DRYING OF EMPTY FRUIT BUNCHES (EFB) USING A SOLAR DRYING SYSTEM OF DOUBLE PASS SOLAR COLLECTOR WITH POROUS MEDIA

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by

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AC	Ash Content (mf wt %)
A	Collector area (m^2)
A_s	Plate surface area (m^2)
g	Gravitational constant (1 kg.m/N.S^2)
h	Convective heat transfer coefficient (W/m^2)
I	Solar irradiance (W/m^2)
k	Thermal conductivity (W/m·K)
L	Characteristic length of solar air heater (m)
M_f	Final moisture content (% dry basis)
M_i	Initial moisture content (% dry basis)
MC	Moisture content of the sample (mf wt%)
N_u	Nusselt number
P	Perimeter of plate (m)
Pr	Prandtl number (0.706)
R_{aL}	Rayleigh number
T_o	Outlet temperature (K)
T_i	Inlet temperature (K)
T_s	Surface temperature (K)
T_a	Ambient temperature (K)
T	Total temperature(K)
t	The total time (h),(s)
W_m	Weight of the sample before dry (g)
W_d	Weight of the sample after dried (g)

W_{SFD}	Weight of sample after second dried (furnace dry at 575^{o}C for 6h) (g)
W_{SOD}	Weight of sample after first dried (oven dry at 105^{o}C for 24h) (g)
W	Width of solar air heater (m)
α	Thermal diffusivity (m^2/s)
ν	Kinematics viscosity (m^2/s)
β	Volumetric thermal expansion coefficient, K^{-1}

LIST OF PRESENTED PAPERS

1. *'A Design and Construction of a Double-Pass Solar Drying System',* National Postgraduate Conference, Universiti Teknologi Petronas,Perak, 25-26 March 2009

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3. '*Temperature Variation of a Double-Pass Solar Drying System with Porous Media',* Persidangan Fizik Kebangsaan, Avillion Legency Hotel, Melaka, 7-9 December 2009.

ABSTRAK

Di dalam tesis ini, rekabentuk bagi sebuah sistem pengeringan suria dengan pengumpul suria dua laluan bermedia berliang dibentangkan. Sistem ini dibina berdasarkan cadangan yang dibuat oleh Ooi [1] dan dibangunkan bagi mengeringkan tandan sawit kosong (EFB) kepada kandungan lembapan kurang daripada 10 mf wt%. Dua set sampel disediakan bagi tujuan ini iaitu sampel yang dirawat dan yang tidak dirawat. Daripada keputusan yang diperolehi, suhu plat penyerap pengumpul suria melebihi 100^oC berjaya direkodkan pada keamatan suria melebihi $800Wm^{-2}$. Suhu laluan pertama dan laluan kedua, setinggi 80^oC dan 90^oC setiap satunya mampu dicapai pada cuaca cerah. Suhu maksimum kebuk pengeringan sebanyak 68^oC berjaya direkodkan. Oleh kerana sistem ini beroperasi secara perolakan lazim, purata kecekapan pengumpul yang direkodkan adalah kecil iaitu sebanyak 4.91% pada cuaca cerah dan 3.80% pada cuaca mendung. Walaubagaimanapun, sistem ini masih dianggap efektif kerana mampu mengeringkan sampel yang telah dirawat dengan kelembapan yang tinggi dalam tempoh masa yang sama dengan tempoh pengeringan bagi sampel yang tidak dirawat iaitu selama 66 jam. Daripada kajian ini, didapati bahawa kadar pengeringan bagi sampel yang dirawat adalah lebih tinggi daripada sampel yang tidak dirawat iaitu pada julat 8.54-12.96 kgh^{-1}(%) dan 3.54-7.27 kgh^{-1}(%) masing-masing. Kandungan abu kurang daripada 3 mf wt% bagi sampel yang dirawat berjaya dicapai. Manakala, kandungan abu bagi sampel yang tidak dirawat adalah lebih tinggi dari yang diinginkan. Ini menunjukan sampel yang dirawat sesuai digunakan dalam proses pirolisis bagi menghasilkan bahan *bio-oil.*

ABSTRACT

In this thesis, the design of a solar drying system of a double-pass solar collector with porous media is presented. The system was constructed based on suggestions made by Ooi [1] and developed to dry empty fruit bunches (EFB) to moisture content of less than 10 mf wt%. Two sets of sample were prepared for this purpose, which is the treated sample and the untreated sample. From the results obtained, the temperature of the absorber plate of the solar collector of up to 100^{o}C was recorded with solar radiation intensity of above 800Wm^{-2}. The temperature of the first and second passes of up to 80^{o}C and 90^{o}C respectively can be obtained on a sunny day. The maximum temperature of the drying chamber at 68^{o}C was successfully recorded. Since this system was operating on natural convection, the average collector efficiency recorded was as low as 4.91% for a sunny day and 3.80% for an overcast day. However, the system is considered effective since it was able to dry the treated sample with high moisture content in the same period of time as the untreated sample at 66 hours of drying. From this study, it was observed that the drying rate for the treated sample was much higher than the untreated sample which ranged from 8.54-12.96 kgh^{-1}(%) and 3.54-7.27 kgh^{-1}(%), respectively. The ash content of less than 3 mf wt% of the treated sample was successfully achieved, while the ash content for the untreated sample was higher than the desired ash content. This shows that the treated sample is suitable to be used in pyrolysis process for producing bio-oil.

