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Development, Design, and Performance of a PV-Ventilated Greenhouse Dryer

S. Janjai*[1], V. Khamvongsa*, and B.K. Bala[+]

Abstract – *A PV-ventilated greenhouse solar dryer was developed. The basement of the dryer is a black concrete floor with an area of 5.5×8.0 m^2. The roof of the dryer was covered with polycarbonate plates and it was designed in the parabolic shape of facilitate the construction. Three fans powered by a solar cell module of 53 W were used to ventilate the dryer. To investigate its performance, the dryer was used to dry 4 batches of chilies during December, 2003 to March, 2004. The air temperature inside the dryer was 60-65°C at the noon of a clear day. High drying air temperature with reasonably low relative humidity inside the dryer during almost whole period of the day demonstrated the potentiality of solar drying inside the greenhouse dryer. The temperatures at three locations (top, middle and bottom) inside the dryer follow the similar pattern. Heat stored in the concrete floor helped to reduce variation of drying air temperature due to the fluctuation of solar radiation. The use of solar cell module helps to regulate indirectly the drying air temperature. The results from the experiments demonstrate that the drying time for drying of 100-150 kg of chilies in the dryer was significantly less than that required for natural sun drying but the drying efficiency increases with loading capacity. The chilies being dried in this PV-ventilated greenhouse dryer was completely protected from insects, animals and rain and good qualities of dried chilies in terms of colour and texture were obtained. The payback period of dryer was estimated to be 3.36 years. To disseminate this type of dryer, two more units of the greenhouse dryer were constructed and used for drying banana and green tea at two locations in Thailand. Users of these dryers were satisfied with the performance of the dryers.*

Keywords – Chilies, greenhouse dryer, PV-ventilation, solar drying, solar energy.

1. INTRODUCTION

Considerable losses of agricultural products occur in developing countries due to improper drying. This is due to the fact that most of the farmers in these countries are still using natural sun drying method to dry their agricultural products. Although this method requires negligible investment cost, the products being dried are usually susceptible to damage by insects and animals and adverse weather conditions. Therefore, an appropriate dryer is required to properly dry these products. As most of the developing countries are situated in the tropics and subtropics which receive relatively abundant of solar radiation and most of farm size is small, the use of a solar dryer is still considered to be a feasible solution of the drying problems in the tropics and subtropics.

Solar drying can be considered as an elaboration of sun drying and is an efficient system of utilizing solar energy [1]-[2]. Considerable studies have been conducted on natural convection drying of agricultural products [3]-[11]. Drying rate is relatively low in natural convection solar dryers due to low buoyancy induced air flow [8], [10] and this has stimulated researchers to develop forced convection solar dryers [12]-[15]. Different types of forced convection solar have been developed for capacity ranging from family size to village size for drying of fruits, vegetables, spices, herbs, fish and meat [16]-[25].

Among the existing solar dryers, the greenhouse type solar dryer has a number of advantages over other types of solar dryers. This is because of the fact that the greenhouse solar dryer has a simple structure, large loading capacity and relatively good thermal performance. In addition, greenhouse solar dryer is based on the technology of agricultural greenhouse, which has been already well developed, both in terms of materials and construction method. Greenhouse type solar dryers have been successfully used in the industrialized countries. However, greenhouse solar dryer has received little attention for application in the developing countries.

Several studies have been reported on greenhouse crop drying [26]-[32] but no study has been reported on PV-ventilated and polycarbonate cover greenhouse solar dryer. The purposes of this work are to develop a multi-purpose greenhouse solar dryer for village-scale use in developing countries and to investigate its experimental performance for drying of chilies as a test case.

2. DESIGN OF GREENHOUSE DRYER

The criteria for the design for this dryer are as follows. The dryer is to be a multi-purpose, meaning that it can be used to dry various types of fruits and vegetables including processed foods like mango leathers or banana pastes. The maximum loading capacity required is approximately 100-150 kg of fresh products, which correspond to the general demand for a village-scale user. In addition, it should be self-sufficient in terms of energy supplies with minimum requirement of maintenance and must be appropriate for use in rural areas in the

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Fig. 1. Greenhouse solar dryer developed in this study

developing countries. Based on these considerations, we propose a PV-ventilated greenhouse solar dryer as shown in Figure 1.

