www.rericjournal.ait.ac.th

Performance Evaluation of a Large-Scale Polyethylene Covered Greenhouse Solar Dryer

Poolsak Intawee*[1] and Serm Janjai*

Abstract – *This paper presents experimental and simulated performance of a polyethylene covered large-scale solar greenhouse dryer. The dryer consists of a parabolic roof structure covered with a polyethylene sheet. This dryer has a width of 7.5 m, length of 20.0 m and height of 3.7 m, with a loading capacity of about 1,000 kg of fresh fruits or vegetables. Six 15-W DC fans powered by three 50-W PV modules were used to ventilate the dryer. The performances of the dryer for drying of chili and banana were investigated. Drying air temperatures inside the dryer varied from 35°C to 64°C. The drying time of these products was 3 to 4 days shorter than that of the natural sun drying and the colour of the dried product obtained from this dryer is better than those from natural sun drying. A system of partial differential equations describing heat and moisture transfer during drying of chili and banana inside the solar greenhouse dryer was developed and this system of non-linear partial differential equations was solved numerically using the finite difference method. The numerical solution was programmed in Compaq Visual FORTRAN version 6.5. The simulated results agreed well with the experimental data for solar drying of chili and banana.*

Keywords –Banana, chili, greenhouse dryer, simulation, solar energy, solar drying.

1. INTRODUCTION

Chili (*Capsicum Frutescens* L.) is an important ingredient in day to day cuisine and it is also a rich source of vitamin A, C and E. It assists in digestion and also prevents heart diseases by dilating blood vessels. Most of the chili produced in Thailand is used as a major ingredient for curry powder in a culinary preparation and chili industry. Therefore, dried chili is a value-added product and it also reduces the importation of dried chili in Thailand.

Banana (*Musa paradisiaca* L. var *sapientum* (L. O. Kuntze)) is one of the major fruits in Thailand. Banana is available year round and it is consumed as fresh and dried fruit. Banana is dried not only for preservation purposes, but also for modification of the taste, flavour and texture to meet consumer preferences and to increase value addition. Traditional methods, mainly open-air drying of banana, are commonly practiced in Thailand.

Drying of chili and banana in the traditional method of sun drying is susceptible to contamination by insects, dust and rain resulting in poor quality dried products. Also solar energy is utilized most inefficiently in traditional method of sun drying.

Drying is an energy intensive operation and Thailand, located in the tropical regions of the Southeast Asia, receives annual average daily solar radiation of 18.2 MJ m^{-2} day^{-1} [1]. Thus, utilization of solar energy to produce high-quality dried chili and banana can be considered to be a promising option. Furthermore, solar drying is a renewable and environmentally-friendly technology.

Solar drying can be considered as an advancement of natural sun drying and it is an efficient technique of utilizing solar energy [2], [3]. With these reasons, several types of solar crop dryer have been developed [4] to [12].

A number of studies have been reported on greenhouse crop drying [8]-[10], [13]-[21]. Limited studies have been reported on modeling of a solar greenhouse dryer [8], [17]-[21]. Kumar and Tiwari [19] reported thermal modeling of jaggery drying in a natural convection solar greenhouse dryer. Barnwal and Tiwari [20] proposed solar drying of grape using hybrid photovoltaic-thermal greenhouse dryer and developed a multi-linear expression to predict moisture evaporation during drying. Janjai *et al.* [21] reported solar drying of fruits and vegetables using polycarbonate covered greenhouse solar dryers and also presented the simulated performances of the scale polycarbonate covered greenhouse solar dryers for drying longan and banana. More recently Rathore and Panwar [10] reported performances of a natural convection walk-in type greenhouse dryer and it was found satisfactory for drying of grapes.

Although polycarbonate covered greenhouse solar dryers have been developed for agro-industrial applications in Thailand [9], [21], it is capital intensive. Furthermore, natural convection dryers are not suitable for agro-industrial applications [3]. This prompted the authors to design a relatively low cost polyethylene covered greenhouse dryer. The objective of this study is to develop a large-scale relatively low cost solar greenhouse dryer with a loading capacity of 1,000 kg of fresh fruits or vegetables. This paper presents the experimental performances of the polyethylene covered greenhouse dryer for drying of chili and banana, simulated drying performances of these products and also presents an economic assessment the polyethylene covered greenhouse dryer.

*Solar Energy Research Laboratory, Department of Physics, Faculty of Science, Silpakorn University, Nakhon Pathom 73000, Thailand.

[1]Corresponding author; Tel: +66 34 270761, Fax: +66 271189.
E-mail: poolsak2496@hotmail.com.

2. MATERIALS AND METHODS

Experimental Study

The greenhouse type solar dryer was installed at Silpakorn University, Nakhon Pathom (13.82°N, 100.04°E) in Thailand. It consists of a parabolic roof structure covered with polyethylene sheets (0.2 mm in thickness) on a concrete floor. The use of polyethylene sheets reduces the capital cost of the dryer significantly, although it needs frequent replacement. The system has a width of 7.5 m, length of 20.0 m and high of 3.7 m with a loading capacity of about 1,000 kg of fruits or vegetables. Six DC fans operated by three 50-Watt solar cell modules were installed in the wall opposite to the air inlet to ventilate the dryer. A pictorial view of the dryer developed in this study is shown in Figure 1.

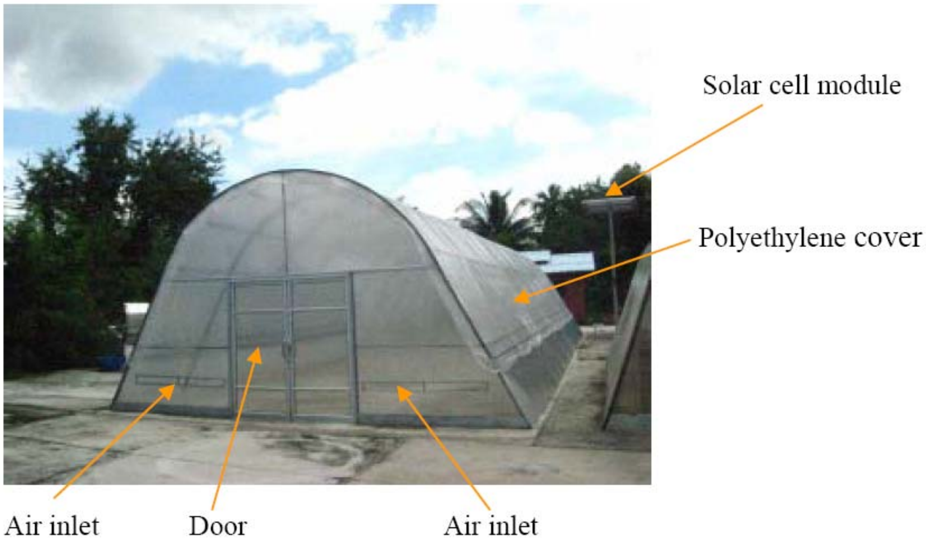

Fig. 1. Schematic diagram of the large-scale polyethylene cover greenhouse solar dryer.

Experimental Procedure

Chili and banana were dried in the solar greenhouse dryer with polyethylene cover to demonstrate its potentials for drying of chili and banana. A total of two experimental runs were conducted during the period of June-September, 2009, one run for each of the products.

