Experimental Evaluation on Large Scale Solar Dryer for Drying Natural Fiber in Malaysia

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Abstract- Drying process is one of the most common application used in solar thermal. This experiment was tested on performance of a large-scale solar dryer to dry natural fiber. The dryer consists of several main components such as solar thermal collector, heat exchangers and confine polycarbonate chamber. Average solar irradiance, ambient temperature and relative humidity recorded were 612.84 W/m^2, 32.42 ^{o}C and 60.01 %. The drying was completed in 3 days or 14.58 hours, and able to reduce 1004.2 kg weight and 70.7 % moisture content wet basis. Performance of the dryer was evaluated based on evaporative capacity, specific moisture extraction rate and specific energy consumption, and the values are 68.88 kg/hr, 3.55 kg/kWh and 0.28 kWh/kg respectively. Cost of operation determined as RM117.13 per cycle and cost of product was RM0.28 for every kilogram dried fiber produced. Based on capital cost, annual return of investment and profit, payback period estimated is about 3.7 years.

Keywords Solar energy, large solar dryer, drying performance, kenaf, natural fiber.

1. Introduction

Solar energy resource can be reached almost everywhere on the earth surface. It is secure, clean and abundance source of energy compared to fossil fuel. In Malaysia, maximum solar irradiance intensity can reach more than 1000 W/m^2 and the average daily value is approximately 500 W/m^2 [1]. Solar energy can be divided into two main groups, solar thermal and solar photovoltaic PV. Solar thermal collect heat from the sunlight spectrum while solar PV converts the spectrum into electricity. An advance invention able to combine these two groups become solar photovoltaic-thermal PVT and produce both heat and electricity [2]. The thermal effect able solar dryer to convert solar energy to usable heat for drying. Drying process is important to preserve quality by preventing fungal problem and expands life time of the agriculture product. Traditionally drying was performed by using open sun drying because of economic and unavailable technology factor. However open sun drying highly depends on existence of sunshine, space and time consuming, and expose to contamination. The contamination may have contributed from insect and bird, litters and dust [3,4]. Other research reported open sun drying was promoting to contaminate of fungi and microbes [5]. These factors can be eliminated by using solar dryer since the product was encapsulated in a chamber, a confine area where heat was supplied. Drying is moisture removal process. The reduction of moisture content determines by the amount of heat supplied and drying duration [6,7]. On the other hand, the quality of the product must be taken into consideration to reach standard safety storage moisture content [8]. The main purpose of using solar drying is to remove moisture using solar energy as the main source of heat and produced better results compare to open sun drying. Literature finding shows various kinds of product were tested such as kenaf core [9], palm oil fronds [3], red chili [10], seaweed [11], silver jewfish [12], copra [13], green peas [14], catfish [15], chili [4], ghost chili and ginger [16]. The number of loads tested in these experiments were not more than 500 kg.

A review on using solar dryer for marine and agriculture product shows the economic effective result and significant for future development [17]. Commonly solar dryer can be divided into three: natural, forced and hybrid convection solar dryer [9]. Natural convection occurs due to temperature and pressure different to create air movement. Force convection produce air flow by using fan or blower either to push or pull moisture out from the product. Hybrid convection is a combination both types of approaches. Evaluation on a solar dryer can be made by many factors such as heat performance, end-product quality, economic aspect and dryer dimension describe as [18]:

- Heat performance, including drying rate, drying efficiency, temperature, humidity and air flow.
- End-product quality related to nutrition and physical change, including texture and color, rehydration capacity and sensory quality.
- Economic aspect of the dryer in terms of cost of the dryer, cost operation and payback period.
- Dimensional or physical features, including size, the amount of loads and practicality of dryer and product handling.

2. Material and Method

2.1. Experiment Setup

The solar dryer was installed in Perlis state of Malaysia. Known as one of Malaysia weather hotspot area, many investigations on solar energy was conducted in Perlis [19,20,21]. The dryer consists of solar tube collectors, storage tank, heater, air handling unit (including blower), pumps and polycarbonate chamber. The diagram of the dryer is shown in Fig. 1.

