colour of fresh osmotically dehydrated tomato changes from light reddish brown to bright reddish brown after drying. The values of the colour indices indicate that the colour of solar dried osmotically dehydrated tomato is bright reddish brown while that of sun dried osmotically dehydrated tomato is light yellow brown. The total colour change of solar dried osmotically dehydrated tomato was 11.3 which indicates a large difference in color while the total change of sun dried osmotically dehydrated tomato was 5.8 which indicates an appreciable color difference. The colour change is more in case of solar dried osmotically dehydrated tomato and this color is the acceptable color in the dried osmotically dehydrated tomato markets and to the consumers of dried osmotically dehydrated tomato.

Table 2. Colour variations of dried osmotically dehydrated tomato

Status	Colour Value				
	L*	a*	b*	C*	h
Fresh osmotically dehydrated tomato	20.378	13.371	24.214	27.660	61.124
Solar dried osmotically dehydrated tomato	24.847	16.643	14.344	21.969	40.783
Natural sun dried osmotically dehydrated tomato	20.758	13.488	17.371	21.993	52.198

3.4 Application of simulation model and economic evaluation

In order to carry out the economic evaluation of these tomatoes, the simulation model was used to simulate the performance of the dryer for one year. The typical meteorological data set for Nakhon Pathom was used for the simulation [36]. The additional thermal energy required during the cloudy and rain period was estimated from the simulation with this thermal energy requirement and heating value of LPG, the quantity of LPG required was calculated. Also, the quality of dried product was estimated by using the simulation.

Based on the estimated production and the capital and operating costs of the drying system for drying of osmotically dehydrated tomato (Table 3), the payback period of the greenhouse solar drying system for this product is estimated and this is found to be about 0.65 years.

3.5 Dissemination

Greenhouse solar dryer with the loading capacity of 1,000 kg of fruits were designed to meet the demand of users for commercial scale production of quality dried fruits and vegetables and it was installed at Nakhon Pathom. After the successful demonstrations of the dryer it is being routinely used to produce osmotically dehydrated tomato for commercial purposes. The quality dried products produced in this solar greenhouse dryer are acceptable in the local and retail markets in Thailand. Other two units of this type of dryer were also constructed and tested, one at a community enterprise supported by the Royal Project in Petchabun (16.40°N,100.98°E) in the North of Thailand for drying bananas and another at a community enterprise in Ubon Ratchathani (15.37°N, 100.82°E) in the Northeast for drying of chilli

(Figure 12). Satisfactory results were obtained from all units. Apart from the improvement of the dried product quality, this type of dryer help to reduce LPG consumption in small-scale dried food industries. This is because the dryer uses solar energy as a main heat source. As a result of this success, the Department of Alternative Energy Development and Efficiency of Thailand has set up a dissemination program to promote the wide spread use of this type of dryer in small-scale food industries and several units of this type of the dryer are being used in a number of these industries across the country.

Table 3. Details of the computation of payback period

Items	Costs and economic parameters
Materials of constructions of the greenhouse dryer	10,860 USD*
Polycarbonate plates	4,000 USD
Solar modules and fans	1,140 USD
Labour costs for constructions	2,285 USD
Auxiliary heater system	2,000 USD
Repair and maintenance cost	1% of capital cost per year
Gas consumption:	
- Amount of LPG for operating	666 kg per year
- Price of LPG for LPG burner	0.43 USD per kg
Electricity consumption:	
- Amount of electricity	252 kWh per year
- Price of electricity	0.114 USD per kWh
Labor cost for operating the dryer:	
- Labour cost	5.7 USD per person per batch
- Number of labour per batch	2 person
Price of dried osmotically dehydrated tomato	4.57 USD
Expected life of the dryer	15 years
Interest rate	7%
Inflation rate	3.5%

* (1USD = 35 Baht)

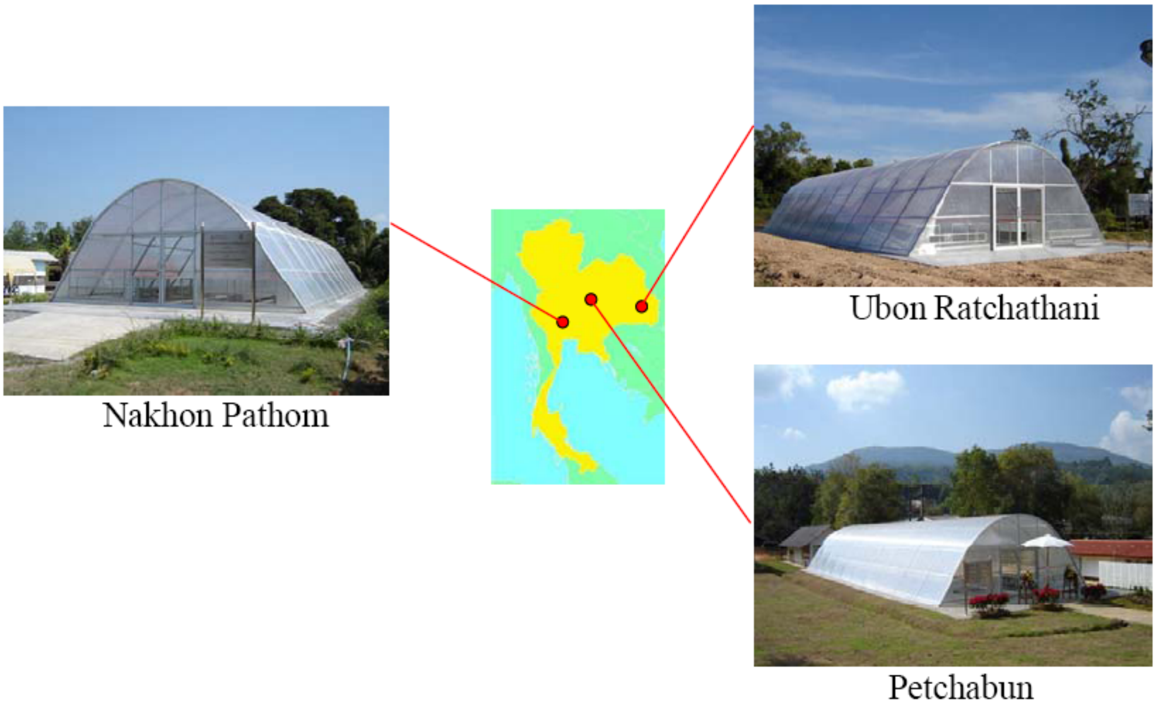

Figure 12. Location where the large-scale greenhouse dryer with LPG burner were installed in this work

4. Conclusion

A large-scale greenhouse solar dryer with LPG burner has been developed and its performance for drying osmotically dehydrated tomato have been investigated. Solar drying of osmotically dehydrated tomato in solar greenhouse dryer resulted in considerable reductions in drying time as compared with the open-air sun drying and the products dried in the solar greenhouse dryer are high quality dried products. The problem of drying interruption by rain and cloudy period has been solved.

A system of partial differential equations for heat and moisture transfer has been developed for solar drying of osmotically dehydrated tomato in the solar greenhouse dryer. The simulated air temperatures inside the dryer agreed well with the observed temperature data. Good agreement was found between the experimental and simulated moisture contents of osmotically dehydrated tomato during drying and the accuracy was within the acceptable range. The model has been used to provide gas quantity consumption and amount of dried products for economic evaluation. The estimated payback periods of the greenhouse type solar dryer for tomato are about 0.65 years. Due to its technical and economic effectiveness, this type of solar dryer has been officially included into the dissemination program by the Department of Alternative Energy Development and Efficiency of Thailand.

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