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 different positions of the dryer (± 2%). Thermocouple positions for temperature measurement are shown in Figure 2. A hot wire anemometers (Airflow, model TA5, accuracy ± 2%) were used to monitor the air speed in the dryer at the air inlet and outlet of the dryer. The outlet consists of six circular openings, each of which has a diameter of 14 cm. In order to measure the air speed at each opening, a cylindrical tube with the diameter of 14 cm and the length of 150 cm was attached to the opening to channel the airflow through the tube. Hot wire anemometers were used to measure air speed inside the tube near its outlet. This method helps to reduce errors of the air speed measurements. However, it is difficult to use this method to measure the speed of inlet air, due to a large dimension of the inlet opening. Therefore, anemometers were used to monitor the air speed directly at several positions of the inlet and the results were averaged to obtain the mean inlet air speed. The anemometers were 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.

The dryer was loaded with 500 kg of chili and 800 kg of banana for the experimental runs. 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 10% wet basis for chili and 19% wet basis for banana) was reached. Figure 3 shows chili and bananas in the greenhouse dryer. Product samples were placed in the dryer at various positions (Figure 2) 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 weight of the product samples was determined by oven method (103°C for 24 hours, accuracy ± 0.5%).The results are presented in Section 3.1.

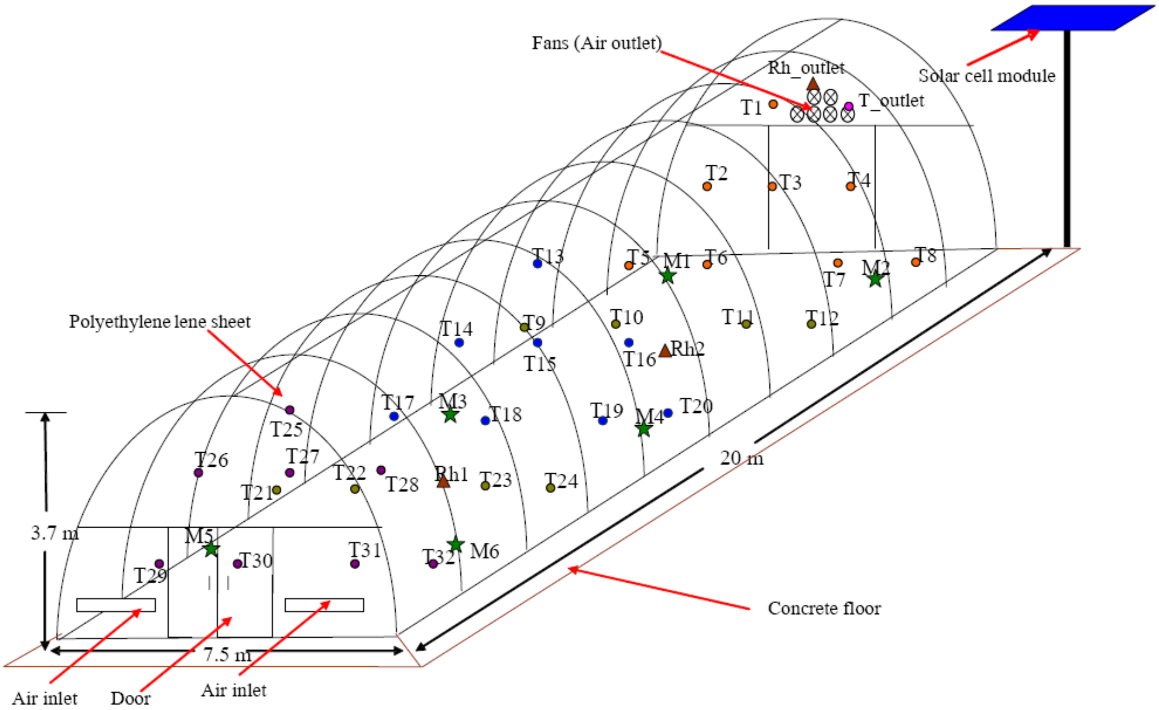

Fig. 2. The positions of the thermocouples (T) and measurements of relative humidity (rh) and weights of the product samples (M).

Fig. 3. chili (a) and bananas (b) in the greenhouse dryer with polyethylene cover.

Uncertainty Analysis

Uncertainty analysis refers to the uncertainty or error in experimental data. A systematic error in the experimental data is a repeated error of constant value and the random error is due to an imprecision. The systematic error can be removed by a calibration but the random error cannot be removed. The imprecision due to the random error can be defined numerically by a calibration. The measured data on solar radiation, temperature and relative humidity were recorded during the calibration. The mean value of the measurements and standard deviation of the random errors of the data on solar radiation, temperature and relative humidity were determined. The variable x_i which has an uncertainty δx_i is expressed as [22]-[24]:

$$x_i = x_{mean}(\text{measured}) \pm \delta x_i \qquad (1)$$

where x_i is actual value of the variable, x_{mean} is mean value of the measurements; and δx_i is the uncertainty in the measurement.

There is an uncertainty in x_i that may be as large as δx_i. The value of δx_i is the precision index which is taken as 2 times the standard deviation and it encloses approximately 95% of the population for a single sample analysis.

Statistical analysis (analysis of variance) was carried out to assess whether there exists any significant difference in drying (moisture removed) in the solar dryer in comparison to drying in the traditional sun drying system with a level of significance, and similar analysis was also conducted for the temperature inside the dryer and the ambient temperature as well as the humidity inside dryer and the ambient relative humidity.

The suitability of the model was evaluated using the value of the root mean square difference (RMSD):

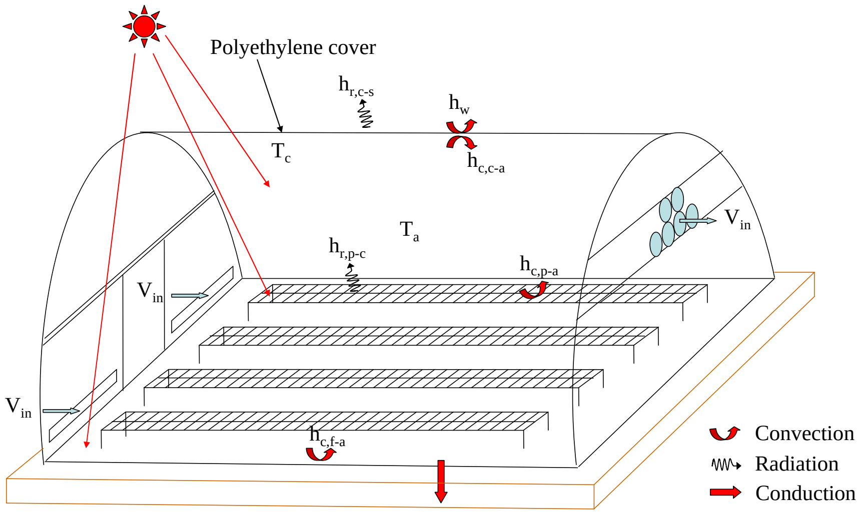

Fig. 4. Schematic diagram of energy transfers inside the solar greenhouse dryer.

$$\mathrm{RMSD} = \frac{\sqrt{\dfrac{\sum_{i=1}^{N}(y_{pre,i} - y_{meas,i})^2}{N}}}{\dfrac{\sum_{i=1}^{N} y_{meas,i}}{N}} \times 100 \qquad (2)$$

where $y_{pre,i}$ and $y_{meas,i}$ are the predicted and measured values of variable y, respectively and N is total number of data points.