CHAPTER 1 INTRODUCTION

1.1 INTRODUCTION TO SOLAR RADIATION IN MALAYSIA

Sun is the main source of energy derives for direct heat, wind energy, hydroelectric power and fossil fuel. Sun supplies energy for the living things and produces gravitational force to make earth stay on its orbit. Sun has a mass (M) of 1.99×10^{30} kg which is almost 3.3×10^{5} times bigger than earth's mass and radius (R) of 6.96×10^{8} m which is almost 109 times bigger than earth's radius [2]. Solar radiation is the energy emitted by the sun in the form of electromagnetic waves.

Peninsular Malaysia stretches from latitude 1.30^0N to 6.60^oN, and longitude 99.50^oE to 103.30^oE. East Malaysia consists of Sabah and Sarawak. Malaysia covers an area of 330,000 km^2. A study showed that Malaysia received average solar energy of 4.210 k Whm^{-2} to 5.159 k Whm^{-2} a year. The highest solar radiation received is estimated at 6.61 k Whm^{-2} in January while the lowest is 1.250 k Whm^{-2} in December. The figure of yearly average daily solar radiations for Malaysia is presented in Figure 1.1.

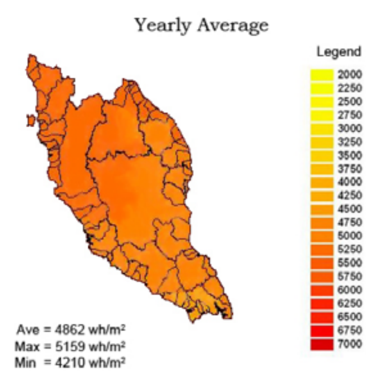

Figure 1.1 Yearly average daily solar radiations for Malaysia [3]

The northern region of Peninsular Malaysia showed the highest potential for solar energy applications as this area received the most solar radiation for almost every month including December. Figure 1.2 shows the monthly average daily solar radiation of Malaysia from January until December (2006) [3,4].

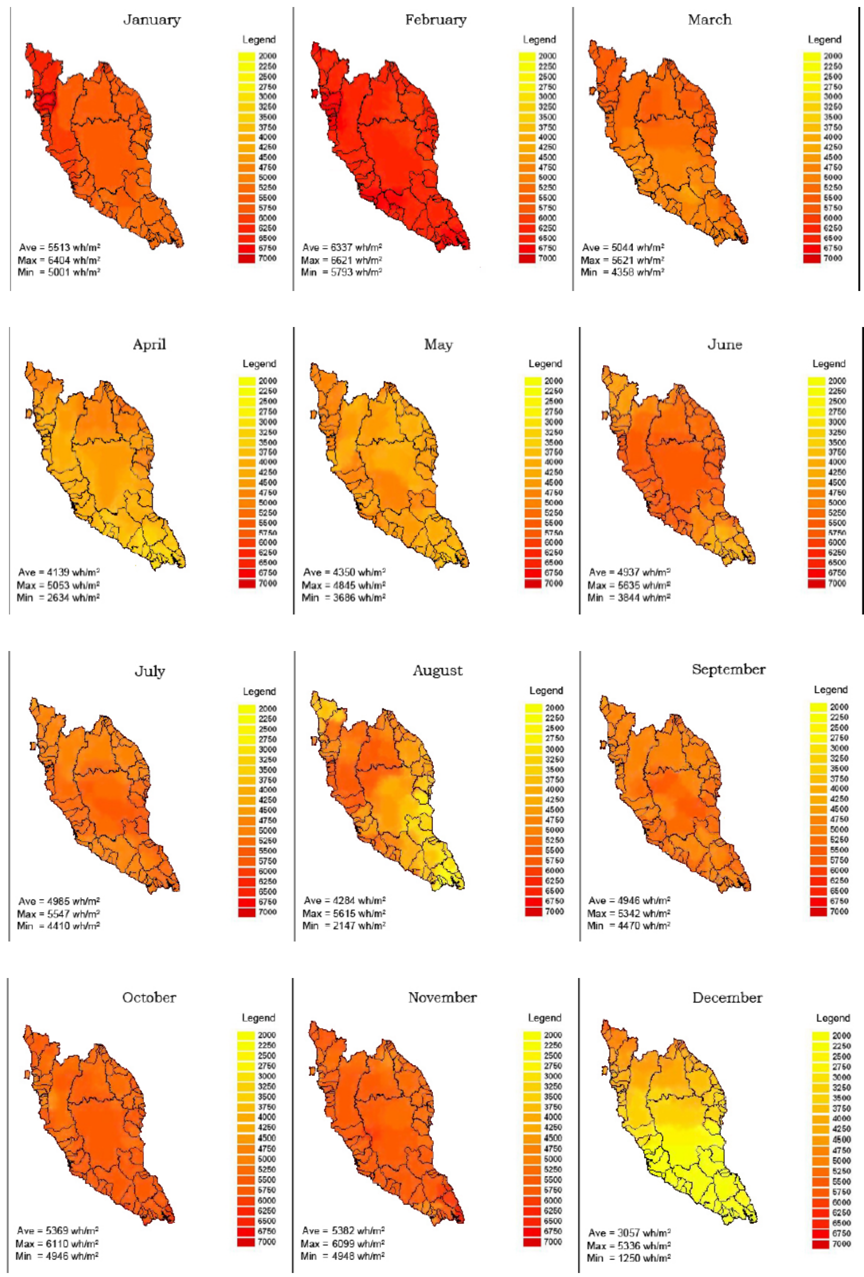

Figure 1.2 Monthly average daily solar radiation of Malaysia [3]

