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# Design and Performance of a Solar Tunnel Dryer with a Polycarbonate Cover (September 2006)

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***Abstract*** *- A solar tunnel dryer with a polycarbonate cover was designed and constructed. The dryer consists of two parts, namely a solar collector and a drying tunnel. Both parts are connected in series on the same structure. A polycarbonate cover is used to reduce heat losses while allowing the incident solar radiation to transmit into the dryer. Loading and unloading of products to be dried are undertaken through windows at a side wall of the dryer. A dc-fan driven by a 15-watt solar cell module is employed to ventilate the dryer. To investigate its performance, the dryer was used to dry five batches of jackfruits. For most cases, the temperature of the drying air in the dryer varied between 35 to 60 °C from 9 A.M. to 5 P.M. This dryer can be used to dry 30 to 70 kg of jackfruits from an initial moisture content of 80% (wb) to a final moisture content of 30% (wb) within 3 days, compared to 4 to 5 days with natural sun drying in the same weather condition. High quality products in terms of flavor, colour and texture were obtained. The payback period of this dryer is approximately 3 years.*

***Keywords*** **- Solar dryer, solar energy, performance study, fruit dryer, polycarbonate cover**

## 1. INTRODUCTION

Solar drying has been considered to be a promising solution for crop drying problems in developing countries [1-5]. This is due to the fact that most of these countries are situated in the sunbelt (10 to 40 degree north and south) which receives relatively high solar radiation. In addition, the agricultural activities are decentralized with low energy density demand for drying. These conditions are well-suited to solar energy utilization. Consequently, a number of solar dryers have been developed during the last thirty years [6-25].

Among the existing solar dryers, the solar tunnel dryer originally developed at the Institute of Agricultural Engineering in the Tropics and Subtropics, Hohenheim University in Germany [26-28] has many advantages for use in developing countries. First, it has a high loading capacity with a reasonable investment cost so that users can use it to produce dried fruits for commercial purposes. Second, it has a modular design, which facilitates construction and transportation of the dryer. Finally, it effectively helps reduce drying time, which consequently eliminates the spoilage of products caused by rains, insects and animals during drying. This type of dryer has been successfully experimented in many countries [29-33].

In 1992, the original design of solar tunnel dryer was modified and successfully tested at the Solar Energy Research Laboratory of Silpakorn University for use in the tropical climate of Thailand [31]. As a result of collaboration between the Institute of Agricultural Engineering in the Tropics and Subtropics, Hohenheim University and Solar Energy Research Laboratory of Silpakorn University, the original design solar tunnel dryer was also experimented at the Royal Chitralada Projects in Bangkok, Thailand in 1995 [32]. Experiences gained from both experiments in Thailand led to the development of a new version of the tunnel dryer with an auxiliary gas heater [33]. Seven units of this new version have been constructed by the Solar Energy Laboratory of Silpakorn University. These have been installed and used in different locations in Thailand. However, experiences from the use of these dryers indicated that the PE-plastic sheet used as a top cover of the collector and the drying tunnel is still a weak point of this type of dryer when used in the topics, since the PE-plastic sheet needs a lot of cares. For example, it needs to be well stretched. Otherwise, rain will accumulate on the sheet and usually damages it. Although the sheet is made of UV-stabilized plastic, it lasts for only 3-6 months due to strong solar ultraviolet radiation and heavy rain in the tropics.

To overcome this problem, we proposed a new version of the solar tunnel drying which uses polycarbonate plates as a transparent cover for both the collector and the drying tunnel. Many parts of the dryer were redesigned to fit this version. The objective of this paper is to present the design and performance of the dryer.