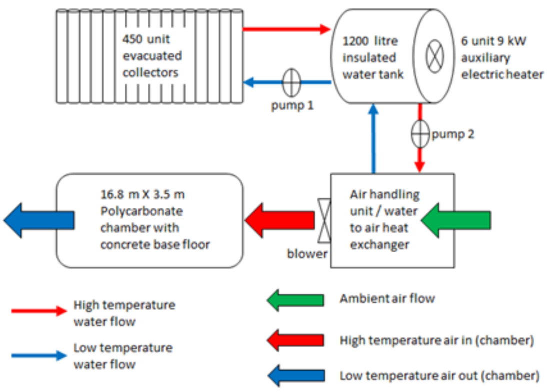

Fig. 1. Diagram of the dryer

The experiment was conducted by drying 1420 kg natural fiber inside the chamber. The natural fiber also known as kenaf (*Hibiscus Cannabinus L*) was supplied by National Kenaf and Tobacco Board from kenaf farm in Perlis and Kelantan states of Malaysia. Kenaf plant will undergo several processes, including, harvesting, decoating, retting and drying to become dried fiber. Conventional open drying method was replaced by utilizing solar energy using this solar dryer. The drying chamber was covered by polycarbonate material and concrete base floor. Figure 2 shows natural fiber was arranged by hanged inside the chamber for drying process.

Fig. 2. Natural fiber was arranged by hanged inside the chamber for drying process.

There are limited sources on kenaf drying. However, a brief review on drying process related to kenaf can be shown in Table 1. The table contained brief review on different medium of kenaf by using various methods and techniques.

Table 1. Several methods used to dry different medium of kenaf.

researcher	method	medium	outcome
[9]	solar assisted solid desiccant	core	drying can be performed during low level of irradiance. Drying time reduced 24% compared to open sun drying to achieve 18% moisture content
[22]	flatbed box with burner	leaves and stems	final moisture content, thermal efficiency and average cost (RM/kg water removed) are around 8.3%, 33-46% and RM 0.46 respectively
[23]	superheated steam	fiber	using readily available steam source in the kenaf factory. Reduce moisture content almost 100% in 15 minutes.
[24]	freeze-dried	seed	the method shows larger pore size and prevent degradation of bioactive compounds compared to oven drying.

[25]	oven drying	stem	testing on microwave rectangular waveguide resonator to identify moisture content of kenaf but only suitable for small diameter cross section sample area.
[26]	different drying time and threshing method	seed	the highest yield recorded at 7 days threshing time without drying process.
[27]	conventional open drying	leaves and stems	the most economic method but produce low quality of kenaf and expose to contamination.

2.2. Experiment Procedure

Several parameters were recorded from the ambient, chamber, fiber and appliances. The parameters, abbreviation and unit can be simplified in Table 2.

Table 2. Parameters measured during drying process.

Parameter, Abbreviation	Unit
irradiance intensity, IRR	W/m^2
ambient temperature, T_a	^{o}C
ambient humidity, RH_a	%
chamber inlet temperature, T_{in}	^{o}C
chamber inlet humidity, RH_{in}	%
chamber outlet temperature, T_{out}	^{o}C
chamber outlet humidity, RH_{out}	%
fiber weight, W	Kg
fiber moisture content wet basis, MC (w.b)	%
electricity consumption, E	kWh
electricity cost, C_E	RM

The irradiance intensity IRR was measured by using pyronometer model Epogee SP-110 with 0.2mV accuracy per W/m^2 and ±5 % uncertainty. Multiple thermocouples type-J (±2.2 ^{o}C or ±0.75 % accuracy) used measure temperatures of the ambient, inlet and outlet of the chamber. Relative humidity also detected at the same point as thermocouple by using KIMO complementary metal oxide sensor (±1 % accuracy). Weighting divided into two: sample and bulk weight. Sample weight was measured to determine to drying curve by using LCM tension load cell (<±0.03 % accuracy). A digital platform scale (max 300 kg and ±0.1 kg accuracy) was used for bulk weighting. It was taken before and after drying process and used to estimate performance of the dryer. The positions of sensors are illustrated in Fig. 3.

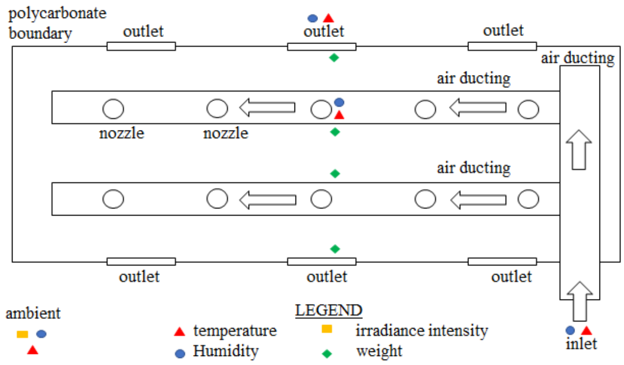

Fig. 3. Chamber top view and position of sensors.