Malaysia is a tropical country with wet, dry climate and uniform temperatures throughout the year. The climate is influenced by the monsoon seasons in Asia. The south-west monsoon brings rain and cloud to the west coast from June to early October, while the north-east monsoon brings rain and cloud to the east coast from November to March. Therefore, the west coast is dry from November to March, while the east coast is dry from June until September. During the dry season, the climate is hot and sunny with intermittent breaks of cloud formation and hence rainfall in the late afternoons due to convection current.

Throughout the year the coastal regions experienced longer daily sunshine than the interior. The northern part of the north region consists of Penang, Perlis and Kedah has an average of 8.2 hours of daily sunshine during the period from January to April and an average of 5.6 hours from August to October. In general, maximum solar radiation occurred between 9:00 a.m. to 12:00 p.m. (local hour) in Peninsular Malaysia. However, Kuala Terengganu and Kota Bharu maximum solar radiation occurred slightly later between 11:00 a.m. to 14:00 p.m. The east coast of Peninsular Malaysia received less hourly average solar radiation in November and December, while the northern region of Peninsular Malaysia received less hourly average solar radiation in September and October.

Most places at the east coast of Peninsular Malaysia recorded long hourly average solar radiation in April while other places recorded long hourly average solar radiation in March. In East Malaysia, Kota Kinabalu received more solar radiation from March to May but Kuching received more solar radiation from July to August. Meanwhile, in

November and December, Kuching and Kota Kinabalu received less solar radiation due to the east Monsoon [4,5].

1.1.2 DAILY SOLAR RADIATION PATTERNS

Malaysia is a tropical climate country with high moisture and blotched cloud shape causes unpredictable solar radiation pattern. Referring to research done by Othman et al. (1993) in Bangi, solar radiation fluke's patterns are liable to change. It can be categorized that Malaysia has five patterns of solar radiation as below:

a. Solar radiation pattern on a bright day.

   On a bright day, the maximum solar radiation intensity is at $971Wm^{-2}$ and received total daily solar radiation at $6.957kWhm^{-2}$. Bright days like this rarely happened with a possibility of about 15.7%. This is because Malaysia has high air humidity that effectuated the solar radiation intensity emitted on earth.

b. Solar radiation on a perfect overcast day.

   Perfect overcast day is a day when the sky is covered by the clouds through the day since early morning until late evening. Days like this only happened at possibility of 13.7% that occurs on monsoon season that brings rain. The maximum solar radiation intensity is about $121.4Wm^{-2}$. Solar radiation intensity was recorded with less than $70Wm^{-2}$ for about 9 hours with total daily solar radiation at $0.50kWh/m^2$. On this day, the solar energy system might not be operated efficiently.

c. Solar radiation pattern on a cloudy day.

This type of solar radiation pattern is subject to change according to the changing of clouds pattern and its thickness. The maximum solar radiation intensity is 1142.9 Wm^{-2} with total solar radiation about 4.43$kWhm^{-2}$. This maximum temporary intensity is obviously higher than the intensity in a bright day. This phenomenon happened because of the existing solar radiation intensity that suddenly converges at one point and because of the reflection and refraction of solar radiation of air molecule, ash and aerosol that exists in the clouds. Almost 51% of the data that had been collected in Bangi are from this radiation pattern. This radiation pattern always happened especially in tropical country like Malaysia.

d. Solar radiation pattern with a solar intensity exceeding the solar constant.

This phenomenon rarely happened in Malaysia and had only happened at a percentage of 2.8% when the solar intensity is bigger than the solar constant (1353 Wm^{-2}).

e. Solar radiation with rain in the evening.

In Peninsular Malaysia, rain falls in the evening is a normal phenomenon that always happens in Malaysia due to the sea breeze that causes rain falls at the coast regions. Research showed that about 16.5% of rain in Bangi falls in the evening [4].

1.2 INTRODUCTION TO BIOMASS AND WASTE IN MALAYSIA

Malaysia has been using energy at about 340 million barrel of oil equivalent (Mboe) every year. The limitation of fossil fuels resources forced the world to start finding other alternative fuels. This caused the increased in interest in renewable energy sources which offer clean and substantial energy. Among the other renewable energy sources, biomass is considered as a primary source because Malaysia is an agriculture-based country which produced abundant of agricultural and forest waste that is potential for producing bio energy [6].

The total contribution of biomass to the primary energy supply of Malaysia has been estimated to be at least 2.5 million tons of oil equivalents (Mtoe) in 1995 [7,8]. In other words, the total contribution of biomass in agricultural sector is about 14% of the primary energy supply. The total biomass waste in Malaysia that has been used as energy supply is only 26.8% from its total value. The balance of 73.2% of the waste is not used and left to decompose naturally or by burning. If this waste has used to produce energy, it is expected that the biomass contribution for the energy utilization in the country would have increased to 53% [9].