## 2. DESIGN AND CONSTRUCTION MATERIALS

### *The dryer*

The new dryer consists of two parts, namely the solar collector and the drying tunnel which are connected in series (Fig. 1), similar to the original version. To overcome the problems with the PE-plastic cover, we proposed to replace it with polycarbonate plates. The polycarbonate plates have many advantages over other transparent materials. First,

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they have high transmittance in the short wavelength solar radiation. The measurement of the spectral transmittance carried out at the School of Energy and Materials, King Mongkut University of Technology is shown in fig 2 [34]. For the thermal long wavelength radiation, the polycarbonate plates have a transmittance of about 0.2 [35]. The transmittances for the short wavelength and the long wavelength indicate that polycarbonate plates have good optical properties for the creation of the greenhouse effect. Second, polycarbonate plates have low thermal conductivity due to the air channels in the plates, which helps reduce heat losses. Third, their low density and high flexibility facilitate the construction. Finally, they have reasonable price with a long life span of over ten years.

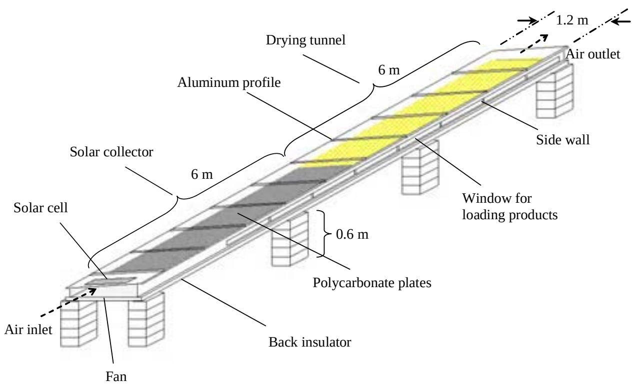


**Fig. 1. Schematic diagram of the solar tunnel dryer with polycarbonate cover.**

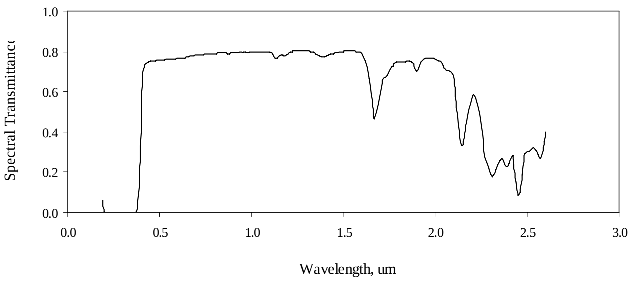


**Fig. 2. Spectral transmittance of the polycarbonate plate.**

As polycarbonate plates are used as a cover material of the dryer, the structure of the dryer was modified from the original version as follows. First, loading and unloading of the products to be dried are undertaken through windows at a side wall of the dryer. Second, the two side walls were designed in such a manner these are supported by the back insulators at the bottom side and the side walls support the polycarbonate plates at the top side of the dryer, as shown in Fig. 1. They are made of galvanized iron sheets. In addition, the two side walls have different heights, so that the polycarbonate plates make a tilted angle of $10^o$ to facilitate drainage of water in case of rain. The higher side wall has windows, each of which has a dimension of 20 cm x 80 cm with a polycarbonate cover. Third, the polycarbonate plates were fixed with silicone glue to the aluminum frames using a special profile to avoid the leakage of rain and to facilitate the cleaning of the dryer. The frames are made of aluminum which is easy to bend to form the designed profile. The joints between the two polycarbonate plates were covered with a rectangle-cross section aluminum profile to prevent the leakage of rain.

The back insulators of the dryer were made of high density foam sandwiched between two galvanized iron sheets. They were also made in a module, each one has an area of 1.0 x 1.2 $m^2$ and they are inter-locked at their sides to prevent air leakage.

