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Experimental performance and mathematical modeling of a large-scale greenhouse solar dryer for drying orchids at Kanchanaburi Province Thailand

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Abstract

This research presents heat and mass transfers modeling of a large-scale greenhouse solar dryer for drying orchids at Kanchanaburi Province, Thailand. Ten batches of orchids drying, for each batch used 2,000 kg of orchids. The parameter used in the heat and mass transfers model is the solar radiation, air temperature, relative humidity, airflow rate and equilibrium moisture content form thin layer drying process. The numerical solution was programmed in Compaq Visual FORTRAN version 6.5. The results showed that the moisture content, calculated from the model corresponding to the measured values, the $RMSE$ = 0.42513 and R^2 = 0.9975. The payback period of a large-scale greenhouse solar dryer for drying orchids is estimated to be about 1 year.

Keywords: Large-scale greenhouse solar dryer; mathematical modeling; orchids

1. Introduction

The family Orchidaceae is one of the largest flowering plant families in the world and contains over 20,000 naturally occurring orchid species and approximately 10,000 man-made hybrids. It is generally accepted that orchids have an ancient origin due to their close association with the Liliaceae, Iridaceae and Amarillidaceae families, of the subclass Monocotyledonae. Orchids are thought to have originated in Malaysia in the Cretaceous period and dispersed throughout the Tertiary period, becoming epiphytic in the Plio-pleistocene [1].

Thailand is the number one manufacture and exporter of tropical orchids in the word. The orchid export is 80.20%, mainly *Dendrobium* and the remaining 19.80% is *Phalaenopsis* and *Cymbidium*, respectively. Orchid is an economic product in the product champion group, bringing in revenue from exports. 2,500 – 3,000 million baht per year. The area of cultivation is about 20,000 rai and 300 exporters. In 2017, the central region had 21,261 rai of orchards producing 52,422 tons of cut orchids and orchid plants. Last year, Thailand ranked first in tropical orchid exports, with cut flowers valued at 2.30 billion baht and plants at 422 million. However, export revenue from cut orchids is expected to remain at last year's level despite production being halved, as prices have doubled on high demand and decreased output. The cluster is asking the government to help orchid farms maintain existing production levels while earning even better prices [2].

In traditional Chinese medicine, the orchid was used to help cure coughs and lung illnesses. In ancient Greece, orchids were associated with virility and male fertility, the belief being that if women ate orchid flowers, they would bear a son to continue the family tradition. The highlight of this research is the return of waste (cut orchids or cut flowers) to value, after the completion of the decorations in the event, it will be left as rubbish.

Consequently, the use of solar dryers for orchids drying is reasonable. Although several types of solar dryers have been developed in the last 45 years [3]. They could not meet the high demand of orchids drying. As a result, our research group has developed a greenhouse solar dryer to dry agricultural products. It was successfully used for drying fruits and vegetable [4]. However, it has not been tested to dry orchids. Therefore, the objectives of this research were to investigate the performance of the large-scale greenhouse solar dryer for drying orchids and developed heat and mass transfer modeling of the large-scale greenhouse solar dryer for drying orchids at Kanchanaburi Province because it is an area that has grown a lot of orchids in Thailand.