The conceptual design of this dryer is that it has a parabolic cross-sectional shape in order to make the structure of the dryer simple. In addition, this shape can withstand well the tropical rain and storm. Polycarbonate plate was selected to be the transparent cover for the dryer, because it has a transmittivity of 0.8 for short wave solar radiation and low transmittivity of 0.2 for the infrared thermal radiation, thus creating a good greenhouse effect inside the dryer. Moreover, it has a low thermal conductivity which helps to reduce heat losses to the environment. In terms of construction, the polycarbonate plate has low density and it can be easily cut and bended as required. As polycarbonate is a common commercial material in architectural constructions, accessories for the joints and fixing of the plates are available in the markets, facilitating the construction at a reasonable price.

The floor of the dryer is made of concrete mixed with black powder paint to serve as a basement of the dryer as well as a solar radiation absorber. As concrete has relatively high heat capacity, it also functions as a heat storage system for the dryer. In addition, its thermal inertia helps to reduce the variation of the drying air temperature due to the fluctuation of incident solar radiation. To ventilate the dryer, three 15W dc-fans are installed at the front wall of the dryer to suck out the moist air from the dryer to the ambient environment. A small window is made at the bottom of the rear side of the dryer to allow the fresh air intake into the dryer (Figure 1). A 53-Wp solar cell module was installed to power the fans directly during the day. Metallic shelves with three levels of drying trays were constructed and were placed inside the dryer for placing products to be dried.

Sizing of the dryer was based on an approximate calculation as follows: chilies were selected as a product to be dried in this dryer. The loading capacity of the dryer was chosen to be 150 kg of fresh chilies. This corresponds to the capacity of a small dried chilies producer for local markets. The fresh chilies with the initial moisture content of 80% (wet basis) is to be dried to the final moisture content of 10% (wet basis) as a normal practice in the production of dried chilies for local markets in Thailand. The mass of water to be removed from chilies is 117 kg.

In general, the drying time for small chilies in the natural sun drying is about 6 days. For this greenhouse dryer, the average drying time was chosen to be three (3) days. Because longer drying time often causes spoilage due to mould while too short drying time increase significantly the solar radiation collecting area and the size of the ventilation system which would consequently increase the drying cost.

To remove the mass of water of 117 kg in three (3) days, the supply of heat required can be estimated from the latent heat of vaporization of water and the mass of the water removed. With the long-term average of global solar energy of 18.2 MJ/m^2 [33], the solar collecting area of the greenhouse dryer was estimated. In consideration of the standard size of polycarbonate plates and structural materials, the dimension of radiation collecting area was selected to be 5.5 m $\times$ 8.0 m.

3. DRYING EFFICIENCY

The drying efficiency of the greenhouse dryer is defined as the ratio of energy output of the dryer to energy input in the dryer. Solar radiation input on the dryer is:

$$Q_{solar} = A_{dryer} \int_0^{t_s} I(t)dt \qquad (1)$$

where, Q_{solar} = solar energy input on the dryer, J
$I(t)$ = solar radiation, at time t, W/m^2
A_{dryer} = dryer area, m^2
t_s = drying time, s

The output of the dryer in terms of energy required for vaporization is:

$$Q_{dryer} = m_r \times L_g \qquad (2)$$

where, Q_{dryer} = energy required for vaporization , J

m_r = moisture removed, kg

L_g = latent heat of vaporization of moisture, J/kg

Thus drying efficiency of the dryer is:

$$\eta_{drying} = \frac{Q_{dryer}}{Q_{solar} + Q_{module}} \tag{3}$$

where, Q_{module} = energy output from the solar cell modules, J

4. EXPERIMENTAL PROCEDURE

The dryer was constructed and installed at the experimental site of Solar Energy Research Laboratory, Silpakorn University at Nakhon Pathom, Thailand (13.82°N, 100.04°E). This dryer is oriented in the north-south direction. Chilies were dried to demonstrate the potentiality of the dryer as a test case. The tests were carried out during the period of December, 2003 to March, 2004. A total of four (4) experiments were carried out.

Sensors and measuring devices were installed inside and outside the dryer to measure the parameters influencing the performance of the dryer. A pyranometer of (Kipp & Zonen model CM3, accuracy ± 0.5%) was installed at the top of the dryer to measure global radiation incident on the dryer. Type K thermocouples were placed at the inlet window of the dryer in front of the fans, above the product in the shelves and along the length of the dryer. The accuracy of the temperature measurement was ± 2%. Hygrometer of Electronik (model EE23, accuracy ± 2%) were used to measure the relative humidity of the drying air inside the dryer. Ammeter and voltmeter were employed to monitor electrical power obtained from the solar cell modules. Air speed was measured using hot wire anemometer (Airflow, model TA5, accuracy ± 2%). Positions of the sensors for the measurements are shown in Figure 2.