Mathematical Modeling

The assumptions in developing the mathematical model for the solar greenhouse dryer are as follows:

(i) There is no stratification of the air inside the dryer.
(ii) Drying computation is based on a thin layer drying model.
(iii) Specific heat of air, cover and product are constant.
(iv) Radiative heat transfers from the floor to the cover and from the floor to the product are negligible.

Schematic diagram of energy transfers of the solar greenhouse dryer is shown in Figure 4 and the following heat and mass balances are formulated:

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:

$$m_c C_{pc}\frac{dT_c}{dt} = A_c h_{c,c-a}(T_a - T_c) + A_c h_{r,c-s}(T_s - T_c) + A_c h_w(T_{am} - T_c) + A_p h_{r,p-c}(T_p - T_c) + A_c \alpha_c I_t \qquad (3)$$

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 solar energy absorbed by the air inside dryer from solar radiation.

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

$$\begin{aligned} m_a C_{pa}\frac{dT_a}{dt} &= A_p h_{c,p-a}(T_p - T_a) + A_f h_{c,f-a}(T_f - T_a) \\ &+ D_p A_p C_{pw} \rho_p (T_p - T_a)\frac{dM_p}{dt} \\ &+ (\rho_a V_{out} C_{pa} T_{out} - \rho_a V_{in} C_{pa} T_{in}) \\ &+ U_c A_c (T_{am} - T_a) + [(1 - F_p)(1 - \alpha_f) \\ &+ (1 - \alpha_p)F_p] I_t A_c \tau_c \end{aligned} \qquad (4)$$

Energy Balance of the Product

The energy balance of the product inside the greenhouse dryer can be written as: 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 thermal energy absorbed by the product.

The energy balance on the product gives:

$$m_p(C_{pg}+C_{pl}M_p)\frac{dT_p}{dt}=A_p h_{c,p-a}(T_a-T_p)+A_p h_{r,p-c}(T_c-T_p)+D_p A_p \rho_p[L_p+C_{pv}(T_a-T_p)]\frac{dM_p}{dt}+F_p\alpha_p I_t A_c \tau_c \quad (5)$$

Energy Balances on the Concrete Floor

The energy balance on the concrete floor of the greenhouse dryer can be written as: 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.

$$m_f C_{pf}\frac{dT_f}{dt}=A_f h_{c,f-a}(T_a-T_f)+A_f h_{D,f-g}(T_g-T_f)+(1-F_p)\alpha_f I_t A_f \tau_c \quad (6)$$

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:

$$\rho_a V\frac{dH}{dt}=A_{in}\rho_a H_{in}v_{in}-A_{out}\rho_a H_{out}v_{out}+D_p A_p \rho_d\frac{dM_p}{dt} \quad (7)$$

Heat Transfer and Heat Loss Coefficients

Radiative heat transfer coefficient from the cover to the sky $(h_{r,c-s})$ is computed according to Duffie and Beckman [25]:

$$h_{r,c-s} = \varepsilon_c\sigma(T_c^2+T_s^2)(T_c+T_s) \quad (8)$$

Radiative heat transfer coefficient between the product and the cover $(h_{r,p-c})$ is computed as [25]:

$$h_{r,p-c} = \varepsilon_p\sigma(T_p^2+T_c^2)(T_p+T_c) \quad (9)$$

The sky temperature (T_s) is computed as [25]:

$$T_s = 0.552T_{am}^{1.5} \quad (10)$$

Convective heat transfer coefficient from the cover to ambient due to wind (h_w) is computed as [25]:

$$h_w = 2.8+3.0V_w \quad (11)$$

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:

$$h_{c,f-a}=h_{c,c-a}=h_{c,p-a}=h_c=\frac{Nu\, k_a}{D_h} \quad (12)$$

where D_h is given by:

$$D_h=\frac{4WD}{2(W+D)} \quad (13)$$

Nusselt number, (Nu) is computed from the following relationship [26]:

$$Nu=0.0158Re^{0.8} \quad (14)$$

where Re is the Reynolds number which is given by:

$$Re=\frac{D_h V_a \rho_a}{\nu} \quad (15)$$

As the wind speed outside the dryer and the speed of drying air inside the dryer are very low, we assumed that the overall heat loss coefficient (U_c) of heat transfer from air inside the dryer to ambient air was approximately equal to the conductive heat transfer coefficient of the cover [27]. This coefficient can be written as:

$$U_c=\frac{k_c}{\delta_c} \quad (16)$$

Thin Layer Drying Equation

The thin layer drying equation for chili developed by Hossain [28] was used and it is written as:

$$\frac{M-M_e}{M_0-M_e}=\exp(-Pt^Q) \quad (17)$$

where t is drying time (h). P and Q are given by:

$$P=0.00955+0.000372T-3.20\times10^{-6}T^2-0.01127rh+0.012408rh^2+0.004737V_a-0.00381V_a^2 \quad (18)$$

$$Q=4.89468-0.137459T+0.001345T^2+0.386002rh-1.142445V_a+0.920444V_a^2 \quad (19)$$

where T is drying air temperature (K), rh is drying air relative humidity (decimal) and V_a is air speed in the dryer (m/s).

The equilibrium moisture content of chili (M_e, db (decimal)) determined experimentally was used [28] and it was given by:

$$M_e=-65.2206-0.06922T+0.022734T^2-29.4079rh+68.31193rh^2-63.4257V_a+56.42796V_a^2 \quad (20)$$

The thin layer drying equation for banana proposed by Smitabhindu *et al.* [29] was used and it is written as:

$$\frac{M - M_e}{M_0 - M_e} = Ae^{-Bt} \tag{21}$$

A and B are given by:

$$A = 1.503574 + 0.505455rh - 0.01327T - 2.1417rh^2 + 0.000094T^2 \tag{22}$$

$$B = 0.1874 + 0.193rh - 0.00635T - 0.7978rh^2 + 0.00081T^2 \tag{23}$$

where rh is relative humidity of drying air (decimal), T is drying air temperature (ºC).

The equilibrium moisture content of banana (M_e, %db) determined experimentally was used and it is given by [29]:

$$M_e = 74.66023 - 1.144253T + 37.07224a_w + 0.001166T^2 + 51.55374a_w^2 \tag{24}$$

where a_w is water activity. The water activity is equal to relative humidity in decimal.

Solution Procedure

The system of Equations 3 to 7 together with Equations 17 or 21 were solved numerically using the finite difference technique. On the basis of the drying air temperature and relative humidity inside the dryer, the drying parameters A and B or P and Q and the equilibrium moisture content (M_e) of the products were computed. Using the A, B, P, Q and M_e values, the change in moisture content of the products, ΔM for all of the product for a time interval, Δt were calculated using Equations 17 or 21. Next, the system of equations consisting of Equations 3 to 6 were expressed in the matrix form for the interval Δt. This matrix equation consists of a set of implicit equations of temperatures for the time interval Δt. These equations were solved by the Gauss–Jordan elimination method using the recorded values for the drying air temperature and relative humidity and the change in moisture content of the products (ΔM) for the given time interval. The process was repeated until the final time was reached. The numerical solution was programmed in Compaq Visual FORTRAN version 6.5.

Economic Evaluation

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

$$C_T = C_m + C_l \tag{25}$$

where C_m is the material cost of the dryer and C_l is the labor cost for construction and installation.

