Experimental performance and modeling of a greenhouse solar dryer for drying macadamia nuts

S. Janjai, C. Phusampao, W. Nilnont, P. Pankaew

Abstract— This paper presents experimental performance and modeling of a greenhouse solar dryer for drying macadamia nuts. The dryer consists of a parabolic roof structure covered by polycarbonate sheets on a concrete floor. Dimension of the dryer is 9 m in width, 12.4 m in length and 3.45 m in height. Six 15-W DC fans powered by two 50-W PV modules were used to ventilate the dryer. The dryer was installed at a macadamia nut producer in Loei Province, Thailand. To investigate its performance, the dryer was used to dry six batches of macadamia nuts. For each batch, 730 kg of in-shell macadamia nuts was dried in the dryer. Results obtained from this investigation showed that drying air temperatures in the dryer varied from 30°C to 65°C. The drying time for macadamia nuts was within 5 days and good quality dried product was obtained. To model the performance of the greenhouse solar dryer, a system of partial different equations describing heat and moisture transfer during drying of the macadamia nuts in the dryer was formulated. This system of partial differential equations was solved numerically using the finite difference method. The simulation results agreed well with the experimental data for solar drying of the macadamia nuts. The estimated of payback period of the dryer is 1 year.

Index Terms— Solar energy, Solar drying, Macadamia nuts, Greenhouse solar dryer.

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1 INTRODUCTION

THE macadamia nut (*Macadamia integrifolia*) is a commercially cultivated food crop that originates from Australia [1]. In Thailand, macadamia tree plantation areas are mainly located in northern and northeastern parts of the country. The macadamia nut was introduced to grow in upland areas in Thailand 40 years ago. Generally, fresh macadamia nuts have high moisture content which is the cause of mold and germination during processing and storage.

Situated in the tropics, Thailand receives abundant solar radiation [2]. Consequently, the use of solar dryers is a good alternative solution of the problem of macadamia nut drying. Although several types of solar dryers have been developed in the last 40 years [3], [4], [5], [6], [7], [8], most of them have small loading capacity which could not meet the demand. Having realized this demand, our research group has developed a polycarbonate sheet-covered greenhouse solar dryer. In this work, the dryer was used to dry macadamia nuts and its performance is reported. In addition, a simulation model of this dryer for drying macadamia nuts was also developed and the experimental results were used to validate the performance of the model.

2 MATERIALS AND METHODS

2.1 Experimental Setup

The greenhouse solar dryer was installed at Loei, Thailand. The dryer consists of a parabolic roof structure made from polycarbonate sheets on a concrete floor. Dimension of the dryer is 9 *m* in width, 12.4 *m* in length and 3.45 *m* in height. To ventilate the dryer, six DC fans operated by two 50-*W* solar cell modules were installed in the wall opposite to the air inlet. The pictorial view of the dryer is shown in Fig. 1. The product dried inside the dryer is shown in Fig. 2.

Solar radiation passing through the polycarbonate roof heats the product in the dryer and the concrete floor. Ambient air is drawn in through an air-inlet at the bottom of the front side of the dryer and is heated by the floor and the products exposed to solar radiation. Direct exposure to solar radiation of the products and the heated air enhance the drying rate of the products. Moist air passing through and over the products is sucked from the dryer by the fans at the top of the rear side of the dryer. Due to the utilization of the PV ventilated system, this type of greenhouse solar dryer can be used in rural areas without electricity grids.

2.2 Experimental Procedure

In this study, macadamia nuts were dried in the greenhouse solar dryer to investigate the dryer potential. The experimental runs were conducted during June, 2013 - February, 2014. Solar radiation was measured by a pyranometer (Kipp&Zonen, model CM 11) placed on the roof of the dryer. Thermocouples (K type) were used to measure air temperatures in the different positions of the dryer. A hot wire anemometer (Airflow, model TA5) was used to monitor the air

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speed inside the dryer. The relative humidity of ambient air and drying air were periodically measured by hygrometers (Electronnik, model EE23). The positions of all measurements are shown in Fig. 3. Measured data from the pyranometer, hygrometers and thermocouples were automatically 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.