1.2.1 STATISTICS ON BIOMASS AND WASTE IN MALAYSIA

Biomass is any organic material from plants or animals, includes agricultural and forestry residues, municipal solid wastes (MSW), industrial wastes and terrestrials, and aquatic crops [10]. Biomass seems to be a potential source of renewable energy for Malaysia compared with other sources. The use of biomass as source of energy such as in power generating or in other applications could help to reduce the un-used residues.

But it also requires some treatment including drying and other thermal conversion technology to produce energy. Malaysia has abundance potential of biomass resources [11]. They are mainly from palm oil (85%), MSW (9.5%), wood (3.7%), rice (0.7%) and sugarcane industries (0.5%) [12]. The productions of energy from biomass and its waste are potential to be used because they are more economical and could help to improve the environmental quality [13].

Palm oil industry represents the highest contributor among others and generates residues during the harvesting, replanting and milling processes. The residues that come from the milling process are fruit fibres, shells and empty fruit bunches (EFB) which have great potential energy resources. Other residues such as trunks and fronds are also available at the plantation area [14]. Palm oil mill effluent (POME) from the wastewater discharged from the sterilization process is also a potential fuel source.

The oil consists only about 10% of the total biomass produced in the oil palm plantation and other 90% are in the wastes form [15]. The total oil palm planted areas in Malaysia is about 4,304,913 hectares in year 2007 [16]. Approximately, 79,013,625 tonnes fresh fruit bunches (FFB) are brought to the mills in year 2007. From the processing of FFB, around 21%-22% empty fruit bunches (EFB), 12%-16% mesocarp fibres and 5%-7% shells are being generate from the mills [17,18]. About 75,900,000 tonnes residues generated in the form of oil palm fronds; 13,920,000 tonnes oil palm trunks and about 16,050,000 tonnes EFB and POME had been produced annually [9].

MSW is made up of organic (combustible) and non-organic (non-combustible) products. It was found that an average about 75% of MSW came from combustible material and the energy content of typical raw MSW is about 10000 kJ/kg [19]. According to Malaysia Energy Center (PTM), composition of MSW in Malaysia consists of 49% domestic, 24% industrial, 16% commercial institutional, 9% construction and 2% municipal consumption. In year 1994, about 5,048,804 tonnes waste are produced and about 7,772,402 tonnes waste will be produced by year 2015 with an increment of 54% [20,21].

The total forest areas in Malaysia are about 20.06 millions hectares (5.97 million hectares in Peninsular Malaysia, 4.25 million hectares in Sabah and 9.84 million hectares in Sarawak) of natural forest which is 61% of total land area [22]. However, due to the concerns for environmental conservation only 1.29% of the total area are allowed for logging industry. Wood industries referred to the saw milling industry, logging industry, furniture industry, panel product industry (plywood, veneer, particleboard and medium density fibreboard) and mould industry.

These industries generate residues equivalent to half of the raw wood it processes, known as sawdust, wood barks and offcuts [14,23]. In year 2007, around 4,647,429 volume m^3 of logs; 2,487,340 volume m^3 of sawn timber; 333,815 volume m^3 of veneer; 341,818 volume m^3 of moulds; 1,125,975 volume m^3 of fibrewood and 4,372,034 volume m^3 of plywood has been exported by Malaysia [24].

Rice, the staple food for Malaysians, produces abundant residues potential for energy generation. The total of paddy planted area in Malaysia increased from 671,820 hectares in 2003 to 676,111 hectares in 2007. Malaysia produced about 2,257,037 tonnes of paddy in 2003 and 2, 375,604 tonnes of paddy in 2007 and estimated to be increased about 27% by the year 2015. Main residues generated during the harvesting and milling processes of paddy are paddy straws (40%) and rice husk (22%). A rice mill produces about 220 kg of husk [14,17, 25,26].

Bagasse is the residue generated from sugar industries. A sugar milling plant produces around 290 kg of baggase by processing a tonne of raw sugarcane. At present, Malaysia sugarcane planted areas are 14,670 hectares and produce about 733,500 metric tonnes of sugarcane. Bagasse is used in sugar mills to generate power and steam for their own consumption [17,27].

Other biomass resources are from animal wastes and plant cultivations, include cocoa bean, tea, pepper, fruits, vegetables, cash crops, flowers, spices, pineapples and herbs. Currently, oil palm waste (51%) and wood waste (27%) are used to produce steam and also for generating electricity. Biomass fuels contribute to about 16% of the energy consumption in the country [17].

Malaysia has great potential of biomass resources and widely used for heat and power generation through combustion process. Because of Malaysia is a humid country, only small proportions of biomass are being used as fuel [28]. This fuel is difficult to handle due to its low calorific value, low density, inconsistence quality, and seasonal supply. For effective use of biomass, a simple pre-treatment of biomass is required by shredding to reduce the size and by drying to reduce the moisture content [17]. For example, EFB used as fuel in palm oil mill processing plant need to be dried until the moisture content reaches about 40% and the burnt waste is used as fertilizer in plantation [29].

