CHAPTER 1
INTRODUCTION

1.1 Background of Study

In many countries of the world, the use of solar thermal systems in the agricultural area to conserve vegetables, fruits, coffee and other crops has shown to be practical, economical and the responsible approach environmentally [2]. The traditional method of solar drying which is by open air often results in food contamination and nutritional deterioration. Some of the problems associated with open-air drying can be solved through the use of solar dryers, depending on the mode of heating or operation which are direct, indirect and mixed mode systems with natural or forced circulation. However, the used of solar energy is limited only on the daytime. In case of low solar irradiation during the day, the drying process can be backed up by a biomass heater. Biomass heater is the alternative way where the biomass will be heated along the night or cloudy days to continue the drying process. Both solar and biomass energy are renewable energy that uses natural resources. Solar energy used the sunlight as the main source while biomass energy production supplied by agriculture. Integration both of this renewable energy will create a 24 hour per day of drying process.

1.1.1 Empty Fruit Bunch (EFB) Fibers Drying

This project aims to investigate the drying performance of solar dryer and biomass backup heater model by drying empty fruit bunch (EFB). Malaysia’s palm-oil industry currently operates more than 300 palm oil mills that process palm oil from 2.5 million hectares of oil palm estates throughout the country and produce more than a million metric tonne of EFB as waste material every year [16]. In the past, EFB waste was either burnt off or left mulching on the ground neither of which is environmentally and economically viable. The EFB fibers are however found to be strong and stable and could be processed easily into various dimensional grades to suit specific applications in mattress and cushion manufacture, soil stabilization/compaction for erosion control, landscaping and horticulture, ceramic and brick manufacture and flat fiber board manufacture. The choice and selection of fibre length is very much dependent on the nature of the manufactured product. For example, long fibre length is suitable for mattress and short fibre makes excellent particle board. Inherent characteristics such as high moisture content will have a detrimental effect on the oil palm residues. Degradation and infection will easily take place thus leading to deterioration in the properties of the fibres. The initial moisture content of EFB is 67% (on wet basis).The fibers are usually dried to a moisture content of less than 8% (on wet basis) before proceeding to another process. This value is comparable to the moisture content for all wood-based fibres [16]. Refer to *Appendix-A* for the picture of EFB fibres.

1.2 Problem Statement

Open-air sub drying has been used since time immemorial to dry plants, seeds, fruit, fish, wood and other agricultural or forest products as a means of preservation. An alternative to traditional drying techniques and a contribution toward the solution of the open-air drying problems is the use of solar drying. Solar dryer technique is the most common way to remove or decrease the percentage of moisture, which means to remove the quantity of water in agricultural crops. As for any other solar system, there is a lack in availability of the solar radiation for continuous operation. Accordingly, there should be auxiliary source of energy to compensate the solar radiation. This will be the study on a solar dryer integrate with the biomass burner as a back up heater.

1.2.1 Significance of Project

One of the most significant potential applications of solar energy is drying. It is the oldest of stabilization operations of agricultural products practiced by people. The drying of various products and matters is intensively carried out in the industry and agriculture. Its mechanism, typically non-stationary and based on complex mass and heat transfer laws, is well known. Its particularly resides in the fact that the departure of water molecules from the products is done due to the difference in water vapor partial pressure between the product surface and surrounding air. This difference in partial pressure is obtained by heating of air circulating in natural convection in a collector.

In case of low solar irradiation during the day especially at night or in the cloudy days, the usage of biomass is to be investigated as a backup heater to enhance the performance of solar dryer. Both sources will function together where solar radiation is the main heat source integrated with biomass heating back up. The biomass resource can be considered as organic matter in which the energy of sunlight is stored in chemical bonds. Biomass energy is generated when organic matter is converted to energy. By using the solar-biomass mode of operation, drying will proceed successfully even under unfavorable weather conditions.

1.3 Objectives of the Project

The objectives of the project are as follow:

1. To design and fabricate hybrid solar dryer with biomass burner as back up heater.
2. To carry out the preliminary experimental investigation.
3. To investigate the integration of biomass as heat source to enhance the performance of hybrid solar dryer.

1.4 Scope of Study

Biomass is a dominant source of energy and commonly burned using inefficient technologies in most developing countries. This resource can provide the required backup thermal energy for solar drying. However, information is scarce on solar drying with integrated collector-storage solar and biomass-backup heaters. The scope of the present study was therefore to develop a solar dryer with a storage component for both solar and biomass thermal energy. The scope of study can be summarized as following:

1. To study on the mechanism of solar energy and solar drying system.
2. To investigate and identify several ways of solar drying with biomass integration methods.
3. To carry out the design for the selected hybrid solar dryer and burner.
4. To make research on the best design criteria of the solar dryer and biomass burner as a back-up heater.
5. To analyze the materials that is going to be used in the model.