The dryer consists of several appliances that consume electricity which are pump 1, pump 2, blower and auxiliary heater. Pump 1 circulate the heat transfer medium (water) between collector and storage tank. Pump 2 circulate the water between storage tank and air handling unit. Blower inside air handling unit will force hot air to flow into the chamber through inlet. Auxiliary heater used to supply backup heat and automatically operated within temperature range of the tank between 70 ^{o}C to 80 ^{o}C. Electricity consumption was measured by using kilowatt-hour meter with 0.1 kWh accuracy and ±0.05 kWh uncertainty. Electricity cost was determined by referring to Tenaga Nasional Berhad electricity tariff for agriculture. The tariff is 0.390 RM/kWh for the first 200 kWh per month and 0.472 RM/kWh for next kWh per month.

Moisture content wet basis w.b was determined by using oven drying method and calculation. The exact dry solid weight estimated by drying the sample at temperature 100 ^{o}C in 24 hours [4]. Another method by manipulating the relationship between weight W and mass m by using Eq. (1) [28,29].

$$W = \frac{m_o(M_i - M_f)}{100 - M_f} \quad (1)$$

Where m_o is initial mass, M_i initial moisture content fraction w.b and M_f is final moisture content fraction w.b

These parameters were recorded every 5 minutes interval by using data acquisition unit model Graptec GL820 data logger. Evaluation of the dryer was done by identifying several drying performances and selected economic aspects. Drying performance evaluation are evaporative capacity, specific moisture extraction rate and specific energy consumption. Selected economic aspect covers the drying cost which are cost of operation and cost of product. Determination of payback period also done based on the profit and annual return of investment.

Evaporative capacity EC indicates the amount of water extracted from the product in a certain period. If the amount of heat enough, EC will depend on the size of the dryer: bigger chamber will give higher value of EC. The unit is kg/hr and the calculation using Eq. (2).

$$EC = \frac{Wr}{t} \tag{2}$$

Where W_r is total weight reduction determined from bulk weight and t is drying time.

Another indicator is specific moisture extraction rate $SMER$, the moisture extracted by the consumption of 1 kWh electricity. This indicator is specific for solar dryer that consumed electric appliances such as pump, blower or fan and monitoring system. It is calculated by using Eq. (3) and the unit is kg/kWh [30,9].

$$SMER = \frac{Wr}{E} \tag{3}$$

Where E is electric consumption.

The performance of the dryer also can to be expressed by specific energy consumption SEC, the amount of energy required to extract 1 kg of moisture from the product. The unit is kWh/kg and calculated using Eq. (4) [28].

$$SEC = \frac{E}{Wr} \tag{4}$$

The electricity cost divided into two, which are cost of operation COO and cost of product COP. The electricity cost determined based on reading from the meter installed. Cost of operation COO represents the price equivalent to energy used to complete a single drying. Optimize amount of load must be determined to achieve the best value of COO. The unit used is RM/cycle and calculated using Eq. (5).

$$COO = \frac{C_E}{drying\ cycle} \tag{5}$$

Where C_E is cost of electricity based on meter reading and electricity tariff price.

Another economic aspect is cost of product COP, it is more specific value to represent the value of energy consumed to produce 1 kg dried product. The unit is RM/kg and determine by Eq. (6).

$$COP = \frac{C_E}{Wr} \tag{6}$$

3. Result and Discussion

The drying process was complete in 3 days or 14.58 hours. Final weight and moisture content are 415.8 kg and 29.3 % respectively. The IRR measured was fluctuated due to overcast and relatively high during middle of the day. Average value of IRR is 612.84 W/m^2, slightly low compare to other research [31]. Figure 4 shows IRR distribution during drying.