Relative humidities of ambient air and drying air were periodically measured with a hygrometer (Defensor, model MS1, accuracy ± 2%). Voltage signals from the pyranometer and thermocouples were recorded every 10 minutes by a 20-channel data logger (Yokogawa, model DC100). For relative humidity of ambient air, it was manually read and recorded at 1-hour intervals. Samples of products in the dryer were weighed at 3-hour intervals using a digital balance (Satorius, model E2000 D, accuracy ± 0.0001 g.). Before the installations, the pyranometer was calibrated against a new pyranometer recently calibrated by Kipps & Zonen, the manufacturer. For the hygrometers, it was calibrated using standard saturated salt solutions supplied by Defensor, the manufacturer. Before being used, the thermocouples were also tested by measuring the boiling and freezing temperatures of water to ensure the accuracy.

For each experiment, the chilies were spread on the trays which were placed on the top, middle and bottom levels of the shelves in the dryer (Figure 3). To compare the performance of the dryer to that of a natural sun drying, another control sample was also placed outside the dryer and dried simultaneously in the same weather conditions.

For the drying tests, 100-150 kg of chilies were used for each experimental run. The experiments were started at 8.00 am and continued till 5.00 pm. The process was repeated until the desired moisture content were reached. About 100 g of the product samples were taken from the dryer as well as from the natural sun drying and weighed at 1-hour intervals. At the end of the drying process, these samples were dried in an oven at 103°C for 24 hours for the determination of the moisture contents of the products.

5. RESULTS AND DISCUSSIONS

Typical results for drying of 100 kg of small chilies in PV-ventilated greenhouse solar dryer are shown in Figures 4 to 12. The variations of solar radiation during drying of chilies are shown in Figure 4. During drying of chilies the solar radiation varied almost sinusoidaly from a minimum in the morning and in the evening to a maximum of 800 W/m^2 at noon. This implies that there is a great solar energy potential for PV-ventilated greenhouse solar dryer for village level use in Thailand.

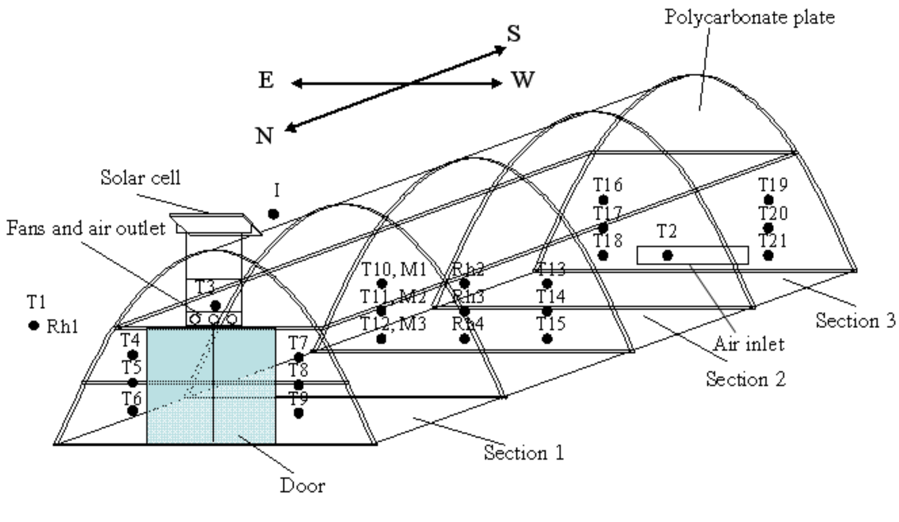

Fig. 2. The position of the sensors of measuring devices
(T = temperature, I = solar radiation, Rh = relative humidity, M = moisture)