The annual cost calculation method proposed by Audsley and Wheeler [30] yields:

$$C_{annual} = \left[C_T + \sum_{i=1}^{N} (C_{main,i} + C_{op,i})\,\omega^i \right] \left[\frac{\omega - 1}{\omega(\omega^N - 1)} \right] \tag{26}$$

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

$$\omega = (100 + i_{in}) / (100 + i_f) \tag{27}$$

where i_{in} and i_f are the interest rate and the inflation rate in percent, respectively. Note that Equation 26 is valid only for the case that i_{in} is not equal to i_f.

The maintenance cost of the first year was assumed to be 1% of the capital cost. The operating cost is the only cost of the labour for operating the dryer ($C_{labor,op}$).

The annual cost per unit of dried product is called the drying cost (Z, USD/kg). It can be written as

$$Z = \frac{C_{annual}}{M_{dry}} \tag{28}$$

where M_{dry} is the mass dried product obtained from this drying system per year

$$\text{Payback period} = \frac{C_T}{M_{dry} P_d - M_f P_f - M_{dry} Z} \tag{29}$$

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

3. RESULTS AND DISCUSSIONS

Experimental results

Drying experiments of chili and banana, in the greenhouse dryer were carried out in June – December in 2009. Figures 5 and 6 shows the variations of solar radiation during the experimental run of solar drying chili and of banana in the solar greenhouse dryer. During the drying of chili and banana, solar radiation increased sharply from 8 am to noon but it considerably decreased in the afternoon. The fluctuations are due to clouds, However, the overall cyclic patterns of the solar radiation were similar.

Figures 7 and 8 shows the comparison of air temperatures at different locations inside the dryer and the ambient air temperature for the experimental runs of solar drying of chili and banana. The patterns of temperature changes in different positions were comparable for all locations. Temperatures in different positions at these locations vary within a narrow band. In addition, temperatures at each of the locations differed significantly from the ambient air temperature.

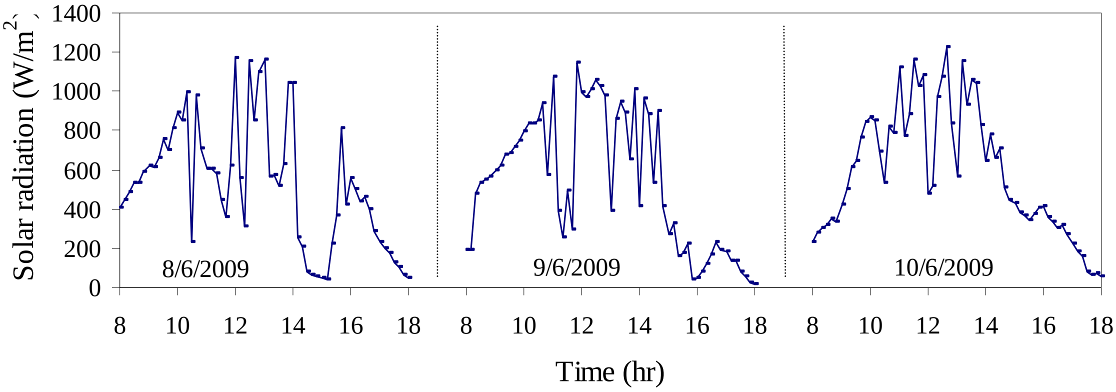

Fig. 5. Variations of solar radiation with time of the day during drying of chili.

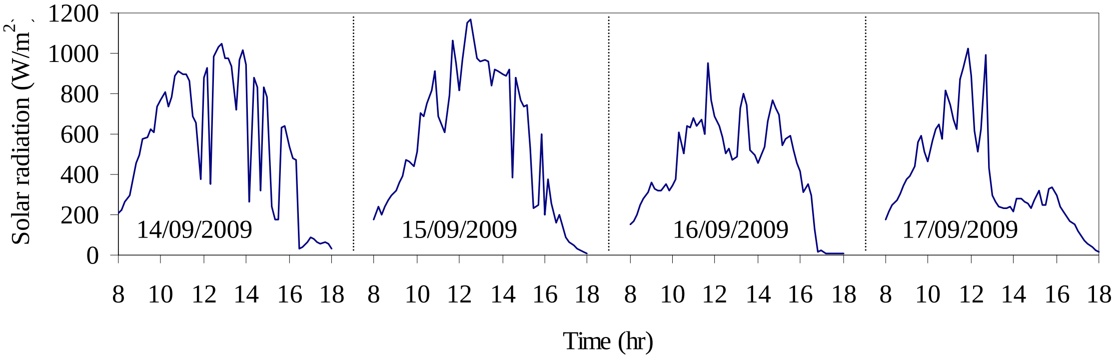

Fig. 6. Variations of solar radiation with time of the day during drying of banana.

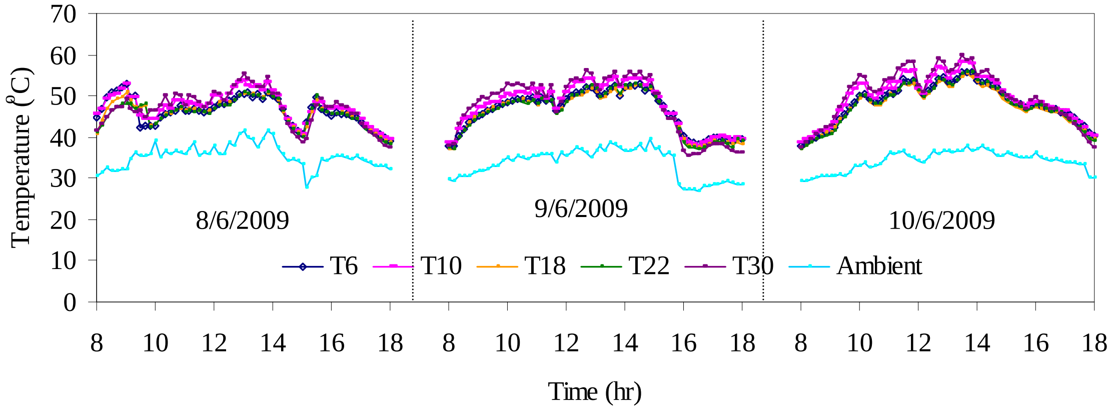

Fig. 7. Variations of ambient temperature and the temperatures at different positions inside the greenhouse solar dryer during drying of chili.

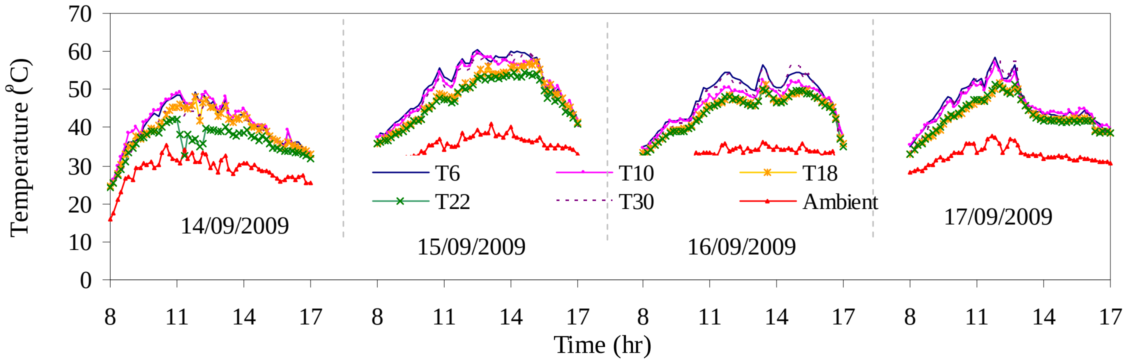

Fig. 8. Variations of ambient temperature and the temperatures inside the greenhouse solar dryer during drying of banana.