Six batches of drying test were carried out. For each batch, 730 *kg* of in-shell macadamia nuts was placed on the trays inside the dryer. Each day, the experiment was started at 8:00 am and lasted until 6:00 pm. The drying was continued on subsequent days until the desired moisture content was reached. Product samples were placed at various positions in the dryer and were weighed periodically at two hour intervals using a digital balance (Kern, model 474 – 42). Product samples about 130 *g* from the dryer were weighed at two hour intervals. At the end of the experimental drying, the exact dry solid weight of the product samples was determined by the oven method (103°C for 24 hours). The moisture content during drying was estimated from the weight of the product samples and the estimated dried solid mass of the samples.

Fig. 1. The pictorial view of polycarbonate-covered greenhouse solar dryer, from the front side

Fig. 2. Macadamia nuts inside the dryer

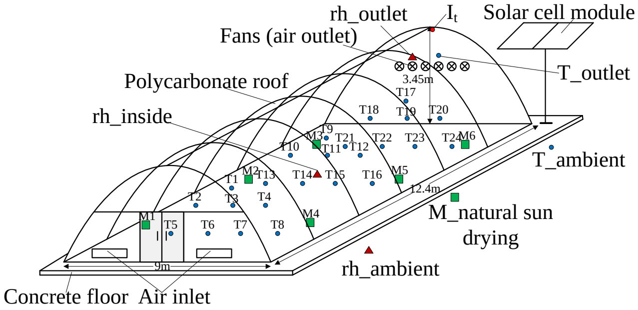

Fig. 3. Structure of the dryer and position of thermocouples (● T), hygrometer (▲ rh), solar radiation (● I_t) and product samples for determining moisture content (🟩 M)

3 MODELING

To facilitate the modeling of the dryer, the following assumptions are made. These are: 1) there is no stratification of air inside the dryer, 2) drying calculation is based on a thin layer drying model and 3) specific heat of air, cover and product is constant. Heat and mass transfer is schematically shown in Fig. 4 and heat and mass balances are formulated as follows.

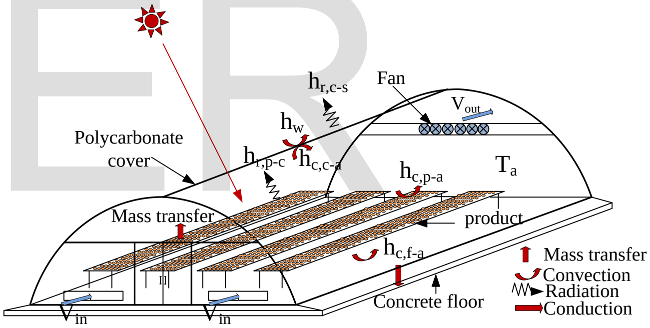

Fig. 4. The schematic diagram showing heat and mass transfers

3.1 Energy balance of the cover

The balance of energy on the polycarbonate cover is considered as: 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 cover gives:

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

where m_c is mass of the cover (*kg*), A_c is the cover area (m^2), A_p is the product area (m^2), $h_{c,c-a}$ is convective heat transfer coefficient between the cover and the air in the greenhouse dryer ($Wm^{-2}K^{-1}$), $h_{r,c-s}$ is radiative heat transfer coefficient between the cover and the sky ($Wm^{-2}K^{-1}$), h_w is convective heat transfer coefficient between the cover and ambient air due to wind ($Wm^{-2}K^{-1}$), $h_{r,p-c}$ is radiative heat transfer coefficient between the product and cover ($Wm^{-2}K^{-1}$). C_{pc} is specific heat of cover ($Jkg^{-1}K^{-1}$), T_a is the drying air temperature (*K*), T_c is the cover temperature (*K*), T_s is the sky temperature (*K*), T_{am} is the ambient temperature (*K*), T_p is the temperature of the product (*K*), I_t is the solar radiation (Wm^{-2}), α_c is the absorptance of the cover (*decimal*).

3.2 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 of the air inside the greenhouse chamber gives:

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

where m_a is mass of the polycarbonate cover (*kg*), C_{pa} is specific heat of air in the product ($Jkg^{-1}K^{-1}$), A_f is floor area (m^2), A_p is product area (m^2), M_p is the moisture content of product in the dryer model (*db, decimal*), ρ_a is density of air (kgm^{-3}), v_{in} is inlet air flow rate (m^3s^{-1}), v_{out} is outlet air flow rate (m^3s^{-1}), $h_{c,p-a}$ is convective heat transfer coefficient between the product and the drying air ($Wm^{-2}K^{-1}$), $h_{c,f-a}$ is convective heat transfer coefficient between the floor and the drying air ($Wm^{-2}K^{-1}$), T_f is temperature of the floor (*K*), T_{in} is temperature of the air at the inlet air of the dryer (*K*), T_{out} is temperature of the air at the outlet of the dryer (*K*), C_{pv} is the specific heat of water vapour ($Jkg^{-1}K^{-1}$), D_p is the average distance between the cover and the product (*m*), F_p is fraction of solar radiation falling on the product (*decimal*), U_c is overall heat loss coefficient from the cover to ambient air ($Wm^{-2}K^{-1}$), τ_c is transmittance of the cover (*decimal*), α_p is absorptance of the product (*decimal*), α_f is absorptance of the floor (*decimal*).

3.3 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:

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

where m_p is mass of product (macadamia nuts) (*kg*), C_{pg} is the specific heat of air in the dryer ($Jkg^{-1}K^{-1}$), C_{pl} is the specific heat of liquid in the product ($Jkg^{-1}K^{-1}$), ρ_p is density of product (kgm^{-3}), L_p is the latent heat of evaporation of the product (Jkg^{-1}).

3.4 Energy balance 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. The energy balance of the floor can be written as:

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

where m_f is mass of floor (*kg*), $h_{D,f-g}$ is conductive heat transfer between the floor and the underground ($Wm^{-2}K^{-1}$), C_{pf} is specific heat of floor ($Jkg^{-1}K^{-1}$), T_g is ground temperature (*K*).

3.5 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:

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

where ρ_d is density of the dried product (kgm^{-3}), V is speed of the air (ms^{-1}), A_{in} is total cross-sectional area of the air inlets (m^2), A_{out} is total cross-sectional area of the air outlets (m^2), H is humidity ratio ($kgkg^{-1}$), H_{in} is humidity ratio of air entering the dryer ($kgkg^{-1}$), H_{out} is humidity ratio of the air leaving the dryer ($kgkg^{-1}$).

3.6 Heat transfer and heat loss coefficients

Radiative heat transfer coefficient from the cover to the sky ($h_{r,c\text{-}s}$) is calculated as [9]:

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

where σ is Stefan-Boltzmann's constant ($Wm^{-2}K^{-4}$), ε_c is the emittance of cover (*decimal*). Radiative heat transfer coefficient between the product and the cover ($h_{r,p\text{-}c}$) is computed as [9]:

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

where ε_p is emissivity of the product *(decimal)*. Convective heat transfer coefficient from the cover to ambient due to wind

(h_w) is computed as [10]:

$$h_w = 2.8 + 3.0V_w\,, \tag{8}$$

where V_w is wind speed (ms^{-1}). Convective heat transfer coefficient inside the solar greenhouse dryer for either the cover or product and floor is computed from the following relationship [11]:

$$h_{c,f\text{-}a} = h_{c,c\text{-}a} = h_{c,p\text{-}a} = \frac{\mathrm{Nu\ K_a}}{D_h}\,. \tag{9}$$

$\mathrm{K_a}$ is thermal conductivity of air ($Wm^{-1}K^{-1}$). D_h is hydraulic diameter of the dryer (m). Nusselt number (Nu) is computed from the Reynolds number (Re) by using the following relationship [9]:

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

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

$$U_c = \frac{\mathrm{K_c}}{\delta_c}, \tag{11}$$

where $\mathrm{K_c}$ is thermal conductivity of insulation material ($Wm^{-1}K^{-1}$), δ_c is thickness of the cover (m).

3.7 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 used for thin layer drying of macadamia nuts:

$$\frac{M - M_e}{M_0 - M_e} = A\exp(-Kt) + B\exp(-Gt) + C\exp(-Pt), \tag{12}$$

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 K, A, B, C, G and P are given as:

$$K = -1.52690+0.04227T+0.06273rh+0.00022Trh -0.00039T^2-0.00172rh^2\,, \tag{13}$$

$$A = 0.230723+0.021691T-0.083943rh+0.000227Trh -0.000065T^2+0.002117rh^2, \tag{14}$$

$$B = 1.449237+0.014082T-0.187288rh+0.000369Trh -0.000097T^2+0.003759rh^2, \tag{15}$$

$$C = 1.204763-0.077930T+0.062076rh+0.000488Trh +0.000881T^2-0.001223rh^2,. \tag{16}$$

$$G = 1.306501-0.043473T-0.047035rh+0.000092Trh +0.000524T^2+0.001292rh^2, \tag{17}$$

$$P = -0.604983+0.059075T-0.080746rh-0.000750Trh -0.000267T^2+0.002314rh^2, \tag{18}$$

where T is temperature (°C) and rh is relative humidity (%). We also conducted experiments to determine the equilibrium moisture content (M_e) under controlled conditions of temperature and relative humidity. The result is written as:

$$a_w = \frac{1}{1+\left[\dfrac{42.18947\text{-}0.24723\mathrm{T}}{M_e}\right]^{8.60964}}, \tag{19}$$

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.