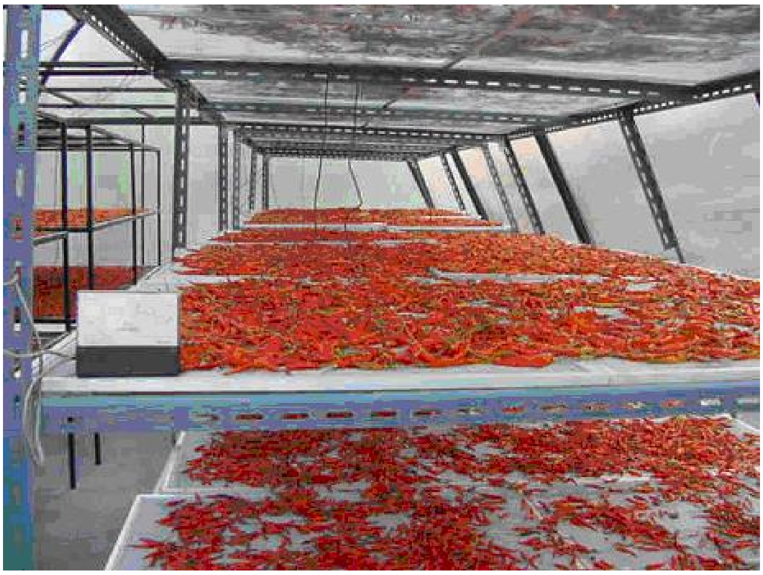

Fig. 3. Chilies on the trays placed on the top, middle and bottom levels of the shelves inside the dryer during the drying experiment

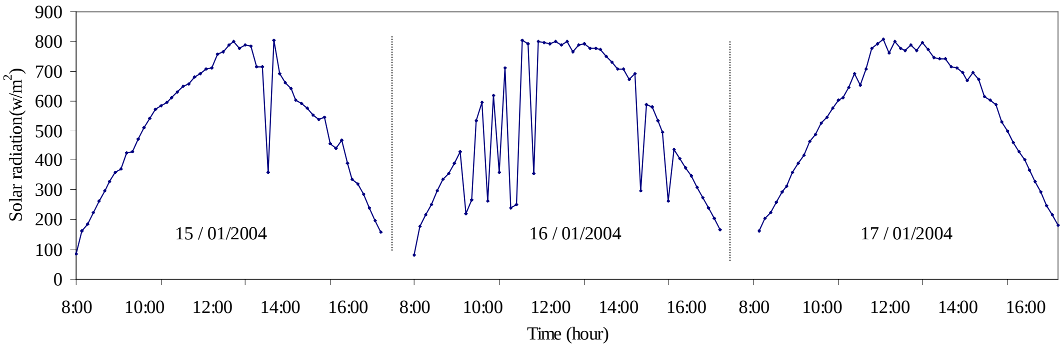

Fig. 4. Variations of solar radiation with time of the day for a typical experimental run during drying of chilies

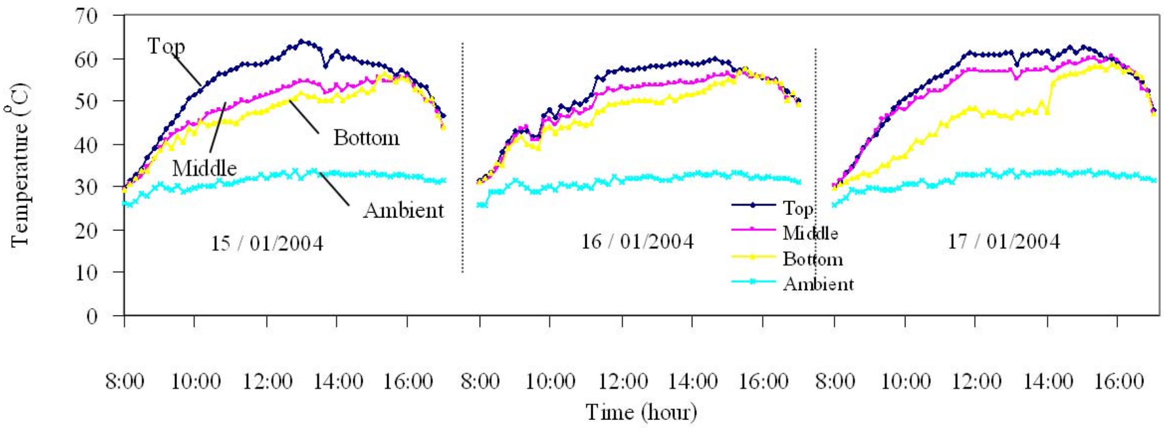

Fig. 5. Variations of ambient temperature and the temperatures in the top, middle and bottom layers inside the greenhouse solar dryer for a typical experimental run during drying of chilies

Figure 5 shows the variations of ambient temperature and temperatures at the top, middle and bottom levels of the shelves inside the greenhouse dryer for a typical experimental run during drying of chilies. The variations of the temperatures were almost constant in the middle period of the day and this ensures that there is no thermal stress due to the rapid change of the temperatures. However, temperature varied from 32 °C in the morning to 53 °C in the middle layer at noon and the temperature is rise was about 20 °C in the middle of the day.