2. Materials and methods

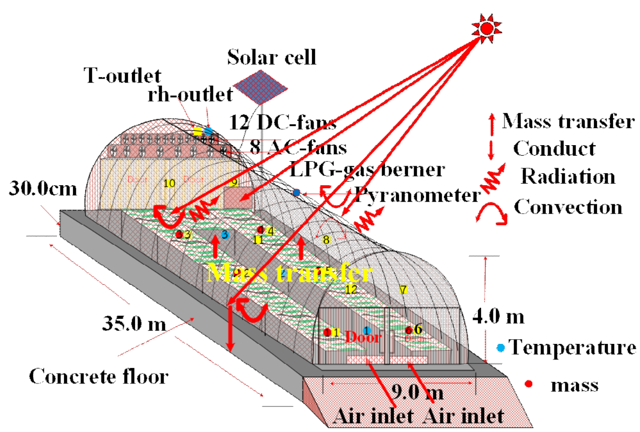
Experimental setup

The large-scale greenhouse solar dryer was installed at Kanchanaburi, 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, 35 m in length and 4 m in height. To ventilate the dryer, twelve DC fans operated by 100W solar cell modules were installed in the wall opposite to the air inlet. The pictorial view of the dryer and the schematic diagram showing heat and mass transfers are shown in Fig. 1. The large-scale greenhouse solar dryer for drying orchids and the orchids were dried in the large-scale greenhouse solar dryer for export and dried orchid for export to China are 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.

The researcher's used data from experiments and mathematic models to develop the dryer for drying orchids. To ensure the continuous drying operation during cloudy or rainy periods, an auxiliary heater using LPG burner as heat source was equipped.

(a)



(b)

Fig. 1 The pictorial view of a large-scale greenhouse solar dryer (a) and the schematic diagram showing heat and mass transfers (b)

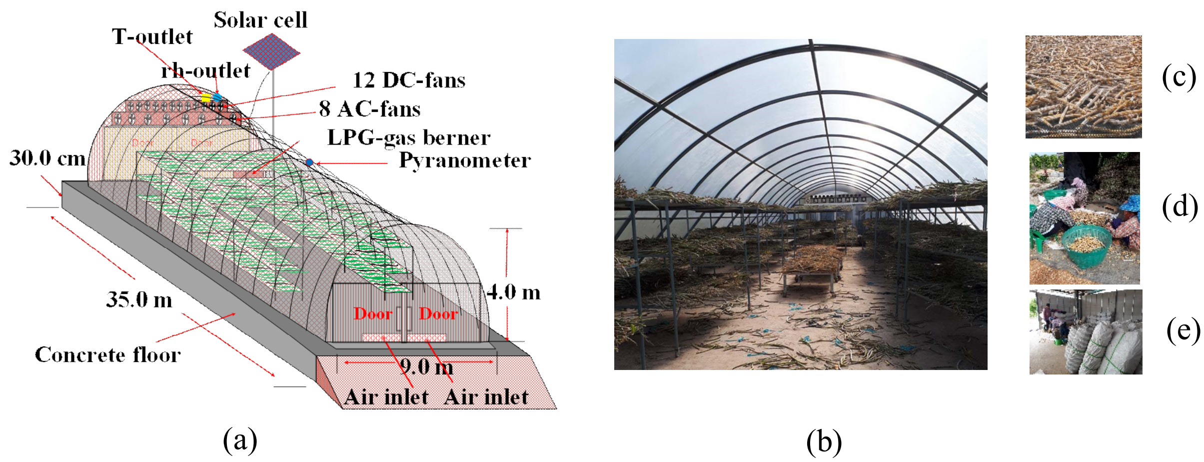


Fig. 2 The large-scale greenhouse solar dryer for drying orchids (a), the orchids were dried in the large-scale greenhouse solar dryer for export (b), dried orchid (c), orchid for export (d), and packet orchid for export (e)

Experimental Procedure

In this study, orchids were dried in the large-scale greenhouse solar dryer to investigate the dryer potential. The experimental runs were conducted during January, 2017 – July, 2018. Solar radiation was measured by a pyranometer (Kipp & Zonen model CMP 3, accuracy ± 0.50%) 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, accuracy ± 2%) was used to monitor the air speed inside the dryer. The relative humidity of ambient air and drying air were periodically measured by hygrometer (Electronnik, model EE23, accuracy ± 2%). 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. Ten batches of drying test were carried out. For each batch, 2,000 kg of orchids 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 (TANITA, model KD-200, accuracy ± 1%). Product samples about 1 kg 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 h, accuracy ± 0.50%). The moisture content during drying was estimated from the weight of the product samples and the estimated dried solid mass of the samples.