3.8 Solution procedure

The system of (1-5) is solved numerically using the finite difference technique. On the basis of the drying air temperature and relative humidity inside the drying chamber, the drying parameters K, A, B, C, G, and P and the equilibrium moisture content (M_e) of the product are computed. Using the K, A, B, C, G, P and M_e values, the change in moisture content of the product, ΔM for a time interval Δt are calculated using (12). Next, the system of equations consisting of (1-4) is expressed in the following form for the interval Δt:

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix} \begin{vmatrix} T_c \\ T_a \\ T_p \\ T_f \end{vmatrix} = \begin{vmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \end{vmatrix}. \tag{20}$$

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.

4 COLOUR MEASUREMENT OF DRIED MACADAMIA NUTS

The colour of dried macadamia nut samples was measured by a chromometer (CR-400, Minolta Co., Ltd., Japan) in Commission Internationale d'Eclairage (CIE) chromaticity coordinates. The instrument was standardized each time with a white ceramic plate. Three readings in term of lightness (L^*), a^* (green to red), and b^* (blue to yellow) 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 [12]. Hue angle *(h)* indicating colour combination is defined as:

$$h = \begin{cases} \tan^{-1}(b^*/a^*) & (\text{when } a^* > 0) \\ 180^\circ + \tan^{-1}(b^*/a^*) & (\text{when } a^* < 0) \end{cases} \tag{21}$$

and chroma (C^*) indicating colour saturation is defined as:

$$C^* = (a^{*2} + b^{*2})^{1/2}. \tag{22}$$

The colour of macadamia kernel from greenhouse solar dryer was measured for comparison with dried kernel using box type dryer, heated by Liquefied Petroleum Gas (LPG). The box type dryer is usually used by dried macadamia nut producers in Thailand.

5 ECONOMIC ANALYSIS

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

$$C_T = C_m + C_l, \tag{23}$$

where C_m is the material cost of the dryer and C_l is the labour cost for the construction. The annual cost calculation method proposed by Audsley and Wheeler [13] was used. According to this method, the annual cost can be expressed as:

$$C_{annual} = \left[C_T + \sum_{i=1}^{N}\left(C_{maint,i} + C_{op,i}\right)w^i\right]\left[\frac{w-1}{w\left(w^N-1\right)}\right], \qquad (24)$$

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 of the year i, respectively. w is expressed as:

$$w = \left(100 + i_{in}\right)/\left(100 + i_f\right), \qquad (25)$$

where i_{in} and i_f are the interest rate and the inflation rate in percent, respectively. The operating cost (C_{op}) is the labour cost for operating the dryer ($C_{labour,op}$).

The maintenance cost of the first year was assumed to be 1% of the capital cost. The annual cost per unit of dried product is called the drying cost (Z, $USDkg^{-1}$). It can be written as:

$$Z = \frac{C_{annual}}{M_{dry}}, \qquad (26)$$

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

The payback period was calculated from the following equation:

$$\text{Payback period} = \frac{C_T}{M_{dry}P_d - M_f P_f - M_{dry}Z}, \qquad (27)$$

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 dried product ($USDkg^{-1}$) and P_f is the price of the fresh product ($USDkg^{-1}$).

6 RESULTS AND DISCUSSION

6.1 Experimental results

Six experiment batches were carried out during June, 2013 - February, 2014, each season. The typical results are shown in Fig. 5 - Fig. 8.

Solar radiation was strongly fluctuated in the experimental days (Fig. 5). Air temperature at three different locations inside the dryer and the outside ambient air temperature have different amplitudes of their fluctuation (Fig. 6). The pattern of temperature inside the dryer at different positions was comparable for all locations. Temperatures in these three positions varied between 30-65 °C. Temperatures at each of the locations inside the dryer differed significantly from the ambient air temperature.