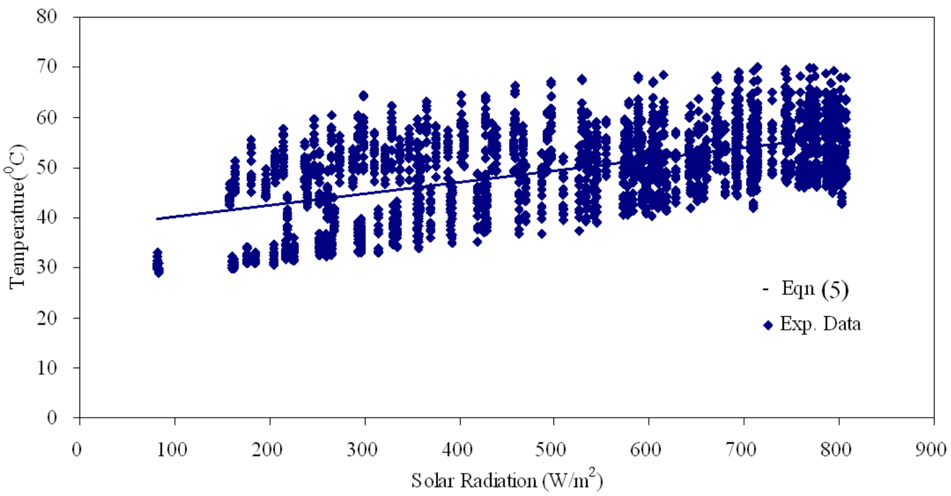

Fig. 6. Drying air temperatures at the different levels of the shelves versus solar radiation

Figure 6 shows the plot of drying air temperatures at the different levels of the shelves versus solar radiation during drying of chilies in the greenhouse dryer. The following equation was developed to express the relationship between the temperatures and the solar radiation:

$$T = 37.895 + 0.0228\,I \qquad R^2 = 0.32 \qquad (4)$$

where T is temperature in °C and I is solar radiation in W/m^2.

The drying air temperatures in the different levels inside the dryer varied with solar radiation and banded around a mean value. This indicates that the air temperatures inside the greenhouse dryer are regulated indirectly by the solar radiation.

Figure 7 shows the variations of ambient relative humidity and relative humidities at the different levels inside the greenhouse dryer of a typical experimental run during drying of chilies. The ambient relative humidity decreased rapidly from a high value of 89 % in the morning to a low value of 49 % at noon and then again increased very slowly to a value of 53 %. The relative humidities in the different layers inside the dryer decreased rapidly from 75 % in the morning to almost about 20 % at noon and then changed slowly with noticeable fluctuations. The middle layer had the lowest relative humidity and the trends in the relative humidity changes are similar for all the three days. The relative humidity inside the dryer is considerably lower than that of the ambient air. Thus, the drying air inside the dryer had high drying potential with high temperature and reasonably low relative humidity for drying of fruits, vegetables and spices.

Figure 8 shows the variations of inlet and outlet temperatures of the greenhouse dryer for a typical experimental run during drying of chilies. The temperature rise at the outlet from the inlet within two hours was 13 °C and maintained a temperature rise of 15 °C. This indicates that the air leaves the dryer with sufficient drying potential and may be considered for further increase in loading capacity and possible recirculation.