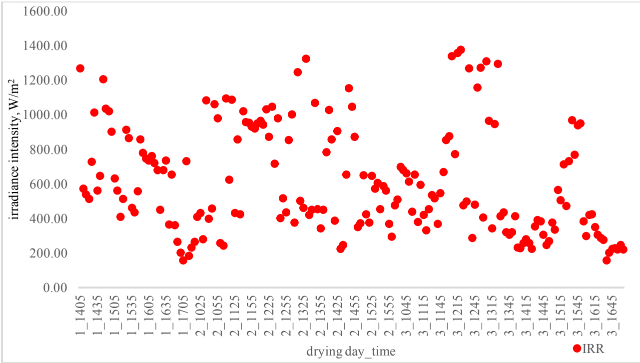

Fig. 4. Irradiance intensity during drying time

The ambient temperature T_a and relative humidity RH_a were observed and ranging between 27.70 ^oC to 36.90 ^oC and 47.53 % to 80.53 % respectively. Figure 5 shows the temperature and humidity. The average T_a is 32.42 ^oC and RH_a is 60.01 %. High T_a will produce better performance of solar thermal system, including solar dryer compare to solar PV system. The performance of PV system will decrease inversely proportional to T_a [32].

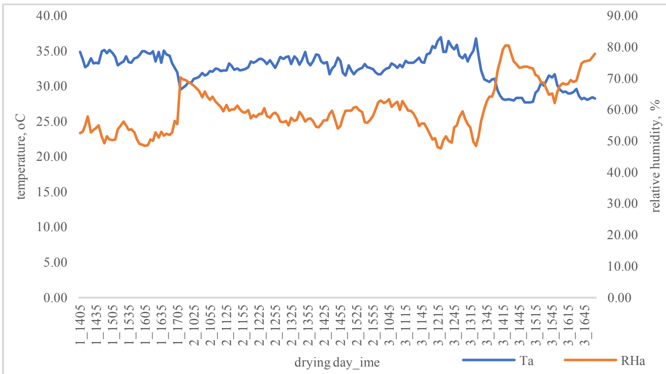

Fig. 5. Ambient temperature and humidity recorded

Observation on the chamber was done by measuring temperature and humidity at the inlet and outlet as shown in Fig. 6. Higher temperature at the initial drying process due to accumulated heat from the tank was released, the heat gradually decreases over drying time.

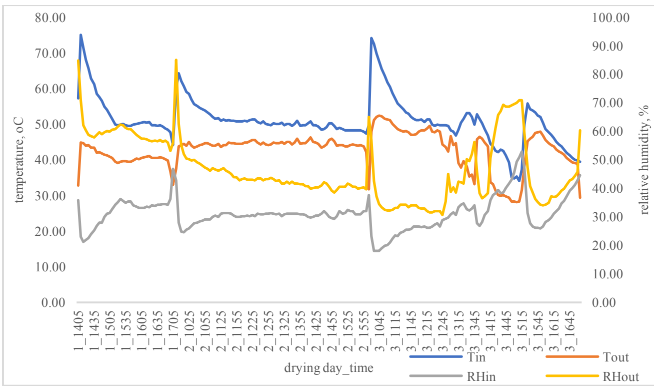

Fig. 6. Temperature and humidity of the drying chamber.

The temperature and humidity trend are inversely proportional each other, increasing temperature decreasing of humidity. Average values for T_{in}, T_{out}, RH_{in} and RH_{out} are 51.12 °C, 42.85 °C, 31.11 % and 46.94 % respectively. Lower T_{out} recorded compared to T_{in}. The temperature drop between T_{in} and T_{out} shows heat energy was absorbed by the fiber. Higher air humidity at the outlet compared to RH_{out} shows moisture was extracted from the fiber and carried out from the chamber by air. Figure 7 shows weight of the fiber samples from load cell sensors. The average weight was reduced from 5 kg to 1.23 kg.

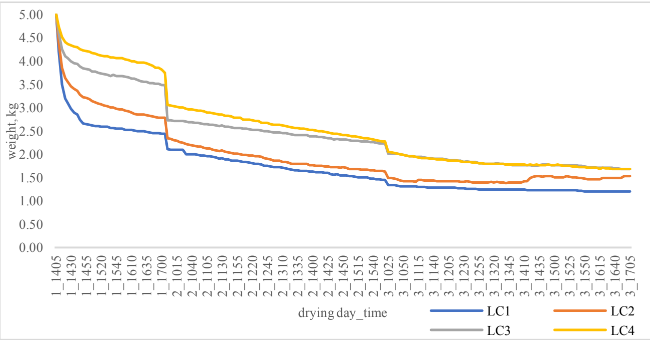

Fig. 7. Drying curve of the natural fiber.