Mathematical modeling

Energy balance of the cover

The balance energy of 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 [5 – 8]:

$$\begin{aligned} m_{cover}C_{p,cover}\frac{dT_{cover}}{dt} &= (h_{c,cover\_air}(T_{air}-T_{cover})A_{cover} \\ &+ h_{r,cover\_sky}(T_{sky}-T_{cover})A_{cover} \\ &+ h_{wind,cover\_ambient}(T_{ambient}-T_{cover})A_{cover} \\ &+ (\alpha_{cover}I_t A_{cover})) \end{aligned} \quad (1)$$

Where m_{cover} is mass of the cover (kg), $C_{p,cover}$ is specific heat of cover (J kg^{-1} K^{-1}), T_{cover} is the cover temperature (K), $h_{c,cover\_air}$ is convective heat transfer coefficient between the cover and the air in the greenhouse dryer (W m^{-2} K^{-1}), T_{air} is the drying air temperature (K), A_{cover} is the cover area (m^2), $h_{r,cover\_sky}$ is radiative heat transfer coefficient between the cover and the sky (W m^{-2} K^{-1}), T_{sky} is the sky temperature (K), $h_{wind,cover\_ambient}$ is convective heat transfer coefficient between the cover and ambient air due to wind (W m^{-2} K^{-1}), $T_{ambient}$ is the ambient temperature (K), α_c is the absorptance of the cover (decimal), I_t is the solar radiation (W m^{-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 [5 – 8]:

$$\begin{aligned} m_{product}C_{product}\frac{dT_{air}}{dt} &= A_{product}h_{c,product-air}(T_{floor}-T_{air}) \\ &+ D_{product}A_{product}C_{product}\alpha_{product}(T_{product}-T_{air})\frac{dM_{product}}{dt} \\ &+ (\rho_{air}\mathrm{v}_{outlet}C_{product-air}T_{outlet}-\rho_{air}\mathrm{v}_{inlet}C_{product-air}T_{inlet}) \\ &+ U_{cover}A_{cover}(T_{ambient}-T_{air}) \\ &+ [(1-F_{product})(1-\alpha_{floor})+(1-\alpha_{product})F_{product}]I_t A_{cover}\tau_{cover} \end{aligned} \quad (2)$$

Where $m_{product}$ is mass of the product (kg), $C_{product}$ is specific heat of air in the product (J kg^{-1} K^{-1}), $A_{product}$ is product area (m^2), $h_{c,product-air}$ is convective heat transfer coefficient between the product and the drying air (W m^{-2} K^{-1}), T_{floor} is temperature of the floor (K), $D_{product}$ is the average distance between the cover and the product (m), $\alpha_{product}$ is the absorptance of the product (decimal), $T_{product}$ is temperature of the product (K), $M_{product}$ is the moisture content of product in the dryer model (db, decimal), ρ_{air} is density of air (kg m^{-3}), v_{out} is outlet air flow rate (m^3 s^{-1}), $C_{product-air}$ is specific heat of air in the product (J kg^{-1} K^{-1}), T_{outlet} is temperature of the air at the outlet of the dryer (K), v_{in} is inlet air flow rate (m^3 s^{-1}), T_{in} is temperature of the air at the inlet air of the dryer (K), U_{cover} is overall heat loss coefficient from the cover to ambient air (W m^{-2} K^{-1}), $F_{product}$ is fraction of solar radiation falling on the product (decimal), α_{floor} is absorptance of the floor (decimal), τ_{cover} is transmittance of the cover (decimal).

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 [5 – 8]:

$$
\begin{aligned}
m_{product}(C_{pg}+C_{pl}M_{product})\frac{dT_{product}}{dt} &= A_{product}h_{c,product-air}(T_{air}-T_{product}) \\
&+ A_{product}\,h_{r,product-cover}(T_{cover}-T_{product}) \\
&+ D_{product}A_{product}\rho_{product}L_{product} \\
&+ C_{pv}(T_{air}-T_{product})\frac{dM_{product}}{dt} \\
&+ F_{product}\alpha_{product}I_tA_{cover}\tau_{cover}
\end{aligned}
\tag{3}
$$

Where $m_{product}$ is mass of product (kg), C_{pg} is the specific heat of air in the dryer (J kg^{-1} K^{-1}), C_{pl} is the specific heat of liquid in the product (J kg^{-1} K^{-1}), $\rho_{product}$ is density of product (kg m^{-3}), $L_{product}$ is the latent heat of evaporation of the product (J kg^{-1} K^{-1}).