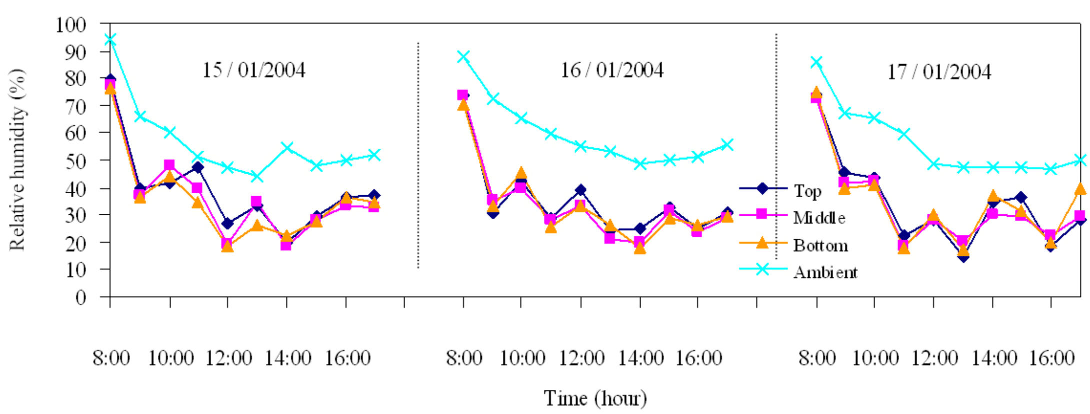

Fig. 7. Variations of ambient relative humidity and relative humidity at top, middle and bottom levels inside the greenhouse dryer with time of the day for a typical experimental run during drying of chilies

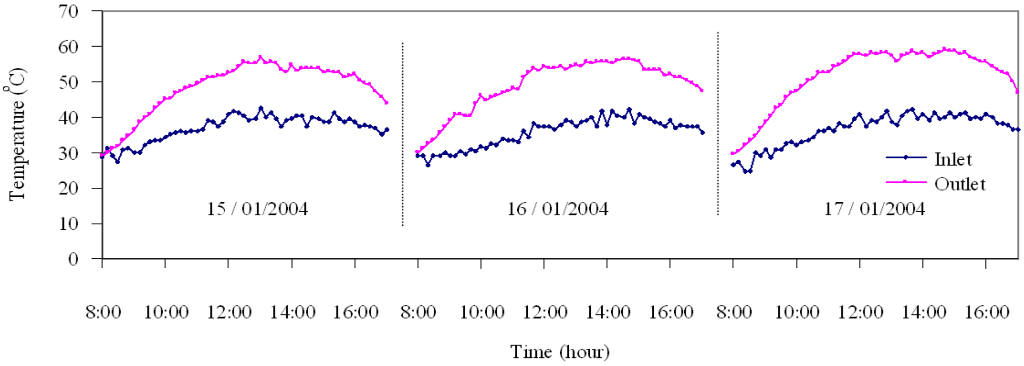

Fig. 8. Variations of inlet and outlet temperatures of the greenhouse dryer with the time of the day for a typical experimental run during drying of chilies

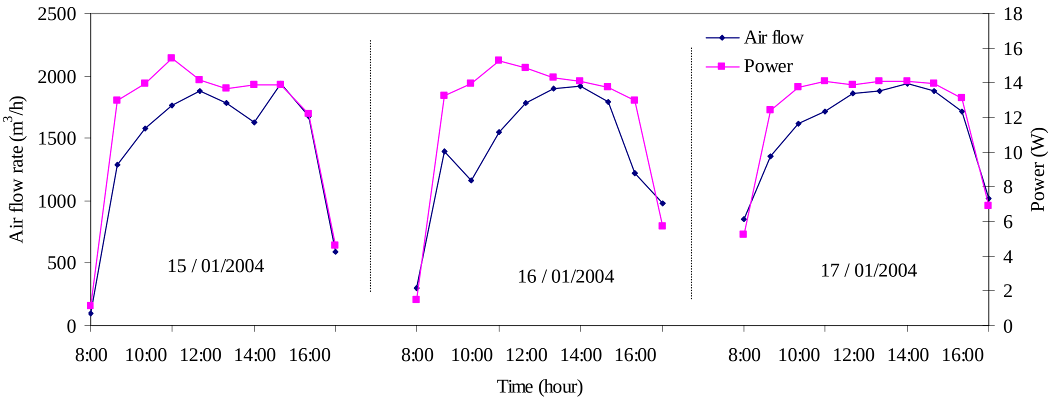

Fig.9. Variations of power generated by the solar modules and air flow inside the greenhouse dryer with time of the day for a typical experimental run during drying of chilies

Figure 9 shows the variations of power generated by the solar modules for operating the fans for providing the required air flow and air flow inside the greenhouse dryer for a typical experimental run during drying of chilies. The power generated by the solar module was very low at 8 am and then jumped to a value of about 12.9 W and then remained almost constant at about value of 13.7 W till 4 pm. Then again it jumped back to 5.7 W in the evening. The air flow during that period reached a value of about 1,940 m^3/h at noon with a value of about 1,348 m^3/h in the morning (9 am) and about 1,305 m^3/h in the afternoon (4 pm). Since the power generated by the solar module was almost constant from 9 am to 4 pm, the air flow rate was also almost constant. Thus, reasonable air flow is maintained from 9 am to 4 pm. However, it can be adjusted by changing the number of fans in operation and solar radiation regulates the temperature inside the dryer.

