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

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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 differential 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.

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
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.

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.

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:
\[ m_c C_p \frac{dT_c}{dt} = A_c h_{c,a} (T_a - T_c) + A_c h_{c,c} (T_c - T_c) \]
\[ + A_p h_{p,a} (T_p - T_a) + A_p h_{p,c} (T_p - T_c) + A_c \alpha_c I_c, \]
where \( m_c \) is mass of the cover (kg), \( A_c \) is the cover area (m²), \( A_p \) is the product area (m²), \( h_{c,a} \) is convective heat transfer coefficient between the cover and the air in the greenhouse dryer (Wm⁻²K⁻¹), \( h_{c,c} \) is radiative heat transfer coefficient between the cover and the sky (Wm⁻²K⁻¹), \( h_{p,a} \) is convective heat transfer coefficient between the product and cover (Wm⁻²K⁻¹), \( h_{p,c} \) is radiative heat transfer coefficient between the cover and the sky (Wm⁻²K⁻¹), \( T_a \) is the inlet air temperature of the dryer (K), \( T_c \) is the cover temperature (K), \( T_p \) is the temperature of the product (K), \( I_c \) is the solar radiation (Wm²), \( \alpha_c \) 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 + Convection + Rate of thermal energy transfer between the floor and the air due to convection + Rate of thermal energy gained by 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:

\[ m_a C_p \frac{dT_a}{dt} = A_p h_{p,a} (T_p - T_a) + A_p h_{p,c} (T_p - T_c) \]
\[ + D_p A_p h_{p,a} \left( T_p - T_a \right) \frac{dM_p}{dt} \]
\[ + \rho_{v, out} C_p \left( T_{out} - T_{in} \right) \frac{dV}{dt} + \frac{1}{1 - F_p} \left( \frac{1}{1 - \alpha_f} \right) \frac{1}{1 - \alpha_p} \left( T_p - T_c \right) \frac{dM_p}{dt}, \]

where \( m_a \) is mass of the polycarbonate cover (kg), \( C_p \) is specific heat of air in the dryer (Jkg⁻¹K⁻¹), \( A_f \) is floor area (m²), \( A_p \) is product area (m²), \( M_p \) is the moisture content of product (kg), \( dM_p/dt \) is the rate of moisture gain from the air in the dryer, \( F_p \) is convective heat transfer coefficient between the floor and the underground (Wm⁻²K⁻¹), \( h_{p,a} \) is convective heat transfer coefficient between the floor and the underground (Wm⁻²K⁻¹), \( h_{p,c} \) is convective heat transfer coefficient between the cover and the floor (Wm⁻²K⁻¹), \( T_f \) is temperature of the floor (K), \( T_{out} \) is temperature of the air at the outlet of the dryer (K), \( T_{in} \) is temperature of the air at the inlet of the dryer (K), \( \rho_{v, out} \) is density of air (kgm⁻³), \( V \) is speed of the air (m²s⁻¹), \( T_{in} \) is total cross-sectional area of the air inlets (m²), \( A_{out} \) is total cross-sectional area of the air outlets (m²), \( H \) 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).

### 3.3 Energy balance of the product

Rate of accumulation 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:

\[ m_p \left( C_{ps} + C_p M_p \right) \frac{dT_p}{dt} = A_p h_{p,a} \left( T_p - T_a \right) + A_p h_{p,c} \left( T_p - T_c \right) \]
\[ + D_p A_p \rho_{v, out} \left( T_{out} - T_{in} \right) \frac{dM_p}{dt} + \frac{1}{1 - F_p} \left( \frac{1}{1 - \alpha_f} \right) \frac{1}{1 - \alpha_p} \left( T_p - T_c \right) \frac{dM_p}{dt}, \]
where \( m_p \) is mass of product (macadamia nuts) (kg), \( C_{ps} \) is the specific heat of air in the dryer (Jkg⁻¹K⁻¹), \( C_p \) is the specific heat of liquid in the product (Jkg⁻¹K⁻¹), \( \rho_p \) is density of product (kgm⁻³), \( L_a \) 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:

\[ m_f C_{pf} \frac{dT_f}{dt} = A_f h_{f,a} \left( T_a - T_f \right) \]
\[ + A_f h_{f,g} \left( T_g - T_f \right) \]
\[ + \left( 1 - F_p \right) \left( 1 - \alpha_f \right) A_f \left( T_p - T_f \right), \]
where \( m_f \) is mass of floor (kg), \( h_{f,g} \) is conductive heat transfer coefficient between the floor and the underground (Wm⁻²K⁻¹), \( C_{pf} \) is specific heat of floor (Jkg⁻¹K⁻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:

\[ \rho_p V \frac{dH}{dt} = \rho_a \rho H_{in} V_{in} - \rho_a \rho H_{out} V_{out} + D_p A_p \rho_{v, out} \frac{dM_p}{dt}, \]