For the sizing of the dryer, an approximate calculation was used as follows. First, jackfruits were selected as the product to be dried in this dryer, since jackfruits are available all year round and fresh jackfruits are usually in oversupply. In addition, dried jackfruits have started to be a popular snack in Thailand and an appropriate dryer for the drying of this fruit is still not available. The loading capacity of the dryer was chosen to be 50 kg of fresh jackfruits per drying batch. This capacity corresponds to the demand of a small dried fruit producer. The drying time for one batch is chosen to be 3 days, because with a drying time shorter than 3 days, case hardening in the products may result, while a longer drying time may cause mould growth. Next, the mass of water ($m_w$) to be removed from the jackfruits was calculated by using the following equation:

$$m_w = m_f \frac{M_i - M_f}{100 - M_f} \tag{1}$$

where $m_f$ is the mass of fresh jackfruits and $M_i$ and $M_f$ are respectively the initial and final moisture contents (%,wb) of the jackfruits. Using $M_i$ = 80 % (wb) and $M_f$ =30 % (wb), correspond to the moisture contents of fresh and dried jackfruits available in markets, the mass of water to be removed was calculated to be 35 kg per batch.

To calculate a heat demand ($Q_{drying}$) for the drying process, the following equation was used.

$$Q_{drying} = m_w L_{eff} \tag{2}$$

$L_{eff}$ is the heat supply to the drying tunnel (Fig. 1) in order to remove 1 kg of water from the jackfruits. This heat is consisted of the heat of evaporation, the sensible heat to increase the product temperature and heat losses from the dryer. In the case of free water at room temperature the heat of vaporization is 2.5 MJ/kg. Since the heat of vaporization of jackfruit is not available from literatures, we used the heat of vaporization of water for the calculation. For the sensible heat required to increase the product temperature and heat losses from the drying tunnel, we estimated their values from experimental results of the original solar tunnel dryer [28]. From this information, the value of $L_{eff}$ was estimated to be 6 MJ/kg. With the values of the input data, the total heat required to dry 50 kg of the fresh jackfruits was estimated to be 210 MJ.

The final step was to calculate the area of the solar collector ($A_c$). To accomplish this, the following equation was used

$$A_c = \frac{Q_{drying}}{\eta H_T N_d} \tag{3}$$

where $\eta$ is the efficiency of the dryer to convert incident solar radiation into heat; $H_T$ is the monthly average of daily solar radiation on a horizontal surface and $N_d$ is the number of days required to dry the product. In this case, $\eta$ was assumed to be 0.3 [28] and $H_T$ =18.2 MJ/m$^2$-day was obtained from the solar radiation maps of Thailand [36]. With these input parameters, the value of $A_c$ = 12.8 m$^2$ was obtained. Due to the standard size of the polycarbonate plates and materials for the back insulators, the width and the length of the dryer of 1.2 m and 12.0 m were chosen, respectively. Therefore, the total area of the dryer is 14.4 m$^2$, half of which is the drying tunnel and the rest is the solar collector.

### *The Ventilating System*

Based on experiences gained from the research and the field experiments of using the solar tunnel dryer [26-33], this type of dryer needs forced–convective ventilation to make it function efficiently. For the new design of the solar tunnel dryer, a PV-ventilated system was used. The system consists of a solar cell module and a dc-axial flow fan. The advantage of this system is that it can be used in remote areas without any electricity supplies. In addition, the PV-ventilated system helps regulate the drying air temperature.

The original version of the tunnel dryer functions properly with the maximum air flow rate of 900 m$^3$/hr [32]. As the drying area of our dryer is approximately half of the area of the original tunnel dryer, the maximum air flow rate of 400 m$^3$/hr was selected for our dryer. To achieve this flow rate, an axial-flow fan with a diameter of 15.8 cm and a dc-motor of 33 W which is available in local markets was chosen for the ventilating system. Before using the dc-axial flow fan, its characteristics were investigated as follows. First, the fan was fixed at one end of a cylindrical tube and a hot-wire anemometer was used to measure the air speed at the other end of the tube, as shown in Fig. 3. The distance between the fan and the anemometer is about 10 times of the diameter of the tube in order to obtain a stable air flow in the tube. Then, the flow rate of the air was varied by changing the voltage of the power supply. The current, voltage and air speed were measured. With the air speed and the cross-section area of the tube, the air flow rate was calculated. The corresponding curves relating the air flow rate and the electrical power used by the fan was plotted in Fig. 4. Finally, by using the curve in Fig. 4, we obtained the