Several information was gathered to estimate performance of the dryer and simplified in Table 3.

Table 3. Information used to estimate dryer performance.

Parameters	Total / different	Abbreviation
drying time	14.58 hr	t
weight reduction	1004.2 kg	W_r
electricity consumption	282.9 kWh	E
electricity cost	117.129 RM	C_E

The determination of EC, $SMER$ and SEC were based on Eq. 2 to Eq. 6 and Table 3. The EC or capability of the dryer to extract water out from the fiber is 68.88 kg/hr. The huge amount contributed by the size of the dryer. The $SMER$ of the dryer estimated as 3.55 kg/kWh. Each kWh electricity used able 3.55 kg of water to be extracted. The electricity consumption can also be measured by weight of the dried fiber. It can be reflected by SEC, where the determination is based on amount of electricity consumed to produce each kilogram of dried fiber. The value for SEC calculated as 0.28 kWh/kg. Table 4 shows comparison result from the experiment with other researchers.

Table 4. Comparison experimental result with other researchers.

researcher	kenaf medium	Load kg	EC kg/hr	$SMER$ kg/kWh	SEC kWh/kg
author	kenaf (fiber)	1420	68.88	3.55	0.28
[9]	kenaf (core)	155	-	0.18	-
[3]	palm oil fronds	100	-	0.29	-
[10]	red chili	40	0.97	-	5.26
[11]	seaweed	40	-	-	2.62
[12]	silver jewfish	51	-	-	2.92
[13]	copra	60	-	-	1.19
[14]	green peas	20	-	-	1.22-1.82
[15]	catfish	200	6.3	0.385	-
[16]	ghost Chili	20	-	-	18.72
[16]	ginger	13	-	-	8.82

In term of economic assessment, selected criteria of the dryer determined. The criteria are based on COO and COP. The value of COO is RM 117.13 per drying cycle and COP is RM 0.28 for each kilogram fiber produced. The profit per drying are based on Eq. (7).

$$profit = (W_f C_{dry}) - (W_i C_{wet}) \tag{7}$$

Where W_i and W_f are initial and final weight respectively. The C_{wet} if the cost of wet kenaf and C_{dry} is the cost of dry kenaf. Annual return of investment ROI and payback period PP estimated by using Eq. (8) and Eq (9).

$$annual\ ROI = profit \times drying\ batch\ per\ month \times 12 \tag{8}$$

$$PP = \frac{capital\ cost}{annual\ ROI} \tag{9}$$

The PP also can be illustrated as intersection of profit or annual ROI line as shows in Fig. 8.

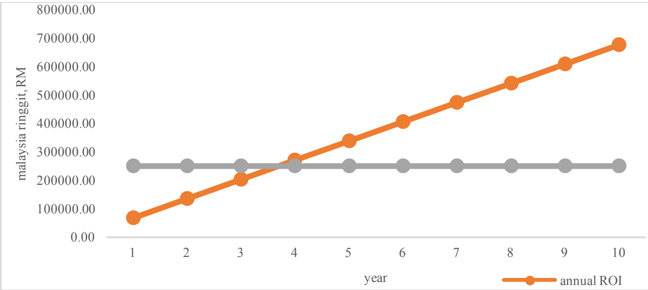

Fig. 8. The payback period based on annual ROI and capital cost of the dryer.

The capital cost of the dryer estimated are RM 250,000. The dryer is capable to perform 8 batch per month or 96 batch drying annually. From this estimation, annual production can achieve 39,916.80 kg dried kenaf. Based on these capital cost and annual ROI, the payback period of the solar drying system for kenaf fiber were estimated to be about 3.7 years.

4. Conclusion

This experimental work to evaluate large scale solar dryer was done by determining several performances including economic aspects. The values for EC, $SMER$, MER, COO and COP were calculated as 68.88 kg/hr, 3.55 kg/kWh, 0.28 kWh/kg, 177.13 RM/cycle and 0.28 RM/kg respectively. High value of EC and COO contributed by the large size of the dryer. Regardless the size factor, the values of $SMER$, SEC and COP can be used for comparison purpose. The dryer can be considered in excellent performance and the payback period estimated about 3.7 years.

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