Figures 9 and 10 shows relative humidity at four different locations inside the dryer and ambient air relative humidity during solar drying of chili and banana. Relative humidity decreases over time at different locations inside the dryer during the first half of the day while the opposite is true for the other half of the day. No significant difference was found between relative humidity of different positions inside the dryer. However, there is a significant difference in relative humidity for all locations inside the dryer compared to the ambient air. The relative humidity of the air inside the dryer is lower than that of the ambient air. Hence, the air leaving the dryer has lower relative humidity than that of the ambient air and this indicates that the exhaust air from the dryer still has drying potential for recirculation to dry the product.

Figures 11 and 12 shows air flow rate during drying of chili and banana. The airflow rate increase with time in the early part of the day and then it decreases with time in the afternoon. The pattern of changes in airflow rate follows the pattern of changes in solar radiation, since the airflow is regulated by the fans powered by the PV modules. However, there is a threshold value of solar radiation for operating the DC motor used to run the fans and if radiation is too low, the fans would not operate.

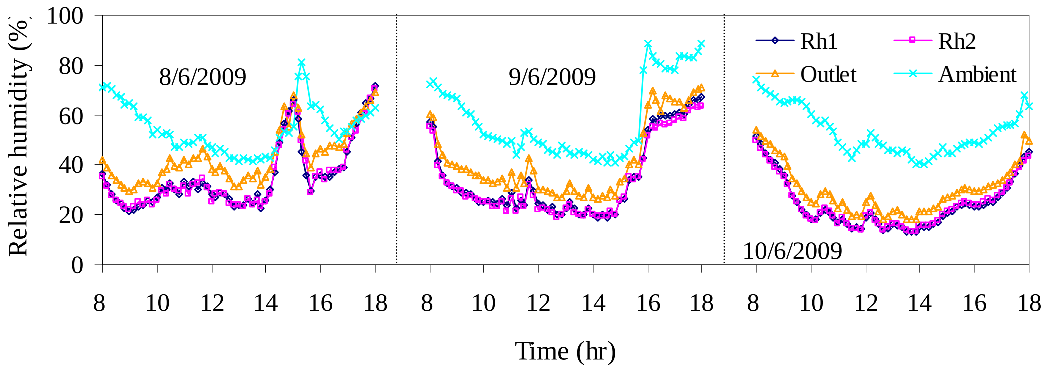

Fig. 9. Variation of ambient relative humidity and relative humidity inside the greenhouse dryer with time of the day during drying of chili.

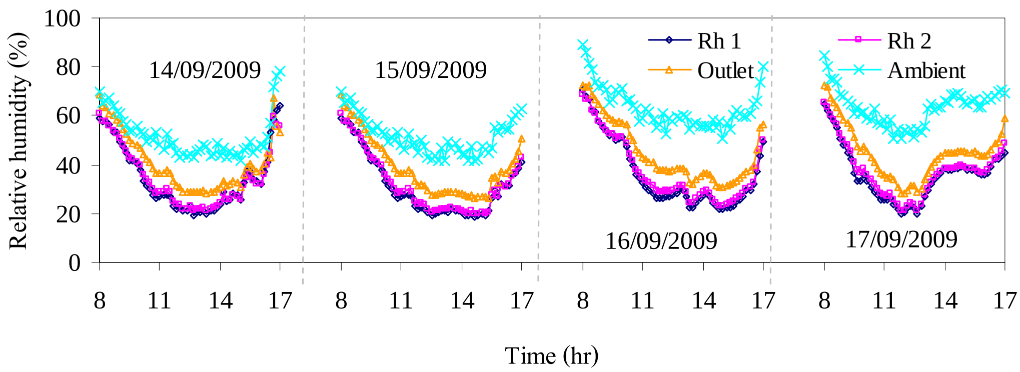

Fig. 10. Variation of ambient relative humidity and relative humidity inside the greenhouse dryer with time of the day during drying of banana.

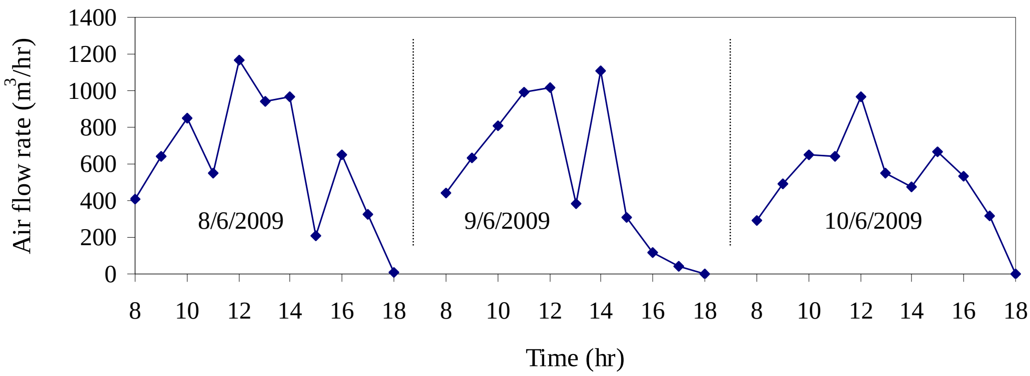

Fig. 11. Variations of air flow inside the greenhouse dryer with time of the day during drying of chili.

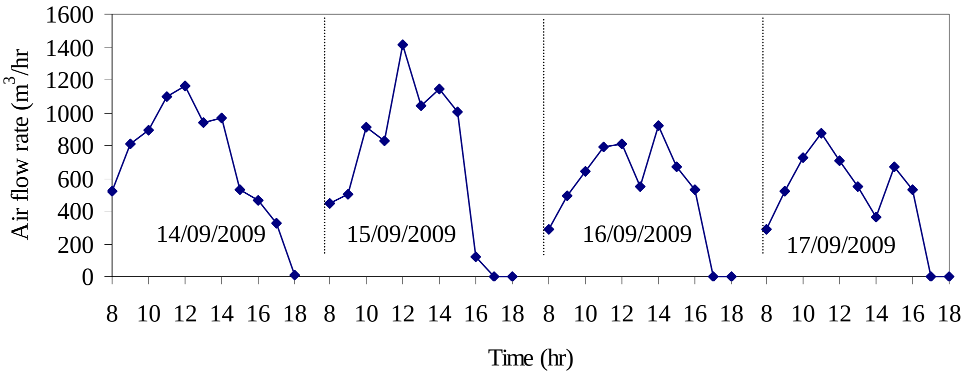

Fig. 12. Variations of air flow inside the greenhouse dryer with time of the day during drying of banana.