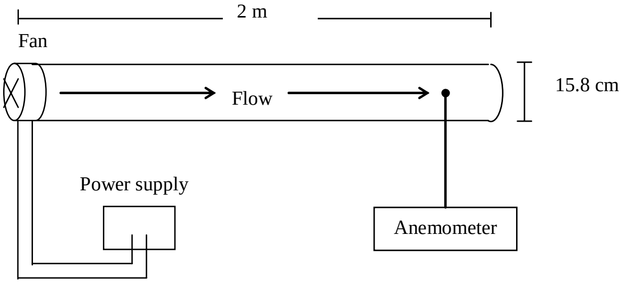


**Fig. 3. Schematic diagram of the equipment for determining the relation between the air flow rate and the power required by dc-axial flow fan.**

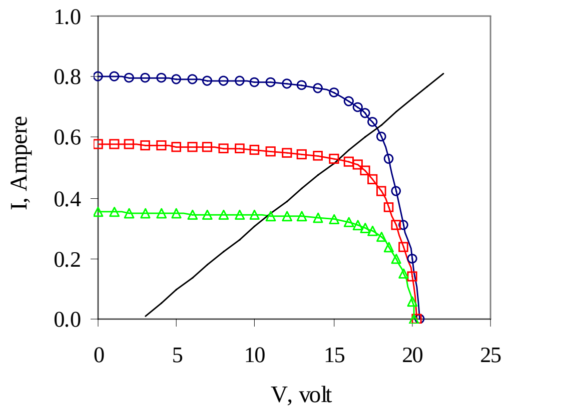


**Fig. 4. Experimental I-V curves of the solar cell module and the dc-axial flow fan.**

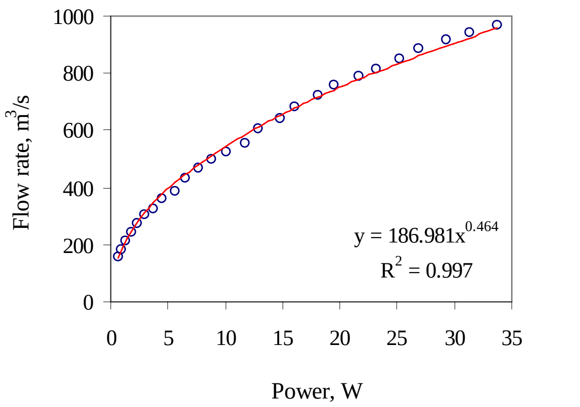


**Fig. 5. Relation between the air flow rate and power required by the dc-axial flow fan.**

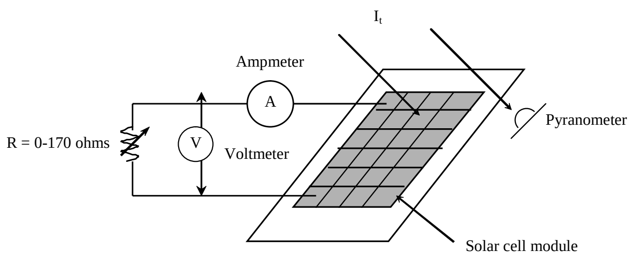


**Fig. 6. Schematic diagram of equipment for determining characteristic curves of the solar cell module.**

values of the electrical power of 7 W to achieve the flow rate of 400 m$^3$/hr.