The design of the dryer in this study will be discussed by considering the solar energy as an alternative way to dry biomass and its waste. Utilization of the suitable solar drying system will help to improve the quality of the product to be dried. There are many researches in this area that have been conducted in order to improve its utilization.

1.3 DEFINITION AND METHOD OF DRYING

Drying is one of the most important processes in agricultural industry. Drying is a process to remove water from the products and also known as dehydration. This process involves removal of biologically active water to reduce the growth of microorganism [30].

There are two reasons why agricultural products need to undergo the drying process. First, the agricultural products were dried to achieve standard value of moisture content to avoid from damage and also to increase the storage life of the products. However, if the products were dried over the drying limit, the products will become brittle and shrunken which cause decreases in the quality and also the quantity of the products. Second, the products were dried to possibly let the chemical reaction occur to recovering the energy of the products [31].

Products with moisture content of less than 10 mf wt% are required to avoid from microorganism attack thus affecting the end-product quality. This is because microorganism cannot grow on the product with moisture content less than 10mf wt%. This happened when the enzymes inside the products became inactive due to the less water content of the products. Therefore, the growth of microorganism on the product becomes ceased. Besides, the products also lose its weight during drying process which makes it easy to manage or move from one place to another. The density of the products is also reduced thus makes it easy for storage [32,33].

There are a few methods of drying that is normally used for drying of agricultural products. Traditionally, open sun drying is used in drying purpose. This method of drying is used since ancient time. The products to be dried are placed under direct sun radiation during the drying process. The products are kept at the drying field during the day time and need to be removed from the field during night or in poor weather condition such as in raining days. A place for storage system needs to be provided to store the products during those periods. Although this method is very economical where the source of energy is free and sustainable, it also has some disadvantages. For example, weather dependent and losses in product quality such as discolour, nutrition content and aroma [34]. Besides, this method of drying is difficult to control and exposed to contamination, infestation and microbial attack. Other than that, the drying times are much longer differed than the other method of drying. For products with large quantities, larger drying area and more manpower is required to supervise the drying process [35,36,37,38].

Other method of drying is by using a conventional oven. However, this method is considered expensive. Besides, this method increases the dependence on the non-renewable energy. The used of conventional oven also can be quite dangerous when the products were dry in unsupervised environment for a long period of time because the drying time of some products can be quite long. For example, to dry a whole bunch of EFB sample to moisture content less than 10%, more than one day of drying is required which means that the oven need to be operated at 105^{o}C at more than 24 hours continuously [29]. However, to reduce the drying time, the used of convectional oven could be considered. Besides, the temperature of the oven can be fixed to a constant temperature value throughout the drying process and produce consistent quality products [39].

Other than that, the products also can be dried using a solar drying system. This system is more efficient to be used in countries with hot climate. The system has three types of drying modes: direct, indirect and mixed-mode that will discuss further in Chapter 2. The system also can be operating in passive or active mode. Passive dryers use only the natural movement of heated air and can be constructed easily with inexpensive, locally available materials. No additional blower or fan is used in this type of dryer to force the air inside the dryer [40].

Active dryers required an external means, like fans, blower or pumps, to drive the heated air from the collector area to the drying chamber, thus increase the performance of the drying system. An auxiliary heat source using an Liquefied Petroleum Gas (LPG) burner also can be used to drive the heated air from the collector to the drying chamber [41].

Therefore, this type of dryer is not suitable for the direct mode dryer system. These dryers can be built in almost any size, from very small to very large, but larger systems are most economical. Instead, the utilization of auxiliary energy such as diesel, gas and electricity can be integrated in some parts of the system. The dryer is best used for big industries [42].

1.4 THE ADVANTAGES OF A SOLAR DRYING SYSTEM

Compared to some other methods of drying, the use of solar drying system is still new in Malaysia. This method of drying gives a lot of advantages to the user as it is easy to operation. Besides, it helps to reduce the dependence of non-renewable energy. Compared to conventional oven drying, the use of the solar drying system is considered economical, free and sustainable. Other advantages of the solar drying system of this research work are as below:

a. Clean and easy to operate.

b. The output temperature of the system is higher than open sun drying.

c. Protected against contamination of microorganism, dust, birds and insect.

d. Protected against poor weather condition such as rain and wind.

e. The drying rate of the product is shorter than in open sun drying.

f. Economical compared to conventional oven drying.

g. Produced better end-product quality.

h. The product can also be stored in the dryer even at night.

i. Suitable to be used in rural area without electricity.

1.5 RESEARCH OBJECTIVE

In this study, the design of the solar drying system is shown. This system, consisted of six solar collectors is design based on the suggestion made by Ooi [1]. The samples used in this study are EFB of oil palm waste. This type of sample is chosen accordingly to a research done by Abdullah which showed that the EFB sample is a potential biomass waste for producing bio-oil [29].

Besides, Malaysia as the largest oil palm producer produces abundant of this waste annually. It is expected that this solar drying system will be an alternative way to dry biomass and waste for other applications to reduce the dependence on non-renewable energy sources. The objectives of this study can be classified is as below:

a. To design and construct a solar drying system that consists of six solar collectors and a drying chamber using local materials.
b. To study the temperature variation of the system and solar radiation intensity during the test run.
c. To apply the pre-treatment process on the EFB sample including cutting, washing and drying process.
d. To study the drying characteristic of the EFB sample for treated and untreated samples.
e. To study the quality of the dried samples in terms of moisture and ash content of the sample for both treated and untreated samples.
f. To evaluate the efficiency of the drying system including the collector efficiency and the drying efficiency.