The air flow increases with the power generated by the solar module. Figure 10 shows the relationship between the air flow rate and solar radiation. The following equation was developed to express the relationship between the air flow rate and solar radiation:

$$\dot{m} = -0.0000009 I^2 + 0.0013 I + 0.0381$$

$$R^2 = 0.82 \qquad (5)$$

Where, $\dot{m}$ is air flow rate in m^3/s and I is solar radiation in W/m^2.

Comparison of the moisture contents of chilies inside the greenhouse dryer with those obtained by the traditional sun drying method for a typical experimental run is shown in Figure 11. As the chilies at the top level of the shelves received energy both from the incident radiation and the hot air in the dryer, the moisture content decreased from 80 % (wet basis) to the final moisture content of 10 % (wet basis) in 2 ½ days. The chilies in the middle and the bottom levels took 3 – 3 ½ days to reach the final moisture content, while the drying time for the natural sun drying chilies were about six (6) days.

The drying efficiency of the greenhouse dryer varies linearly with the loading capacity. Figure 12 shows the variations of the efficiency with loading capacity and this implies that the dryer should be operated at the highest permissible efficiency. The following relationship has been developed for the variations of efficiency with loading capacity:

$$\eta = 2.2767 + 0.115 M_p$$

$$R^2 = 0.98 \qquad (6)$$

where, η is drying efficiency in % and M_p is loading capacity in kg.

For the economic evaluation of this dryer, various costs and economic parameters were estimated as follows:

-	Polycarbonate plates	1,800	USD
-	Solar cell modules and fans	375	USD
-	Structural and basement materials	1,087	USD
-	Labour	375	USD
-	Expected life of dryer	15	years

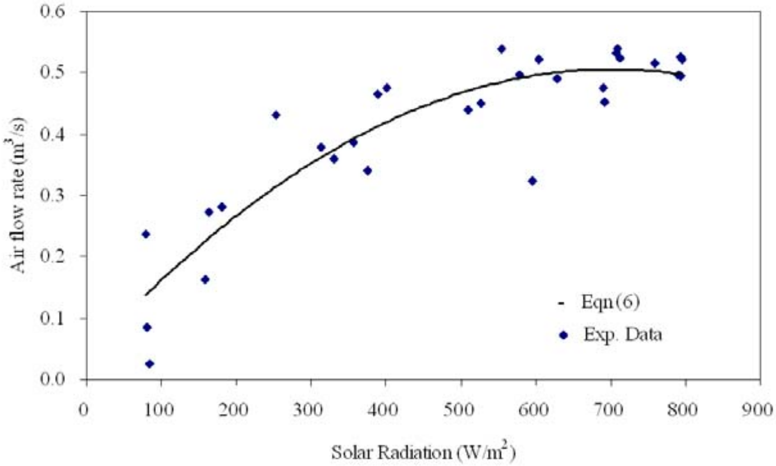

Fig. 10. Variations of air flow rate with solar radiation

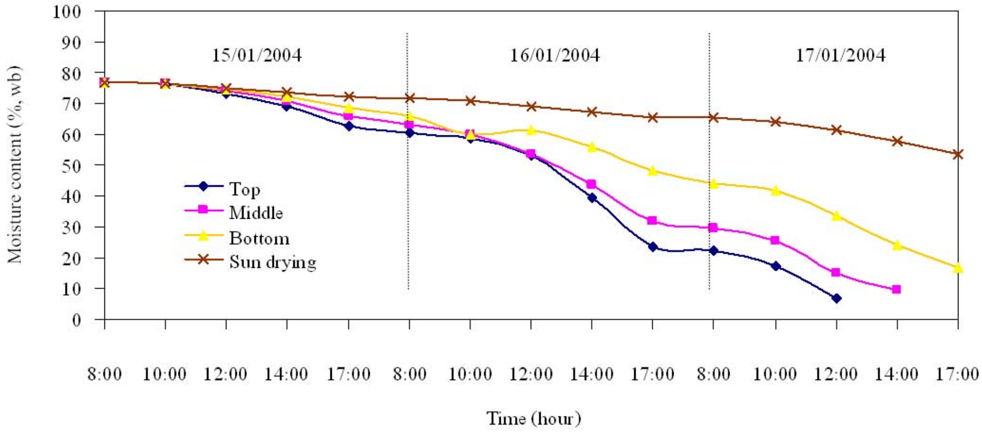

Fig. 11. Comparison of the moisture contents of chilies inside the greenhouse dryer at different levels of the shelves with the traditional sun drying method for a typical experimental run