In this work, a 15 W-solar cell module was chosen to power the fan. This is because of the fact that it is the only solar cell module available in local markets, which can supply the power nearest to the required power of the fan. To ensure the proper functioning of the solar cell module, an experiment was carried out to determine its characteristics. It was exposed to solar radiation at noon time on a cloudless day. An electrical circuit (Fig. 6) was made in such a manner that the current (I) and voltage (V) from the solar cell module can be measured for varied values of the external resistant (R). The solar radiation on the plan of the solar cell module was measured with a thermopile-type pyranometer (Kipp&Zonen, model CM11). Then the I-V curves obtained from this experiment and that of the fan were plotted in the same graph, as depicted in figure 4. From the graph, it is shown that this solar cell module can supply the electrical power of 4 to 10 W for the range of the solar radiation of 400 to 1000 W/m$^2$ which corresponds to the flow rate of 300 to 500 kg/hr. This range of the flow rate covers the value of the flow rates required by the dryer.

For the construction of the dryer, most parts of dryer were constructed at the workshop of the Physics Department, Silpakorn University. The dryer was installed in the east-west direction at the experimental site of Solar Energy Research Laboratory, Silpakorn University (13.82° N and 100.04° E).

## 3. EXPERIMENTAL TESTS

### *Measuring Instruments*

To monitor the parameters affecting the performance of the dryer, various measuring instruments were used. The type K thermocouples were used to measure air temperature along the length of the dryer. A pyranometer of Kipp&Zonen (model CM11) was employed to measure incident solar radiation on the dryer. This pyranometer has a flat spectrum response in the range of 305 to 2800 nm. which can effectively measure the incoming solar radiation. The effect of atmospheric radiation on the measurement is negligible. To monitor the relative humidity of the drying air and the ambient air, a hygrometer of Defensor (model ms1) was employed. The air speed in the dryer was measured by a hot wire anemometer of Airflow (model TA5). All signals from these instruments, except for the hygrometer, were recorded by a data logger of Yokogawa (model DC100) with a sampling rate of 10 minutes. The output of the hygrometer was manually recorded.

### *Method*

To investigate its performance, the dryer was used to dry five batches of jackfruits during October 2002 to April 2003, covering every season of the year.

For the experiments, 30 to 70 kg of fresh jackfruits with a moisture content of 80 % (wb) was spread in a thin layer in the drying tunnel of the dryer. The drying started at 9:00 AM and stopped at 5:00 PM. The jackfruits were collected from the dryer in the evening and were placed in plastic boxes during the night in order to induce fermentation and allow moisture diffusion in the jackfruits. To compare the performance of the dryer with that of the natural sun drying, 100 gm of a control sample of jackfruits was also spread on a tray near the dryer and dried simultaneously in the same weather conditions.

## 4. RESULTS AND DISCUSSION

### *Experiment Results*

A typical result of an experiment is shown in Fig. 7-13. This experiment was carried out during 10-12 December, 2002. It was winter in Thailand with a clear sky for most time of the days. The solar radiation varied relatively smoothly during this experiment, except for the morning of the first day, as shown in Fig. 7. The peak solar radiation at noon time was approximately 800 W/m$^2$. The absorbed solar radiation by both parts of the dryer was converted into heat, causing the diurnal variation of the outlet air temperature of the collector or the inlet of the drying tunnel and the outlet of the drying tunnel similar to that of the solar radiation, as shown in Fig. 8. The temperature rise relative to the ambient air at the outlet of the collector during 9 A.M. to 4 P.M. was in the range of 10 °C to 25 °C and the peak temperatures of the outlet air were in the range of 50 °C to 60 °C for most cases, depending on weather conditions. This range of temperature helps accelerate the vaporization of water in the jackfruits without any damage to this product. As shown in Fig. 8, the temperature difference between the outlet and the inlet drying air temperature decreased in the course of the drying. This is due to the fact that the energy required for the drying process decreased with the decreasing of the product moisture content.