where \( \rho_p \) is density of the dried product (kgm⁻³), \( V \) is speed of the air (m²s⁻¹), \( H_{in} \) is total cross-sectional area of the air inlets (m²), \( A_{out} \) is total cross-sectional area of the air outlets (m²), \( H \) is humidity ratio (kgkg⁻¹), \( H_{out} \) is humidity ratio of air entering the dryer (kgkg⁻¹), \( H_{in} \) 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_{c,c}) is calculated as [9]:

\[ h_{c,c} = \varepsilon_c \sigma (T_c^2 + T_s^2) (T_c + T_s), \]

where \( \sigma \) is Stefan-Boltzmann’s constant (Wm⁻²K⁻⁴), \( \varepsilon_c \) is the emittance of cover (decimal). Radiative heat transfer coefficient between the product and the cover (h_{p,c}) is computed as [9]:

\[ h_{p,c} = \varepsilon_p \sigma (T_p^2 + T_c^2) (T_p + T_c), \]

where \( \varepsilon_p \) 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]:
\[
 h_{c,f,a} = h_{c,f,a} = \frac{Nu K_a}{D_b}. \tag{9}
\]
\( K_a \) is thermal conductivity of air (Wm\(^{-1}\)K\(^{-1}\)), \( D_b \) is hydraulic diameter of the dryer (m). Nusselt number (Nu) is computed from the Reynolds number (Re) by using the following relationship [9]:
\[
 Nu = 0.158Re^{0.8}. \tag{10}
\]
The overall heat loss coefficient from the greenhouse cover \( (U_c) \) is computed from the following relation:
\[
 U_c = \frac{K_g}{\delta_c}. \tag{11}
\]
where \( K_g \) is thermal conductivity of insulation material (Wm\(^{-1}\)K\(^{-1}\)), \( \delta_c \) 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:
\[
 M - M_e = A \exp(-Kt) + B \exp(-Gt) + C \exp(-Pt), \tag{12}
\]
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 \( K, A, B, G, \) and \( P \) are given as:
\[
 K = -1.52690 + 0.042273 rh + 0.000222 Trh - 0.0003976 - 0.00172 rh^2, \tag{13}
\]
\[
 A = 0.230723 + 0.021691 T - 0.0083943 rh + 0.0002227 Trh - 0.0000657 + 0.0012117 rh^2, \tag{14}
\]
\[
 B = 1.449273 + 0.0140827 + 0.187288 rh + 0.000369 Trh - 0.0000977 + 0.0037275 rh^2, \tag{15}
\]
\[
 C = 1.204763 - 0.077930 T + 0.062076 rh + 0.000488 Trh + 0.000387 + 0.001223 rh^2, \tag{16}
\]
\[
 G = 1.306501 - 0.0434737 + 0.047035 rh + 0.000927 Trh + 0.0005247 + 0.001922 rh^2, \tag{17}
\]
\[
 P = -0.649803 + 0.0590735 - 0.080746 rh - 0.000750 Trh - 0.000267 + 0.002314 rh^2, \tag{18}
\]
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:
\[
 a_w = \left[ \frac{1}{1 + \left( \frac{24.18947 - 0.24723 T}{M_e} \right)^{8.60964}} \right]. \tag{19}
\]
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 \( K, A, B, G, \) and \( P \) and the equilibrium moisture content \( (M_e) \) of the product are computed. Using the \( K, A, B, G, \) and \( P \) and the \( M_e \) values, the change in moisture content of the product, \( \Delta M \) for a time interval \( \Delta t \) are calculated using (12). Next, the system of equations consisting of (1-4) is expressed in the following form for the interval \( \Delta t \):
\[
 \begin{bmatrix}
 a_{11} & a_{12} & a_{13} & a_{14} & T_1 \\
 a_{21} & a_{22} & a_{23} & a_{24} & T_2 \\
 a_{31} & a_{32} & a_{33} & a_{34} & T_3 \\
 a_{41} & a_{42} & a_{43} & a_{44} & T_4 \\
 a_{51} & a_{52} & a_{53} & a_{54} & T_5 \\
 \end{bmatrix}
 = \begin{bmatrix}
 b_1 \\
 b_2 \\
 b_3 \\
 b_4 \\
 b_5 \\
 \end{bmatrix}. \tag{20}
\]
This system of equations is a set of implicit calculations for the time interval \( \Delta t \). 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 \( (\Delta M) \) 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:
\[
 h = \tan^{-1} (b^* / a^*) \quad \text{(when } a^* > 0) \tag{21}
\]
\[
 180^\circ + \tan^{-1} (b^* / a^*) \quad \text{(when } a^* < 0) \tag{22}
\]
and chroma \( (C^*) \) indicating colour saturation is defined as:
\[
 C^* = (a^{*2} + b^{*2})^{1/2}. \tag{23}
\]

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:
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-yellow-brown ($L^*=71.61$) 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].

### 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 payback period is calculated to be approximately 1 year.

### 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.

### 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 hu-
midity 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.

References