Relative humidity at two different positions inside the dryer is lower than the outside ambient air relative humidity with the same pattern of variation (Fig. 7). Relative humidity decreased 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 was a significant difference in relative humidity for all locations inside the dryer compared to relative humidity of the ambient air. The relative humidity of the air inside the dryer was lower than that of the outside ambient air. Hence, the air leaving the dryer had lower relative humidity than that of the ambient air. This indicated that the exhaust air from the dryer still had drying potential for recirculation to dry the product.

The moisture content of macadamia nuts in the solar dryer was reduced from an initial value of 14-16% (wb) to a final value of 2-3% (wb) in 5 days (Fig. 8).

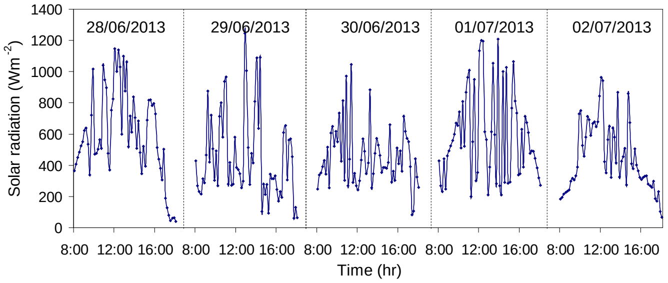

Fig. 5. Variation of solar radiation with time of the day during drying of macadamia nuts

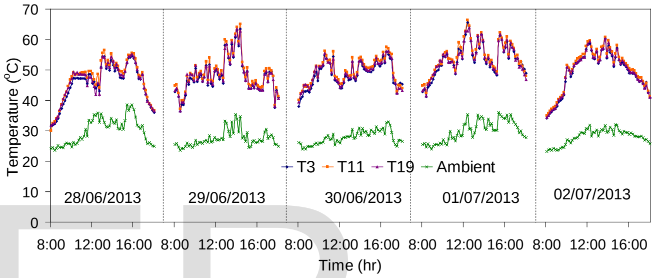

Fig. 6. Variation of ambient temperature and the temperature at different positions inside the greenhouse solar dryer during drying of macadamia nuts

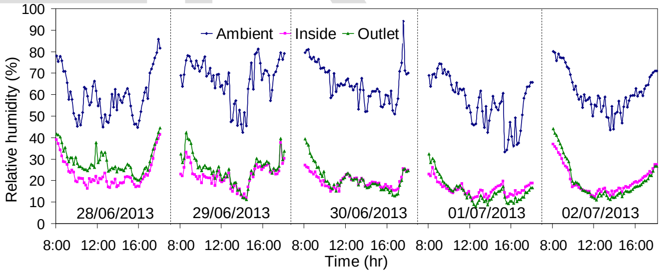

Fig. 7. Temporal variation of ambient relative humidity and relative humidity inside the greenhouse dryer during drying of macadamia nuts

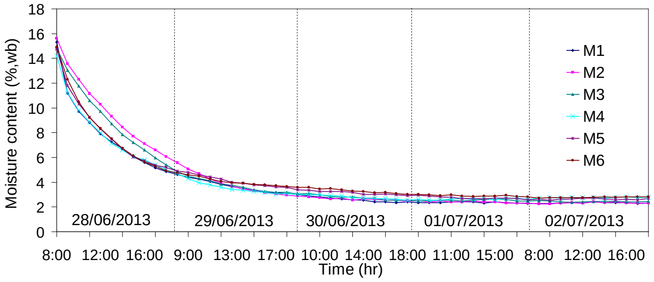

Fig. 8. Temporal variation of the moisture contents of macadamia nuts at different positions inside the greenhouse dryer

6.2 Colour change

The colour of dried macadamia kernels was measured using the chromometer (CR-400, Minolta Co. Ltd, Japan). The colour of the kernel of macadamia nuts dried using the greenhouse solar dryer was compared with that of the kernel of macadamia nuts dried employing the box type dryer (Table 1). The colour of macadamia kernels changed from white to light-cream (L^*=71.61) after having dried using the greenhouse dryer. The colour of the kernels dried using the box type dryer is dark-yellow-brown (L^*=58.76). This comparison indicated that macadamia nuts dried using the greenhouse dryer has better colour than that dried employing the box type dryer [14].