CHAPTER 2 REVIEW OF SOLAR DRYING SYSTEM

2.1 INTRODUCTION

This chapter discussed about the basic components of a flat plate solar collector and a solar drying chamber. The types of solar dryer includes direct, indirect and mixed-mode dryer, and the review of solar drying system in Malaysia and other countries are also discussed in this chapter.

2.2 BASIC COMPONENTS OF A FLAT PLATE SOLAR COLLECTOR

A collector is the main component in an indirect solar drying system performed as heat exchanger. An efficient collector should have the ability to transform the incoming solar radiation into heat and transfer it to air that enters into the collector [43]. In a solar drying system, the performance of the system is influenced by the performance of the collector. Several researches have been conducted in order to find an efficient solar collector. It was found that the efficiency of a double pass solar collector is more efficient with 10%-15% higher than a single pass solar collector. This type of solar collector was introduced by Satcunanathan and Deonarine in 1973 [44,45,46].

After that, several researches have been conducted by other researchers to improve the performance of the double-pass solar collector. The uses of porous media has been introduced and applied in the second pass of the collector to increase the performance of the collector [47,48,49]. It was found that the efficiency of the collector with porous media is higher than without porous media [47,50,51]. Therefore in this study the solar collector of double-pass with porous media was used in order to obtain higher outlet temperature of the solar collector to enhance the performance of the solar drying system. The design of this solar drying system is further discussed in Chapter 4.

The diagrams of a single pass and double-pass solar collector are showed in Figures 2.1 and 2.2.

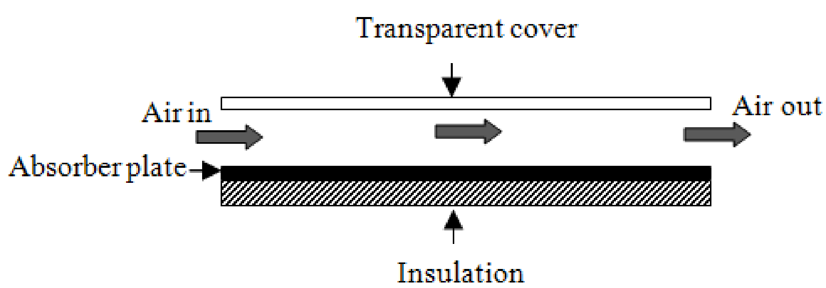

Figure 2.1 Side view of a single pass flat plate solar collector [47]

In a single pass solar collector, air entered the collector through the entrance set between the glass cover and the absorber plate. The air then was heated by the direct solar radiation that entered through the glass cover and also heated by the absorber plate which then trapped the heat in the collector and exits the collector to the drying chamber.

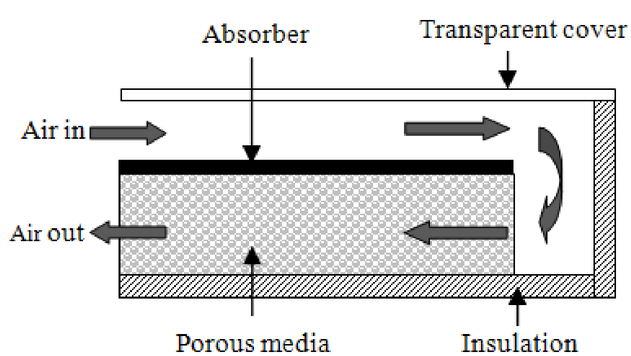

Figure 2.2 Side view of a double pass flat plate solar collector [48]

For double-pass type solar collector, air entered the collector through the first pass of the collector between the glass cover and the absorber plate and flowed to the second pass of the collector. Porous media can be install in the second channel to helps to extended the surface area and help to increase the heat transferred to the air stream.

Basically, for drying purpose, a flat plate solar collector is normally used compared to the other types of collector. This is due to its low cost and easy to operate. Besides, this type of solar collector provides sufficient area to transfer heat from the absorber plate to the air stream. A solar collector mainly consisted of a transparent cover, an absorber plate, thermal insulation, working fluid (air in this case) and a collector's frame [52].

2.2.1 TRANSPARENT COVER

Heat loss through the upper side of a solar collector can be minimized by placing a transparent cover on the top of the collector. It allows short waves radiation from the atmosphere to pass through it but blocked the longer wavelength which is reradiated from the absorber plate and traps the heat in the collector similar to that of the green house effect. Therefore, it helps in increasing the temperature inside the collector and the collector's efficiency [53].

More than one transparent cover can be used to improve the performance of the collector thus minimize the heat losses from the upper side of the collector. However, the radiation transmittance value of the transparent cover is decreased by increasing the number of the transparent covers [54]. Glass and plastic are the most suitable materials to be used as the cover.

However, the uses of transparent plastics such as polycarbonates and acrylics have a lot of disadvantages compared with the use of glass. Even if the used of plastics is cheaper and resistance to breakage, the lifetime of the transparent plastics is short due to the effects of ultraviolet radiation. Besides, their transmittance for the longer wavelength is also high and not as good as glass for trapping the heat, resulting in more heat losses [53].