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 [5 – 8]:

$$
\begin{aligned}
m_{floor}C_{pf}\frac{dT_{floor}}{dt} &= A_{floor}h_{c,floor\text{-}air}(T_{air}-T_{floor}) \\
&+ A_{floor}h_{D,floor\text{-}underground}(T_{underground}-T_{floor}) \\
&+ (1-F_{product})\alpha_{floor}I_tA_{floor}\tau_{cover}
\end{aligned}
\tag{4}
$$

Where m_f is mass of floor (kg), $h_{D,floor\text{-}underground}$ is conductive heat transfer between the floor and the underground (W m^{-2} K^{-1}), C_{pf} is specific heat of floor (J kg^{-1} K^{-1}), $T_{underground}$ is ground temperature (K).

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 [5 – 8]:

$$\rho_{air} v \frac{dH}{dt} = A_{in} \rho_{air} H_{in} v_{in} - A_{out} \rho_{air} H_{out} v_{out} + D_{product} A_{product} \rho_{dry\ product} \frac{dM_{product}}{dt} \quad (5)$$

Where v is speed of the air (m s^{-1}), A_{in} 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 (kg kg^{-1}), H_{in} is humidity ratio of air entering the dryer (kg kg^{-1}), H_{out} is humidity ratio of the air leaving the dryer (kg kg^{-1}) and $\rho_{dry\ product}$ is density of the dried product (kg m^{-3}).

Solution procedure

The system of Eqs (1) – (5) are solved numerically using the finite difference technique. The time interval should be small enough for the air conditions to be constant, but for the economy of computing, a compromise between the computing time and accuracy must be considered. On the basis of the drying air temperature and relative humidity inside the drying chamber, the drying parameters A, B, E, K, G, P and the equilibrium moisture content (M_e) of the product are computed. Using the A, B, E, K, G, P and M_e values, the change in moisture content of the product, ΔM for a time interval, Δt are calculated using Eqs (6). Next, the system of equations consisting of Eqs. (1), (2), (3) and (4) are expressed in the following form for the interval Δt.

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix} \begin{vmatrix} T_{cover} \\ T_{air} \\ T_{product} \\ T_{floor} \end{vmatrix} = \begin{vmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \end{vmatrix} \quad (6)$$

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. Performance Analysis, three statistical parameters were used for performance analysis. Root mean square error ($RMSE$), and determination coefficient (R^2) of agreement were computed to estimate the overall model performance.

Fig. 3. Shown the schematic diagram of mathematical modeling of a large-scale greenhouse solar dryer for drying orchids.