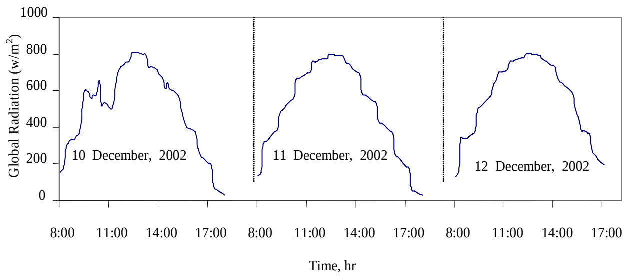


**Fig. 7. Variation of global solar radiation in the course of the drying.**

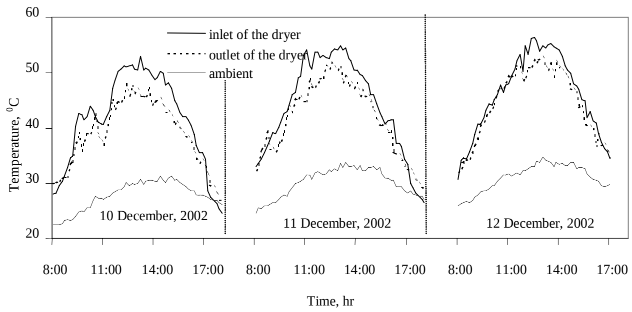


**Fig. 8. Variation of the temperatures of the air at the inlet and outlet of the dryer and the ambient air in the course of the dryer.**

As a result of the increase of the drying air temperature, the relative humidity decreased when compared to the relative humidity of ambient air (Fig. 9). After air has been blown through the product in the drying tunnel, the air absorbed water vapour from the product, thus increasing its relative humidity as shown in Fig. 9.

For the variation of the drying air temperature (Fig. 10), it rapidly increased up to 2 m from the inlet of the collector, and then became nearly constant along the length of the dryer. This constant temperature was caused by the balance between the maximum of the energy gain and the energy loss in the section between 2 and 6 m from the collector inlet. This section can be utilized as a drying area of the dryer. Therefore, jackfruits can be placed in the dryer starting from the distance of 2 m from the air inlet of the collector to the end of the drying tunnel.

Sometimes, the drying air temperatures fluctuated at the outlet of the drying tunnel due to the outside wind which disturbed the outlet air. The drying temperature of the first day was lower than that of the second and the

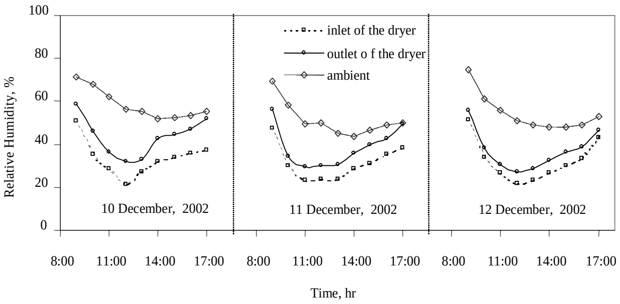


**Fig. 9. Variation of the relative humidity of the air at the inlet and outlet of the dryer and the ambient air in the course of the drying.**

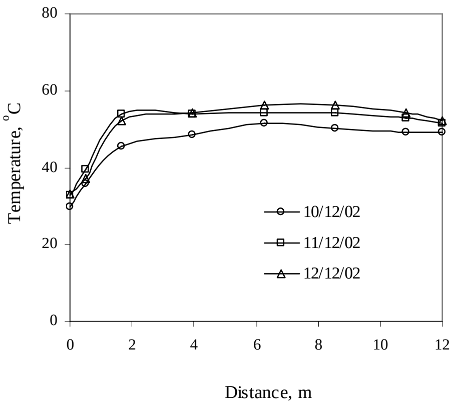


**Fig. 10. Variation of the drying air along the length of the dryer at noon time.**

third days because more heat energy was required for the evaporation during the first day.

It was observed that the exhausted air from the dryer had still high temperature and low relative humidity. This indicated that more fresh jackfruits can be dried in this dryer. This can be done by placing some fresh jackfruits in the section between 2 to 6 m of the collector in order to utilize the full potentials of this dryer.

For all experiments, the drying air temperature did not exceed 60 °C. With the favorable drying condition in the dryer, good quality of dried jackfruits were obtained in all experiments. In addition, no adverse effect on dried jackfruits caused by excessively high temperature of the product has been found. This indicated that the temperature of jackfruits in the dryer was not too high during drying.