Other than that, the transparent cover is also used as the top cover for the collector to protect the absorber plate from rain. It is important to keep the surface of the transparent cover always clean and clear from dirt and dust. The presence of dirt will reduce the performance of the collector. A study done by Garg in 1974 [55] showed that, the heat transfer coefficient of the transparent cover covered with dust reduced about 8% compared with clear cover.

Besides, the performance of the collector can be improved by applying the transparent honeycomb plate, made of thin-walled glass tubes between the double layer transparent cover. Fiberglass Reinforce Plastic (FRP) material can be used as top cover for this purpose to support the plates. Honeycomb structures suppress the natural convection and obstructed the infrared radiation heat loss. It is found that the air temperature of the collector with honeycomb was higher than without honeycomb [56]. Furthermore, the solar transmittance of a transparent cover can be improved up to 6% by applied antireflective (AR) coating to the cover [57].

2.2.2 ABSORBER PLATE

The performance of a collector is strongly influenced by the performance of the absorber plate. The absorber plate is the main element for the conversion of solar energy into thermal energy in a collector. The function of an absorber is to absorb solar radiation as much as possible and to transfer the heat to the working fluid in an efficient way.

To reduce the radiation emittance by the absorber, the surface of the absorber plate is painted black. On the other hand, black painted absorber also helps to increase the absorber’s absorption value. The absorptance value of the absorber plate which is painted black ranged between 0.89-0.96 [58].It is found that the efficiency of the coated absorber plate is higher than the uncoated absorber plate. Besides, it helps to minimize the heat losses of the absorber plate [59].

Materials with high absorptance and low emittance values such as iron, aluminum, steel and others are suitable to be used as absorber plate. The surface area of the absorber also affects the collector’s efficiency. The bigger the absorber area, the more solar radiation will be absorbed and the more heat will be transferred to the working fluid [60,61].

There are two main types of absorber for solar air collector; which are plate absorber and matrix absorber. Plate absorber is made up of metal plates where air flows over and under the plate surface (shown in Figure 2.3). Matrix absorber plate can be made from a thick porous bed or a set of black wire screens (shown in Figure 2.4). In this type of absorber the air flows through the matrix absorber [62,63].

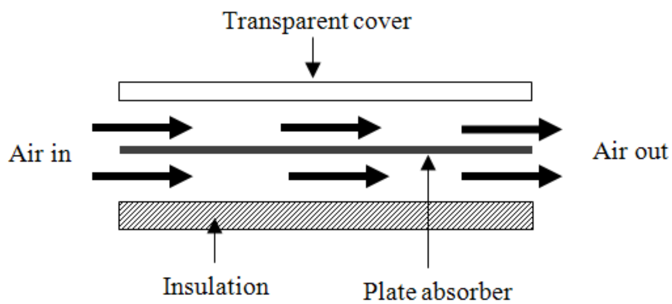

Figure 2.3 Side view of a solar collector with plate absorber type [61]

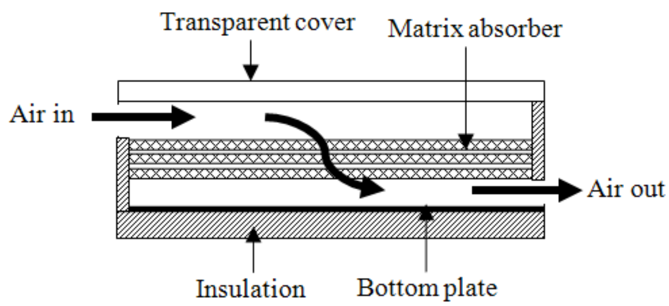

Figure 2.4 Side view of a solar collector with matrix absorber type [64]

A study done by Hassab in 1989 [62] showed that, a matrix absorber of uniform screens with different mesh sizes is also suitable to be used as absorber plate for solar collector applications. He found that compared to the absorber with mesh of the same size, the absorber with different mesh sizes gave higher collector's performance. He also found that the heat losses through reradiating and convection to the surrounding can be reduced by applying multiple layers of mesh screens as absorber. However, the efficiency of the collector reduces if the number of screens is increased over 5 to 6 pieces because the effective radiation cannot be received by the lower layer. It is seen that absorber with small porosity (larger number of wires) in their lower layers absorbed more energy than absorber with larger porosity (smaller number of wires).

To increase thermal efficiency of the collector, several researches have been conducted in order to find the best design of the absorber plate thus improved the heat transfer to the air flow in the collector. Garg et al. in 1991[65] has introduced the absorber plate with fins attached. It is found that the efficiency of the collector with fins attached to the absorber plate is higher than without fins. The fins also helped to increase the heat transfer thus increased the outlet temperature.

Kurtbas and Turgut [66] in 2006 studied the solar collector with free and fixed fins. They found that collector with fixed fins attached on the absorber plate was more effective than free fins absorber plate. It was obtained that the efficiency of the collector for free and fixed fins increased 1.35 and 1.44 times than other flat plate collectors.