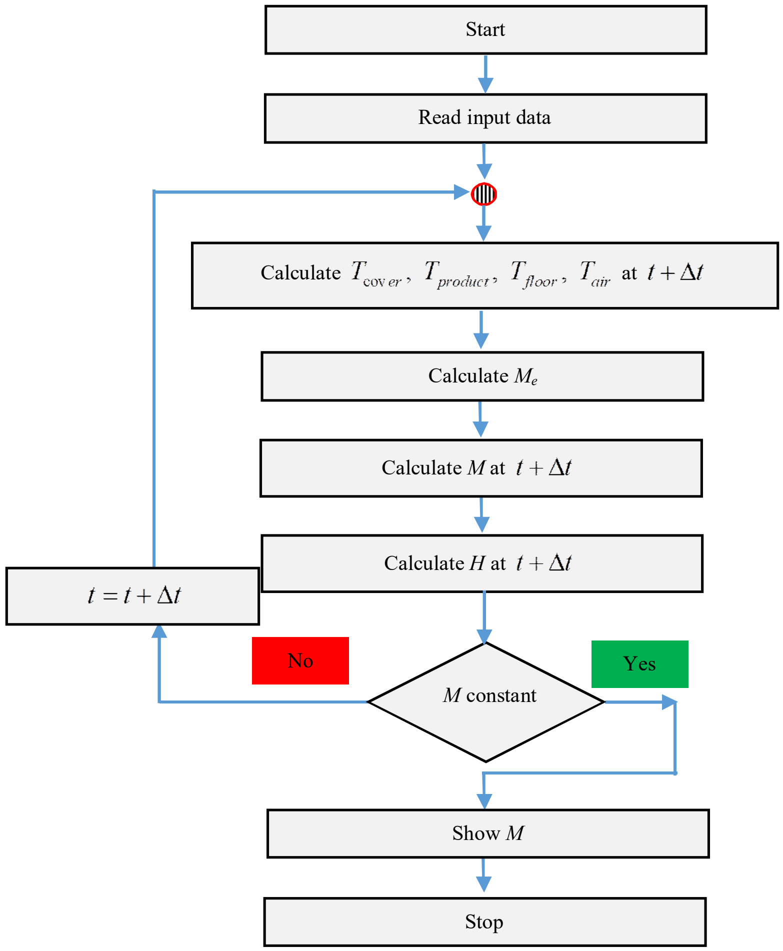


Fig. 3 The schematic of mathematical modeling of a large-scale greenhouse solar dryer for drying orchids

Economic analysis

The total capital cost for the large-scale greenhouse solar dryer C_T is given by the following equation, where C_m is the material cost of the dryer and C_l is the labor cost for the construction. The annual cost calculation method proposed by Audsley and Wheeler yields [9 – 10]:

$$C_{annual} = \left[C_T + \sum_{i=1}^{N} \left(C_{maint,i} + C_{op,i} \right) w^i \right] \left[\frac{w-1}{w\left(w^N - 1\right)} \right] \quad (7)$$

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. w is expressed as; where i_{in} and i_f are the interest rate and the inflation rate in percent, respectively. The operating cost (C_{op}) is the labor 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, USD kg^{-1}). It can be written as:

$$\text{Payback period} = \frac{C_T}{M_{dry}P_{dry} - M_{fresh}P_{fresh} - M_{dry}Z} \tag{8}$$

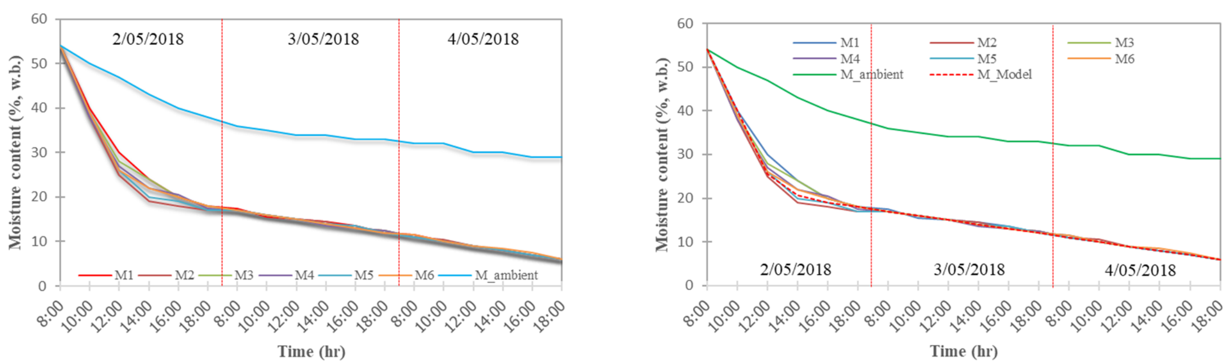
Where M_{dry} is the dried product obtained from this dryer per year (kg), M_{fresh} is the amount of fresh product per year (kg), P_{dry} is the price of the dry product (USD kg^{-1}) and P_{fresh} is the price of the fresh product (USD kg^{-1}).