CHAPTER 2
LITERATURE REVIEW

2.1 Mechanism of Drying

Moisture held in loose chemical combination, present as a liquid solution within the solid or even trapped in the microstructure of the solid, which exerts a vapor pressure less than that of pure liquid is called bound moisture. Moisture in excess of bound moisture is called unbound moisture (Mujumdar, 2005) which is covered in this study. The moisture contained in a wet solid exerts a vapor pressure to an extent depending upon the nature of moisture, the nature of solid, and the temperature. A wet solid exposed to a continuous supply of fresh gas continues to lose moisture until the vapor pressure of the moisture in the solid equal to the partial pressure of the vapor in the gas. The solid and gas are then said to be in equilibrium, and the moisture content of the solid is called equilibrium moisture content under the prevailing conditions. Further exposure to this air for indefinitely long periods will not bring about any additional loss of moisture. The moisture content in the solid could be reduced further by exposing it to air of lower relative humidity.

There are two methods of removing unbound moisture which are evaporation and vaporization (Mujumdar, 2005). Evaporation occurs when the vapor pressure of the moisture on the solid surface is equal to the atmospheric pressure. This is done by raising the temperature of the moisture to the boiling point. Second in vaporization, drying is carried by convection that is by passing warm air over the product. The air cooled by the product, and moisture is transferred to the air by the product and carried away. In this case, the saturation vapor pressure of the moisture over the solid is less than atmospheric pressure.

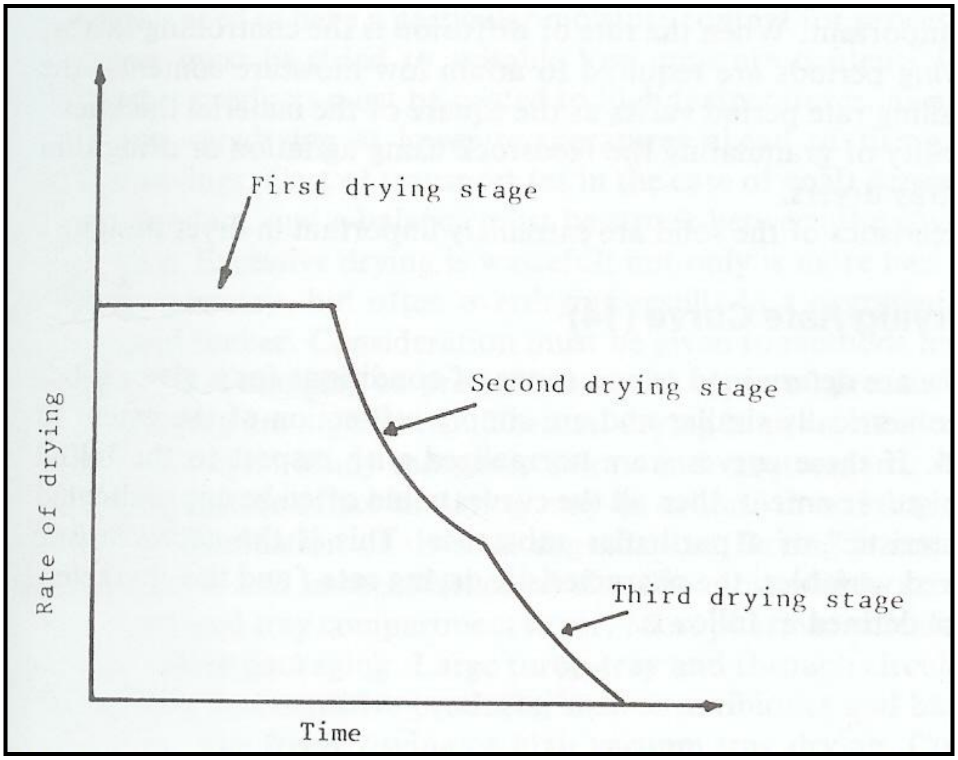


Figure 2.1: Typical rate-of-drying curve, constant drying conditions (*Reference No. 1*)

Products that contain water behave differently on drying according to their moisture content. The drying process can be divided into 3 stages as shown in Figure 1. During the first stage of drying the drying rate is constant. The surface contains free moisture. Vaporization takes place from there, and some shrinkage might occur as the moisture surface is drawn back toward the solid surface. In this stage of drying the rate-controlling step is the diffusion of the water vapor across the air-moisture interface and the rate at which the surface for diffusion is removed. Toward the end of the constant rate period, moisture has to be transported from the inside of the solid to the surface by capillary forces and the drying rate may still be constant.