Karim and Hawlader [67] in 2004 have performed an experimental study on three types of solar collectors with flat plate absorber, finned absorber and V-corrugated absorber. They reported that the most efficient collector is a collector with V-corrugated absorber. They also found that the collector with flat plate absorber is less efficient among other types of absorber. However, to enhance the performance of the flat plate absorber, porous media could be applied in the flow channel. The function of porous media is discussed further in Section 2.2.5.

Other studies include investigations on corrugated absorber plate [68], porous absorber plate [69], solid matrix absorber [70,64], metal matrix absorber [71], absorber plate with different roughness element [72] and V-groove absorber plate [50,73]. It is also found that to achieve better thermal performance, a small size of the V-groove absorber with high absorptivity of solar radiation should be considered [50]. The efficiency and the outlet temperature of the V-groove collector increased when the channel flow depth decreased [73].

2.2.3 THERMAL INSULATION

To prevent heat losses from the sides and bottom, the collector should be insulated with materials of low thermal conductivity such as polystyrene, fibreglass, glass wool, mineral wool and others [74,75,76]. Other than that, the collector also can be insulated with flat thermocol sheet [77]. The performance of the collector can be improved by using a good thermal insulation.

2.2.4 COLLECTOR'S FRAME

The collector's frame must be made of strong materials that can endure the hot and rainy seasons. It also acts as an insulator if made up from material with low thermal conductivity [43]. Galvanized iron sheet and steel are suitable to be used as collector's frame. They are strong and can endure poor weather condition such as rainy seasons [77,78]. Other than that, wood also can be used as collector's frame. It is cheaper than other materials. However, this type of material needs high maintenance due to its low endurance to poor weather conditions. Glass wool sandwiched between two galvanized iron sheets also can be used as collector's frame [79].

2.2.5 POROUS MEDIA

The performance of the collector also can be improved or enhanced by using porous media to the air flow channel. Porous media formed an extensive area for heat transfer. It enhanced the heat transfer from the absorber to the air stream. As a result, the air temperature of the collector with porous media is higher than without porous media. It is found that the heat transfer rate of the collector with porous media is 25.2% higher with the efficiency increased about 20%-40% than without porous media [80,63,64].

For double-pass type collector, the porous media which is placed in the second pass will increased the air temperature of the second pass. Besides, porous media also act as storage system where it helped to maintain the temperature of the second pass even on poor weather condition [48]. A study done by Sopian et al. [51] showed that the typical thermal performance of the double-pass solar collector with porous media is about 60%-70%.

Yousef and Adam [81] studied a mathematical simulation to predict the effect of different parameters on the performance of the single and double-pass flat plate collector with and without porous media. They found that the efficiency of the double-pass collector with porous media gave the highest result. Besides, with increasing the mass flow rate through the collector, the efficiency and pressure drop of the collector is also increased. The collector with small depth resulted in higher collector efficiency that increased the outlet temperature of the collector. The collector length also has an effect to the performance of the collector. It was found that, the collector with short channel is more efficient than with longer channel.

A mathematical simulation to predict the effect of different parameters on system thermal performance of V-groove absorber in single and double flow mode with and without porous media have been developed by Bashria et al. [50] in 2007. They found that the efficiency of the solar collector with double flow is 7% higher than single flow. It is also obtained that the efficiency of the double flow collector with porous media is 2%-3% higher than without porous media.

According to Choudhury and Garg [82], the types of material used as porous media is not giving much effects to the performance of the collector. The material with smaller size (diameter) gave higher performance to the collector. Besides, the shape of the porous media also should be considered. This is because the materials with cylindrical shape will give higher performance followed by spherical and ring shape materials

However, a research done by Ramadan et al. [83] in 2007 showed that the material used as porous media also showed some effects to the performance of the collector. They found that the thermal efficiency of the double-pass solar collector without porous media was only 41.4% while, the thermal efficiency of the collector with limestone and gravel as porous media was 55.8% and 57.2% respectively.

Other than that, material such as steel wool [48], glass wool [81], iron scraps [84], iron-chips, aluminum-chips and pebbles packing [85] can be used as porous media in a solar air collector.

2.3 BASIC COMPONENTS OF A DRING CHAMBER

Drying chamber is an enclosed area used to place the product that will be dried. Therefore, the drying chamber should be well constructed. The hot air from the collector will enter the drying chamber through the entrance which is normally at the bottom side of the drying chamber. There are three types of drying chamber that are suitable to be used to dry biomass product. First is the indirect drying chamber which is fully dependent on the heated air from the solar collector. Second is the direct dryer where no auxiliary heater is applied to the drying chamber, also known as box or cabinet type dryer. This type of dryer used only direct solar radiation coming from the top cover. The third is the drying chamber with mixed-mode operation, which is a combination of direct and indirect type of dryer where the product is dried by the heated air which is supplied from the solar collector and from direct radiation.

The drying chamber has internal and external walls that is made up of strong materials and can endure hot and rainy seasons. The use of high thermal conductivity materials such as zinc, aluminum sheet and others materials for internal walls can help to improve the heat transfer process. To improve the performance of the drying chamber, the internal walls can be painted in black to enhance the absortance value of the plate. To reduce the heat losses through the walls, insulation should be installed between the internal and external walls. Materials with lower thermal conductivity are suitable for this application such as fibre glass, air and polystyrene. For external walls, materials such as concrete and bricks are suitable to be used [86,87].