Figures 13 and 14 shows the variations in moisture content of chili and banana that different positions inside the dryer compared to the control sample dried by natural sun drying. The moisture content of chili in the solar dryer was reduced from an initial value of 76 % (wb) to a final value of 10% (wb) within 3 days whereas the moisture content of the natural sun-dried samples was reduced to 44 % (wb) in the same period. The moisture content of banana in the dryer decreased from 62% (wb) to 19% (wb) within 4 days, whereas the moisture content of the sun dried samples reduced to 32% (wb) in the same period. There is no significant difference in solar drying of the products in the different positions inside the solar greenhouse dryer.

The colour of banana was measured by using a chromometer (CR-400, Minolta Co, Ltd, Japan). The details of measurements are similar to those reported by [21]. It was found that there was a significant different between solar-dried and sun-dried samples. The dried banana obtained from the dryer has a golden brown colour which corresponds to colour of high quality dried banana while the colour of sun dried banana was dark yellow. For the case of chili, unfortunately its colour could not be accurately measured by such instrument, due to the high reflectivity of the surface of dried chili. Only visual inspections of the samples were carried out. The results showed that the colour of solar-dried chili was comparable to that of good quality dried- chili in local markets.

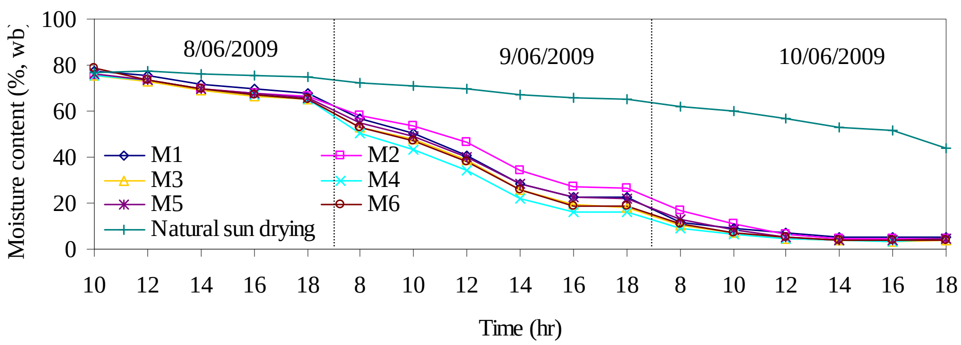

Fig. 13. Comparison of the moisture contents of chili at different positions inside the greenhouse dryer with those obtained by the traditional sun drying method.

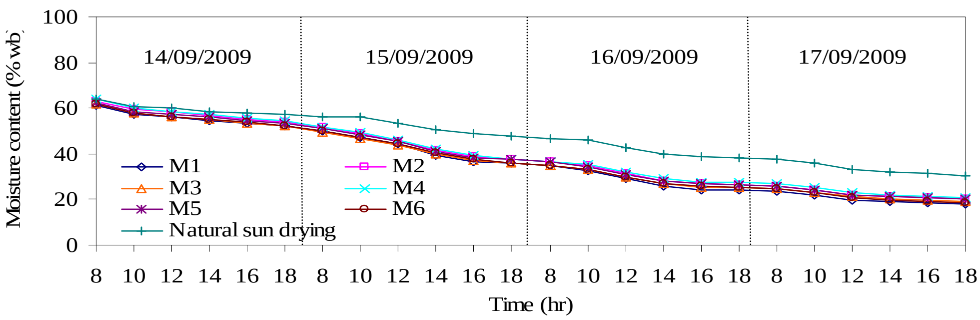

Fig. 14. Comparison of the moisture contents of banana at different positions inside the greenhouse dryer with those obtained by the traditional sun drying method.

Simulated Results

Figures 15 and 16 shows comparisons of the predicted and observed temperatures of chili and banana inside the dryer. The model predictions of drying air temperature of chili and banana were evaluated on the basis of root mean square difference (RMSD). RMSD of the prediction of the temperatures inside the dryer were 3.5% and 2.7% for chili and banana, respectively. This study indicates that the model can predict the temperatures with a reasonable accuracy.

Figures 17 and 18 shows comparisons of the predicted and observed moisture contents of chili and banana inside the dryer. The model predictions for drying of chili and banana were also evaluated on the basis of root mean square difference (RMSD). RMSD of the predictions of moisture contents of chili and banana were 9.1% and 6.0%, respectively. The model predicts well the moisture content changes of chili and banana during drying. Thus, the model predictions are reasonably accurate. Furthermore, predictions are also within the acceptable limit (10%) [31].

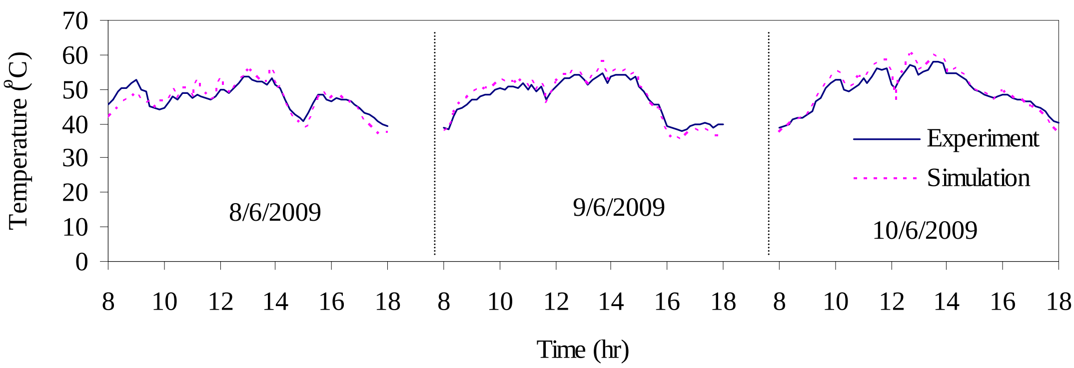

Fig. 15. Comparison of the simulated and observed temperatures inside the greenhouse dryer during drying of chili.

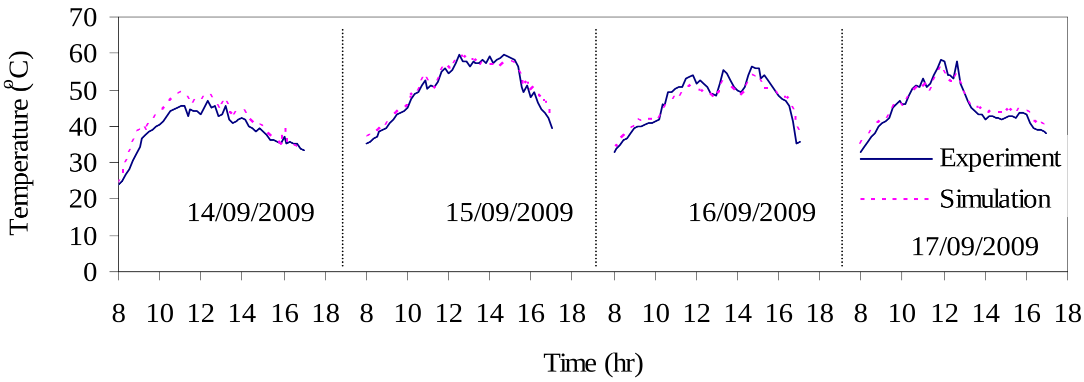

Fig. 16. Comparison of the simulated and observed temperatures inside the greenhouse dryer during drying of banana.