When the average moisture content has reached the critical moisture content X_c, the surface film of moisture has been so reduced by evaporation that further drying causes dry spots to appear upon the surface. Since, however, the rate is computed with respect to the overall solid surface area, the drying rate falls even though the rate per unit wet solid surface area remains constant. This gives rise to the second drying stage or the first part of the falling rate period, the period of unsaturated surface drying. This stage proceeds until the surface film of liquid is entirely evaporated. This part of the curve may be missing entirely, or it may constitute the whole falling rate period.

On further drying (the second falling rate period or the third drying stage), the rate at which moisture may move through the solid as a result of concentration gradients between the deeper parts and the surface is the controlling step. The heat transmission now consists of heat transfer to the surface and heat conduction in the product[1]. Since the average depth of the moisture level increases progressively and the heat conductivity of the dry external zones is very small, the drying rate is increasingly influenced by the heat conduction. However, if the dry product has a relatively high bulk density and a small cavity volume with very small pores, drying is determined not so much by heat conduction but a rather high resistance to diffusion within the product. The drying rate is controlled by diffusion or moisture from the inside to the surface and then mass transfer from the surface. During this stage some of the moisture bound sorption is being removed. As the moisture concentration is lowered by the drying, the rate of internal movement of moisture decreases. The rate of drying falls even more rapidly than before and continues until the moisture content falls down to the equilibrium value X* for the prevailing air humidity and then drying stops. The transition from one drying stage to another is not sharp, as indicated in Figure 1 (Mujumdar, 2005).

2.2 Hybrid Solar Dryer with Biomass Integration

Dehydration is a common technique for preservation of agricultural and other products, including fruits and vegetables. In developing countries, the traditional method of dehydration is by open air, which often results in food contamination and nutritional deterioration (Ratti and Mujumdar, 1997). A hybrid solar dryers means although sun is used to dry products, other technologies are used to cause air movement in the dryers which is fan. Some of the problems associated with open-air drying can be solved through the use of solar dryers are generally classified, depending on the mode of heating or operation, into: (a) direct, (b) indirect and, (c) mixed mode systems with natural or forced circulation of the drying air. In the direct dryer, solar radiation passes through a transparent cover fitted on the top part of the dryer and is directly absorbed by the crop placed on the drying bed under the transparent cover. In an indirect dryer, air is heated in a separate solar collector and circulated through the drying bed where it picks moisture from the crop. The mixed mode possesses both features of the direct and indirect categories of solar dryers. In particular, dryers of the natural-convection variety are popular because they are cheap and simple to operate and maintain (Soponronnarit, 1995). They exhibit enormous potential for exploitation in remote areas of developing countries, where most of the rural communities have no access to electricity. Nevertheless, one disadvantage of solar drying is that the dehydration process is interrupted at night or under low insulation, resulting in a poor quality of the dried product. For commercial producers, this factor limits their ability to process a crop when the weather is poor. It also extends the drying time because drying can only occur during the daytime when there is adequate solar radiation. This not only limits production but can result in an inferior product. For commercial producers, the ability to process continuously with reliability is important to satisfy their markets. A review of the literature indicates that there have been few attempts to overcome this limitation in simple natural convection solar dryers.

2.3 Solar Drying Methods

Based on the research by the previous Final Year Project (FYP) student on solar dryer, which entitled Study on Empty Fruit Bunch (EFB) Solar Drying, 2007 by Ayu, there was 3 methods of solar dryer were taken into consideration in designing the solar dryer. This research is utilized to ensure the applicability of the project. The study of the finalize design is based on the combination of certain concepts and criteria used in the solar dryer below.

2.3.1 Glass roof solar dryer

The glass roof solar dryer is identical with a solar Green house, as shown in (Figure 2a). This unit consists of two parallel rows of drying platforms made of galvanized iron mesh laid over wooden beams. It is covered with a slanted long glass roof aligned lengthwise along the north–south direction. On top of the roof, a cap is provided with a gap, so that the moist warm air can go out, creating a partial vacuum inside, and due to which, fresh ambient air is sucked through holes provided on the sidewalls facing east and west below the drying platforms. The trays and inner side of the dryer are painted black. Shutters are provided in the lower portion of the wall below the glass roof and above the drying platforms, so that fresh air can enter into the dryer to control the inside dryer temperature. The product gets heated using solar radiation which penetrates through the glass roof and, thus, increases the inside temperature. In cloudy or rainy seasons, to enhance the drying rate, gas heaters are provided below one of the platforms. Such types of dryers are used in Brazil for drying of cocoa also (Nair and Bongivar, 1994).