6.3 Food quality

In general, the total fat is the most important parameter indicating food quality of macadamia nuts and the good quality macadamia nuts have to have a total fat in the range of 72.0-78.0 $g(100g)^{-1}$ [15], [16]. The total fat of the macadamia nuts dried by using the greenhouse solar dryer is 75.2 $g(100g)^{-1}$ which implies that these macadamia nuts are in good quality [14].

TABLE 1
COMPARISON OF THE COLOUR KERNEL OF MACADAMIA NUTS DRIED USING THE GREENHOUSE SOLAR DRYER AND THAT DRIED EMPLOYING THE BOX TYPE DRYER

Drying method	Colour value				
	*L**	*a**	*b**	*C**	*h*
Greenhouse solar dryer	71.61	0.13	20.23	20.23	1.56
Box type dryer	58.76	0.17	17.23	17.23	1.56

6.4 Economic result

As there are now several units of this type of dryer being used for production of dried macadamia nuts, information used for economic evaluation is based on the field level data and recent prices of the materials used for construction of the dryers. Data on costs involved and economic parameters are shown in Table 2.

The dryer can be used for 6 months per year for drying macadamia nuts and approximately 3,250 *kg* of dried macadamia kernel is annually obtained. Based on this production and the capital and operating costs of the dryer (Table 2), the drying cost (*Z*) is estimated to be 0.367 $USDkg^{-1}$ and the pay-back period is calculated to be approximately 1 year.

TABLE 2
DATA ON COST AND ECONOMIC PARAMETER

Items	costs and economic parameters
Polycarbonate sheets	2257 *USD*
Solar modules and fans	450 *USD*
Materials of constructions	1285 *USD*
Labour costs for constructions	571 *USD*
Repair and maintenance cost	1% *of capital cost per year*
Operating cost	171 *USD per year*
Price of fresh in shell macadamia nuts	2.03 *USD per kg*
Price of dried macadamia kernels	26.59 *USD per kg*
Expected life of the dryer	15 *years*
Interest rate	7.3%
Inflation rate	2.5%

(1USD = 31.97 Baht)

6.5 Modeling result

The model predicts well the variation of the moisture content during the drying (Fig. 9). Predicted temperature shows plausible behavior, and the predicted and the observed values are in good agreement (Fig. 10).

The model predictions for drying macadamia nuts were evaluated using root mean square difference (RMSD). The RMSD from overall comparison of the simulated temperature in the dryer is 11.8%. The RMSD from overall comparison of the simulated moisture contents is 1.9%. These comparisons indicate that the simulation model can predict the moisture content and the temperature with a reasonable accuracy.

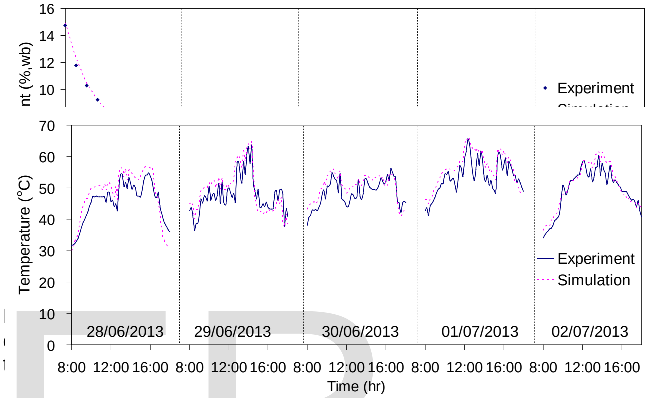

Fig. 10. Comparison between the simulated and observed temperatures inside the greenhouse dryer at the middle position during drying macadamia nuts for a typical experimental run

7 CONCLUSIONS

The system of partial differential equations for heat and moisture transfer has been used for simulation of solar drying of macadamia nuts in the solar greenhouse dryer. From the validation, the simulated air temperature inside the dryer reasonably agreed with the measured temperature. Good agreement was found between the experimental and simulated moisture contents. Simulation using this method is useful for providing data for further design of solar greenhouse dryers.

Solar radiation has high variation through the experiment days. Sinusoidal-like around the peak at noon, the solar radiation influences other ambient parameters of the macadamia. Inside the greenhouse dryer, air temperature variation follows the variation of the solar radiation. The ambient relative humidity varies almost the inverse pattern with the solar radiation. The dried macadamia nuts using the solar greenhouse dryer are high-quality product. The estimated payback periods for drying macadamia nuts using this greenhouse solar dryer is about 1 year.

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