The relative humidity of the drying air along the length of the dryer (Fig. 11) decreased rapidly in the solar collector, then increased in the first few meters along the length of the drying tunnel for the first and the second day of drying. However, for the third day, the relative humidity decreased and then remained stable, because the jackfruits in the dryer were nearly dried and less humidity was released.

In terms of the air flow rate, it varied in the course of the drying because of the variation of the input power supply by the solar cell module (Fig. 12). The variation of the air flow rate indirectly helped regulate the drying air temperature. This is due to the fact that during a high solar radiation period, the solar dryer received more energy, which tended to increase the drying air temperature. However an excessively high temperature was not observed because of the increase of the air flow during the same period. A reverse situation was observed for a low radiation period.

For the drying curves (Fig. 13), it is shown that the moisture content of the jackfruits both in the dryer and in the natural sun drying decreased slowly on the first day because the jackfruits were very wet with fructose from the jackfruits which difficult to dry. However the moisture content of jackfruits in the dryer deceased more rapidly than those dried with natural sun drying.

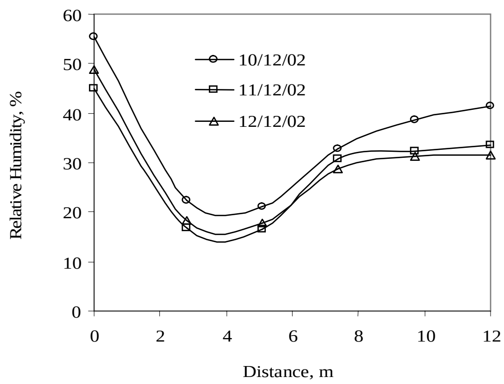


**Fig. 11. Variation of the relative humidity of the drying air along the lenght of the dryer at noon.**

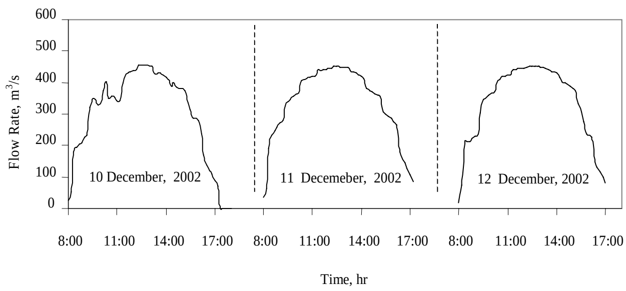


**Fig. 12. Variation of the air flow rate.**

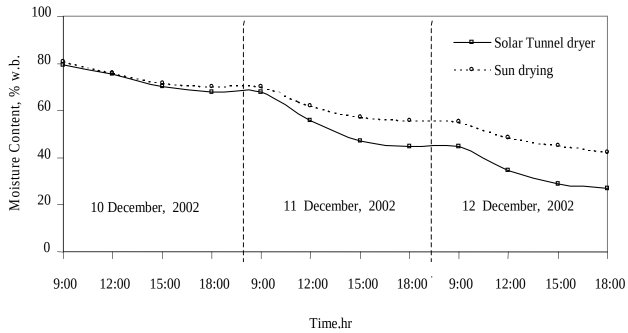


**Fig. 13. The moisture contents of jackfruits dried in the tunnel dryer and the jackfruits dried with the natural sun drying.**

This is because of the fact that the jackfruits in the dryer received energy both from the hot air blowing from the collector and from the incident solar radiation.

The quality of dried jackfruits was also preliminarily investigated. The jackfruits dried with the tunnel dryer had a yellow-brown colour and soft texture which corresponded to a good quality product in the market. In addition, dried jackfruits were not contaminated with insects and completely protected from the rain.

As in the design, we assumed the value of $L_{eff}$ in (2) to be 6 MJ/kg, this value can be verified from the experimental data as follows.