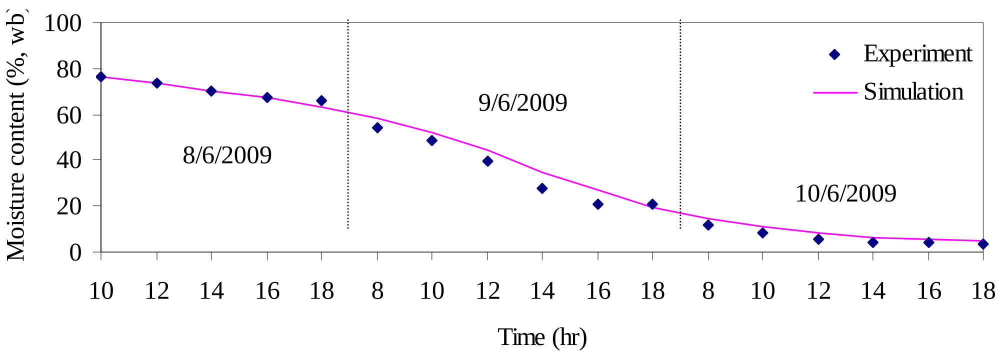

Fig. 17. Comparison of the simulated and observed moisture content during drying of chill.

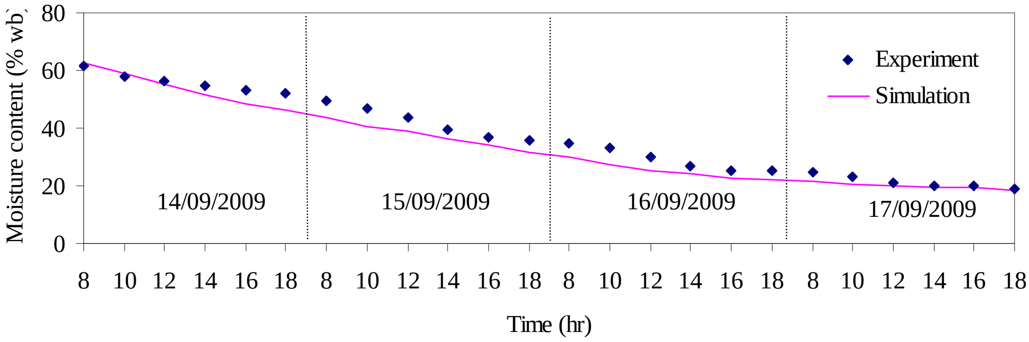

Fig. 18. Comparison of the simulated and observed moisture content during drying of banana.

Table 1. Data on costs and economic parameters.

Items	Costs and economic parameters
Polyethylene sheets	140 USD*
Solar module and fans	950 USD
Materials of constructions	3600 USD
Labour cost	580 USD
Maintenance cost	1% of capital cost/year
Operating cost	850 USD/year
Price of fresh chili	0.57 USD/kg
Price of dried chili	3.4 USD/kg
Price of fresh banana	0.2 USD/kg
Price of dried banana	1.4 USD/kg
Expected life of the dryer	15 year
Interest rate	7%
Inflation rate	3%

Economic Evaluation

The capital cost for construction and installation of the solar greenhouse dryer with polyethylene cover is 5,270 USD which is about 30% less than the capital cost of polycarbonate covered greenhouse dryer. The capacity of dryer is 1,000 kg. It is estimated that the dryer can be used for 6 months for drying of chili and another 6 months for drying of banana. This estimation is based on not only the experiments in this work but also the experiments from our previous works on solar drying of chili and banana in polycarbonate-covered greenhouse dryers at the same location [9], [21]. From this estimation, approximately 5,550 kg of dry chili and 12,950 kg of dry banana are produced annually. Based on this information on production scales of chili and banana, capital and operating costs of the drying system and price of the dried products, the payback period of the greenhouse solar drying system for drying chili and banana are estimated. The details of the information for computation of payback period are shown in Table 1. By using Equations 25 to 29 together with the economic data, the payback period is estimated to be 1.2 years.

5. CONCLUSION

A large-scale relatively low cost plastic covered solar greenhouse dryer has been constructed and tested at Silpakorn University to demonstrate its potentials of drying of chili and banana. Solar drying in the solar greenhouse dryer resulted in considerable reductions in drying time as compared with the natural sun drying and the colour of products dried in the solar greenhouse dryer are better than natural sun dried samples. The estimated payback period of the greenhouse solar dryer is about 1.2 years. Although the polyethylene requires replacements, its price is low. This dryer can be used for solar drying of fruits, vegetables, spices and medicinal plants in the developing countries where sufficient solar radiation is available.

A system of partial differential equations for heat and moisture transfer during drying of chili and banana in the solar greenhouse dryer has been developed to simulate the performances for solar drying of these products. Reasonable agreements were found between the experimental and simulated results. This model can be used for providing design data for the solar greenhouse dryer at any other locations.

NOMENCLATURES

A_c	area of the cover material (m^2)
A_f	area of the concrete floor (m^2)
A_{in}	cross-section area of the air inlet (m^2)
A_{out}	cross-section area of the air outlet (m^2)
A_p	area of the product (m^2)
a_w	water activity (decimal)
C_{annual}	annual cost of the system (USD)
C_{dry}	annual product of dry product (kg)
C_l	labor cost for construction and installation (USD)
C_m	material cost of the dryer (USD)

$C_{maint,i}$ maintenance cost (USD)
$C_{op,i}$ operating cost (USD)
C_{pa} specific heat of air (J/kg –K)
C_{pc} specific heat of cover material (J/kg –K)
C_{pl} specific heat of liquid (J/kg –K)
C_{pp} specific heat of product (J/kg –K)
C_{pw} specific heat of water vapour (J/kg –K)
C_T capital cost for the solar drying system (USD)
D average distance between the floor and the cover (m)
D_p thickness of the product (m)
F_p fraction of solar radiation falling on the product (decimal)
H humidity ratio of air inside the dryer (kg/kg)
H_{in} humidity ratio of air entering the dryer (kg/kg)
H_{out} humidity ratio of the air leaving the dryer (kg/kg)
$h_{c,c-a}$ convective heat transfer between the cover and the air (W/m^2-K)
$h_{c,f-a}$ convective heat transfer between thw floor cover and the air (W/m^2-K)
$h_{c,p-a}$ convective heat transfer between the product and the air (W/m^2-K)
$h_{r,c-s}$ radiative heat transfer between the cover and the sky (W/m^2-K)
$h_{r,p-c}$ radiative heat transfer between the product and the cover (W/m^2-K)
h_w convective heat transfer between the cover and the ambient (W/m^2-K)
$h_{D,f-g}$ conductive heat transfer between the floor and the underground (W/m^2-K)
I_t incident solar radiation (W/m^2)
k_a thermal conductivity of air (W/m-K)
k_f thermal conductivity of floor material (W/m-K)
k_c thermal conductivity of the cover (W/m-K)
L_p latent heat of vaporization of moisture from product (J/kg)
M moisture content of product (db, decimal)
M_{dry} annual production of dried product (kg)
M_e equilibrium moisture content of product (db, decimal)
M_f mass fresh product (kg)
M_o initial moisture content of product (db, decimal)
M_p Moisture content of dry product (db, decimal)
m_a mass of air inside the dryer (kg)
m_c mass of the cover (kg)
m_f mass of concrete floor (kg)
m_p mass of product (kg)
N total number of data points (-)
Nu Nusselt number, dimensionless
P_d price of the dry product (USD/kg)
P_f price of the fresh product (USD/kg)
Re Reynolds number, dimensionless
rh relative humidity (decimal)
T_a air temperature in the dryer (K)
T_{am} ambient temperature (K)
T_c cover temperature (K)
T_f floor temperature (K)
T_{in} temperature of the inlet air of the dryer (K)
T_{out} temperature of the outlet air of the dryer (K)
T_p temperature of product (K)
T_s sky temperature (K)
t time (s)
U_c overall heat loss coefficient from air inside the dryer through the cover to ambient air (W/m^2-K)
V volume of the drying chamber (m^3)
V_a air speed in the dryer (m/s)
V_{in} inlet air flow rate (m^3/s)
V_{out} outlet air flow rate (m^3/s)
V_w wind speed (m/s)
v air speed (m/s)
v_{in} inlet air speed (m/s)
v_{out} outlet air speed (m/s)
W width of the dryer floor (m)
x_i actual value of the variable (-)
x_{mean} mean value of the measurements (-)
$y_{meas,i}$ the measured values of variable y (-)
$y_{pre,i}$ the predicted values of variable y (-)
Z drying cost (USD/kg)
α_c absorptance of the cover material (decimal)
α_f absorptance of floor (decimal)
α_p absorptance of product (decimal)
δ_c thickness of the cover (m)
δx_i uncertainty in the measurement (-)
σ Stefan -Boltzmann's constant (W/m^2-K^4)
ρ_a density of air (kg/m^3)
ρ_c density of the cover material (kg/m^3)
ρ_d density of the dry product (kg/m^3)
ρ_p density of the product (kg/m^3)
τ_c transmittance of the cover material (decimal)
ε_c emissivity of the cover material(decimal)
ε_p emissivity of the product (decimal)
ν viscosity of air (m^2/s)