3. Results and Discussion

Experimental results

Drying experiments of orchids in the large-scale greenhouse solar dryer were carried out in January, 2017 – July, 2018. Ten batches of experimental run were carried out. The comparison of air temperature at six different locations inside the dryer and the ambient air temperature for the experimental runs of solar drying of orchids. The pattern of temperature change in different positions was comparable for all locations. Temperatures in different positions at these six locations varied within a narrow band. In addition, temperatures at each of the locations differed significantly from the ambient air temperature. Relative humidity at three different positions inside the dryer is lower than the outside ambient air relative humidity with the same pattern of variation. 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. Airflow rate of the large-scale greenhouse solar dryer for drying orchid is 29 – 1, 800 (m^3 s^{-1}).

Fig. 4(a): The comparison of moisture content at six different locations inside the dryer and the open sun drying for the experimental runs of solar drying of orchids. The moisture content of orchids in the large-scale greenhouse solar dryer was reduced from an initial value of 55% (w.b.) to a final value of 7 – 8% (w.b.) within 3 days whereas the moisture content of the open sun-dried samples was reduced to 20% (w.b.) in the same period.



(a) (b)

Fig. 4 Variation of the moisture contents (a) and comparison of moisture content (b)

Modeling results

In this work, the researcher designed as follows: 1. The floor of the dryer; by letting the edge of the dryer floor on every side up 10 centimeters to prevent water from entering and retain the heat. 2. Adjust the air inlet to be smaller so that the air flow rate decreases, resulting in higher heat inside the dryer.

Fig. 4(b): The model predicts well the variation of the moisture content during the drying. The $RMSE$ and R^2 from overall comparison of the simulated moisture content are 0.42513 and 0.9975 respectively.

Economic Evaluation

As there are now several units of this type of dryer are being used for production of dried orchids, information used for economic evaluation is based on the field level data and recent prices of the materials used for construction of the dryers [9 – 10]. Data on costs involved and economic parameters are shown in Table 1. In term of economic evaluation, the capital cost for construction and installation of the large-scale greenhouse solar dryer is estimated to be USD 30,000 (1 USD = 31.97 baht; 11-05-2018). It is estimated that 240,000 kg of dry orchids are produced annually. Based on these production scales, capital and operating costs, the payback period of the large-scale greenhouse solar dryer for drying orchids is estimated to be about 1 year.

Table 1 Data on costs involved and economic parameters

Items	Costs and Economic Parameters
Polycarbonate plates	2,500 USD
Solar modules and fans	600 USD
Materials of constructions	23,700 USD
Labor costs for constructions	3,200 USD
Repair and maintenance cost	1% of capital cost per year
Operating cost	1,500 USD per year
Price of fresh orchids	0.187 USD kg^{-1}
Price of dried orchids	5.0 USD kg^{-1}
Expected life of the dryer	15 years
Interest rate	1.50% (Bank of Thailand)
Inflation rate	1.46% (Bank of Thailand)

4. Conclusion

Ten sets of full scale field level drying runs for drying of orchids were conducted and the temperature of the drying air varied from 29 °C to 65 °C during drying. This drier can be used to dry up to 2,000 kg of fresh orchids. The orchids dried in the large-scale greenhouse solar dryer were completely protected from rain, insects and dust, and the dried orchids were a high-quality product. The performance of the large-scale greenhouse solar dryer for drying orchids has been experimentally investigated. The moisture content of orchids in the large-scale greenhouse solar dryer was reduced from an initial value of 55% (w.b.) to a final value of 7 – 8% (w.b.) within 3 days whereas the moisture content of the open sun-dried samples was reduced to 20% (w.b.) in the same period. The payback period of the large-scale greenhouse solar dryer for drying orchids is estimated to be about 1 year.

A system of equations for heat and mass transfer has been developed for solar drying of orchid in a large-scale greenhouse solar dryer. The simulated air temperatures inside the dryer reasonably agreed with the observed temperature data. Reasonable agreement was found between the experimental and simulated moisture contents of orchid during drying and the accuracy was within the acceptable range. This model can be used for providing design data for the greenhouse solar dryer and also for optimization of this type of solar dryer.

5. Acknowledgements

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