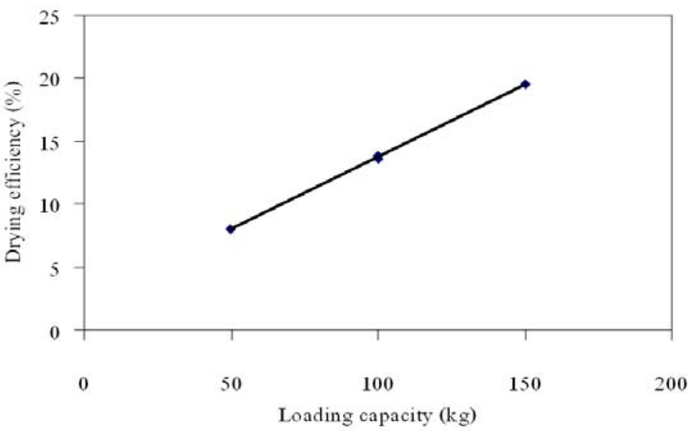

Fig. 12. Variations of the drying efficiency with loading capacity

The total investment cost of the dryer was calculated to be 3,637 USD (1 USD = 40 Bahts). This dryer was sometimes used to dry chilies for farmers as a public service activity of the University. Based on this activity, it was estimated that the dryer can be used to dry 40 batches per year with 100 kg of fresh chilies per batch. In general, 24 kg of dried chilies were obtained from one batch of drying. The average market prices of fresh chilies and good quality dried chilies were 0.75 USD and 4.5 USD, respectively. The labour cost for drying operation was approximately five (5) USD per batch and the annual maintenance cost was estimated to be 1% of the total investment cost. With the gross income from the production of dried chilies from this dryer, it would take 3.36 years to recover the money back.

In all cases the quality of the chilies dried in greenhouse dryer was a quality product as compared to sun dried sample and the drying time is significantly reduced. In general, chilies dried with natural sun drying were usually damaged by insects and rain. However, the chilies dried in this dryer were completely protected from these damages. Thus, this study demonstrated the potentiality of the greenhouse dryer for village level drying of chilies in Thailand.

6. DISSEMINATION OF THE DRYER

For the dissemination of the dryer, we have constructed two units of this type of dryer at Suan Phoeng Educational Park in Ratchaburi and in Narathiwat, Thailand. In Ratchaburi, the dryer is used to dry banana while in Narathiwat the dryer is employed for drying green tea under the economic development program for Muslim people of the Thai government. For both cases, users of the dryers are satisfied with the performance of the dryer.

7. CONCLUSION

Four sets of experimental runs demonstrated the potentiality of solar drying of chilies in solar greenhouse dryer. The loading capacity of the dryer is 100-150 kg of fresh chilies. The temperatures at three levels of the drying shelves (top, middle and bottom) inside the dryer follow the similar pattern. Drying in the greenhouse results in considerable reduction of drying time and drying efficiency increases with loading capacity. The chilies dried in the greenhouse dryer was completely protected from rain, insects and dusts, and the dried chilies were a high quality dried product compared to the high quality chilies the markets. The payback period of dryer is estimated to be 3.36 years. Two more units of this type of dryer were constructed and used for dissemination purposes. Users of these dryer were satisfied with the performance of the dryers.

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NOMENCLATURE

A_{dryer}	dryer area, m^2
I	solar radiation, W/m^2
L_g	latent heat of vaporization of moisture, J/kg
M_p	loading capacity, kg.
m_r	moisture removed, kg
$\dot{m}$	air flow rate, m^3/s
Q_{dryer}	energy required for vaporization, J
Q_{module}	energy output from the solar modules, J
Q_{solar}	solar energy input on the dryer, J
T	temperature, °C
t	time, s
t_s	drying time, s
η	drying efficiency, %

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