ACKNOWLEDGEMENTS

The authors would like to thank Prof. B.K. Bala for his valuable advice. The authors are grateful to Mr. Sarawut Nabnean and Mr. Niroot Lamlert for the assistance in the drying experiments.

REFERENCES

[1] Janjai, S., Laksanaboonsong, J., Nunez, M., Thongsathitya, A., 2005. Development of a method for generating operational solar radiation maps

from satellite data for a tropical environment. *Solar Energy* 78: 739-751.
[2] Bala, B.K., 1998. *Solar drying systems*. Agrotech Publishing Academy, Udaipur, India.
[3] Muhlbauer, W., 1986. Present status of solar crop drying. *Energy in Agriculture* 5: 121-137.
[4] Exell, R.H.B. and S. Kornsakoo, 1978. A low-cost solar rice dryer. *Appropriate Technology* 5: 23-24.
[5] Sharma, V.K., Colangelo, A., Spagna, G., 1995. Experimental investigation of different solar driers suitable for fruits and vegetable drying. *Renewable Energy* 6: 413-424.
[6] Oosthuizen, P.H., 1995. The design of indirect solar rice dryers. *Journal of Engineering for International Development* 2: 20-27.
[7] Esper, A., and W. Mühlbauer, 1996. Solar tunnel dryer for fruits. *Plant Research and Development* 44: 61-80.
[8] Jain, D., and G.N. Tiwari, 2004. Effect of greenhouse on crop drying under natural and forced convection II. Thermal modeling and experimental validation. *Energy Conversion and Management* 45: 2777-2793.
[9] Janjai, S., Khamvongsa, V., and Bala, B.K., 2007. Development, design and Performance of a PV-ventilated greenhouse dryer. *International Energy Journal* 8: 249-258.
[10] Rathore, N.S. and N.L. Panwar, 2010. Experimental studies on hemi cylindrical walk-in type solar tunnel dryer. *Applied Energy* 87: 2764-2767.
[11] Montero, I., Blanco, J., Miranda, T., Rojas, S., and Celma, A.R., 2010. Design, construction and performance testing of a solar dryer for agroindustrial by-products. *Energy Conversion and Management* 51: 1510-1521.
[12] Amer, B.M.A., Hossain, M.A., and Gottshalk, K., 2010. Design and performance evaluation of a new hybrid solar dryer for banana. *Energy Conversion and Management* 51: 813-820.
[13] Condori, M., Echaz, R., and Saravia, L., 2001. Solar drying of sweet pepper and garlic using the tunnel greenhouse drier. *Renewable Energy* 22: 447-460.
[14] Condori, M. and L. Saravia, 1998. The performance of forced convection greenhouse driers. *Renewable Energy* 13: 453-469.
[15] Garg, H.M. and R. Kumar, 2000. Studies on semi-cylindrical solar tunnel dryers: Thermal performance of collector. *Applied Thermal Engineering* 115-131.
[16] Sethi, V.P. and S. Arora, 2009. Improvement in greenhouse solar drying using inclined north wall reflection. *Solar Energy* 83: 1472-1484.
[17] Jain, D., 2005. Modeling the performance of greenhouse with packed bed thermal storage on crop drying application. *Journal of Food Engineering* 71: 170-178.
[18] Farhat, A., Kooli, S., Kerkeni, C., Maalej, M., Fadhel, A., and Belghith, A., 2004. Validation of a pepper drying model in a polyethylene tunnel greenhouse. *International Journal of Thermal Sciences* 43: 53-58.
[19] Kumar, A. and G.N. Tiwari, 2006. Thermal modeling of a natural convection greenhouse drying system for jaggery: an experimental validation. *Solar Energy* 80: 1135-1144.
[20] Barnwal, P. And G.N. Tiwari, 2008. Grape drying using hybrid photovoltaic-thermal greenhouse dryer: an experimental study. *Solar Energy* 82: 1131-1144.
[21] Janjai, S., Lamlert, N., Intawee, P., Mahayothee, B., Bala, B.K., Nagle, M., and Muller, J., 2009. Experimental and simulation performance of a PV-ventilated solar greenhouse dryer for drying of peeled longan and banana. *Solar Energy* 83:1550-1565.
[22] Doiebelin, E.O., 1976. *Measurement Systems*. McGraw Hill, New York.
[23] Holman, J.P., 1978. *Experimental Method for Engineers*. McGraw Hill, New York.
[24] Schenck, H., and R.J. Hawks, 1979. *Theories of Engineering Experimentation.* McGraw Hill, New York.
[25] Duffie, J.A. and W.A. Beckman, 1991. *Solar Engineering of Thermal Processes.* John Wiley and Sons, New York.
[26] Kays, W.M. and M.E. Crawford, 1980. *Convective Heat and Mass Transfer*. McGraw Hill, New York.
[27] Tiwari, G.N., 2003. *Greenhouse Technology for Controlled Environment*. Narosa Publishing House. New Delhi, India.
[28] Hossain, M.A., 2003. *Forced convection solar drying of chili.* Ph.D. thesis, Bangladesh Agricultural University, Mymensingh, Bangladesh.
[29] Smitabhindu, R., 2008. *Optimization of a solar-assisted drying system for drying bananas*. Ph.D. Thesis, Kasetsart University, Bangkok, Thailand.
[30] Audsley, E.and J. Wheeler, 1978. The annual cost of machinery calculated actual cash flows. *Journal of Agricultural Engineering Research* 23: 189-201.
[31] O'Callaghan, J.R., Menzies, D.J., and Bailey, P.H., 1971. Digital simulation of agricultural drier performance. *Journal of Agricultural Engineering Research* 16: 223-244.