The simplified energy balance in the drying tunnel where the products were placed, can be written as:

$$\eta \int_0^{t_s} A_{cd} I(t) dt + \int_0^{t_s} \dot{m}(t) c_p (T_{co} - T_{ci}) dt = m_w L_{eff} \quad (4)$$

where $I(t)$ is solar radiation incident on the drying tunnel, $A_{cd}$ is the area of the drying tunnel , $t_s$ is the drying time, $\eta$ is the efficiency of the drying tunnel for the converting the incident solar radiation into heat, $\dot{m}(t)$ is the mass flow rate of the drying air, $T_{co}$ is the outlet temperature of the collector, $T_{ci}$ is the inlet temperature of the collector, $m_w$ is the mass of water to be removed from the products, $C_p$ is the specific heat of the air, $t$ is time and $L_{eff}$ is the heat supply to the drying tunnel in order to remove 1 kg of water from the product. With the values of these parameters obtained from the experiment, the value of $L_{eff}$ = 6.8 MJ/kg was calculated from (4). This value is nearly the same as the assumed value.

### *Economic Evaluation*

To evaluate the economic performance of the dryer, the annual cost of this dryer was calculated using the method proposed by Audsley and Wheeler [37]. Based on the economic condition in Thailand, the various construction and operating costs of the dryer are given as follows :
(1 USD = 40 Baht):

- material cost of the dryer (polycarbonate plates, galvanized sheet, high density foam, silicone glue, aluminum frame, etc.) 780 USD
- solar cell module 112 USD
- dc fan 14 USD
- labour cost for bending and cutting metal sheets and assembling the dryer 160 USD
- operating cost 3 USD/batch

The maintenance cost was assumed to be 1 % of the total cost of construction of the dryer. The inflation rate and interest rate are 5% and 7%, respectively. The life span of the dryer was assumed to be 10 years. Using these mentioned economic parameters and the cost data, the annual cost of 150 USD per year was obtained. According to the experiences from the experiments, this dryer can be used to dry at least 48 batches per year. The production of dried jackfruits per year is approximately 1,200 kg. Therefore, the drying cost defined as the annual cost divided by the production of dried product per year, was found to be 0.125 USD/kg. With the price of fresh jackfruit price of 0.5 USD/kg and the price of dried jackfruit price of 2 USD/kg, it was found that the payback period of this dryer is approximately 3 years.

For the natural sun drying, the drying cost is negligible. However, dried products obtained from this drying method are often in poor qualities and their sale price is lower than that of high quality products obtained from our solar dryer. In addition, products dried with natural sun drying are usually damaged from rain and mould, causing losses of income of dried fruit producers. In our dryer, a user of the dryer can produce 1,200 kg of dried jackfruits per year and earns 2,400 USD. If the same amount of fresh jackfruits is dried with natural sun drying and ten percents of losses are assumed [2], these losses are 240 USD per year. For the case of solar dryer, the user has to spend 150 USD per year for the drying cost. This expense is less than the losses occurred for the case of natural sun drying. Therefore, the use of this solar dryer is more beneficial than that of the natural sun drying.

## 5. CONCLUSION

A solar tunnel dryer with a polycarbonate cover has been developed. To investigate the performance, the solar tunnel dryer was used to dry five batches of jackfruits during October 2002 to April 2003 with the fresh weight of 30 to 70 kg. It was found that the temperature of the drying air in the dryer varied from 35 to 60 °C for most cases and the air flow rate in the dryer was about 100-500 $m^3$/h depending on weather conditions. The solar tunnel dryer is able to reduce the drying time and to increase the product quality in comparison to the sun drying. With the economic conditions in Thailand, the drying cost for drying jackfruits is 0.125 USD/kg and the payback period of this dryer is about 3 years. From its thermal performance and economic evaluation, this dryer has a high potential for use to dry jackfruits for commercial purposes.

## ACKNOWLEDGEMENTS

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