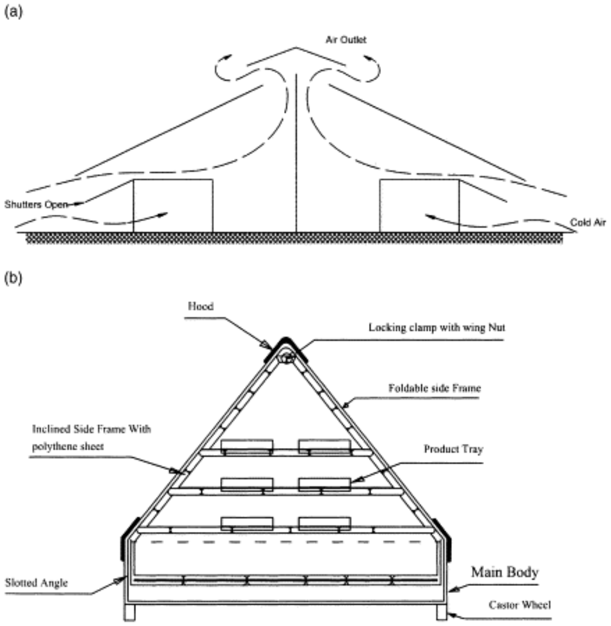


Figure 2.2: (a) Glass roof solar dryer and (b) foldable solar crop dryer (*Reference No. 5*)

2.3.2 Solar dryer with natural ventilation

The solar dryer with natural ventilation for drying of crops was studied by Eissen, Muhlbauer and Kutzbach, 1985. It consist mainly of two components, a solar collector for heating the air and a drying chamber used to hold the trays in which the crops to be dried are spread (Figure 3). The solar collector consists of a transparent foil cover and a black absorber sheet. The drying chamber was covered by a transparent foil, which protects the crops from rain and dust. The ventilation was provided by natural convection inside the collector and drying chamber. This effect was increased by a sucking effect at the air outlet caused by the wind. The maximum temperature recorded in the drying chamber was 50°C when the ambient temperature was 30°C. The loading capacity of the drying chamber was 100 kg of fresh crops per square meter of drying chamber or 25 kg of crops per square meter of collector area.

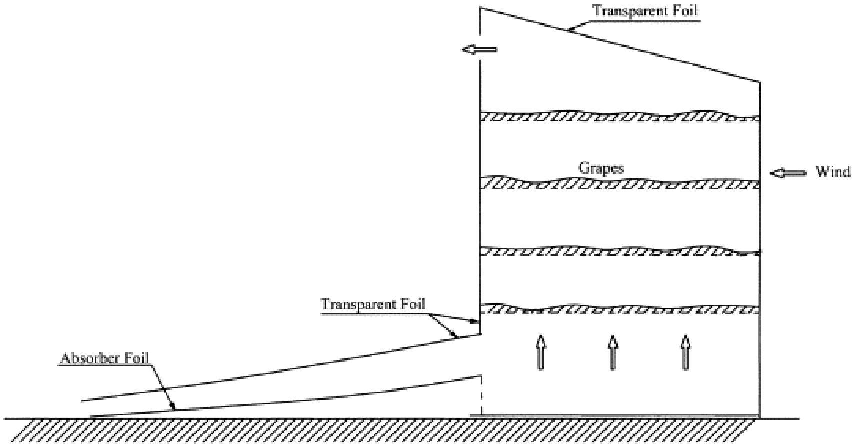


Figure 2.3: Solar dryer with natural ventilation (*Reference No. 5*)

They found that this dryer reduces the drying time to seven to eight days, which was not significantly different, compared to that of open sun drying, i.e. 8–10 days. This dryer protects the product completely from rain and dust, which helps in improving the quality of dried crops. The draw back of this dryer was the small capacity. This type of dryer can be operated in both direct and indirect heating modes.

2.3.3 Solar cabinet dryer

This is the simple solar dryer and can be constructed by village artisans, using locally available materials. It is a small hot box, usually made with wood, having a length about three times its width (to minimize the shading effect of the side panels), i.e. 1 m in length and 0.30 m width (Figure 4). The sides and bottom of the cabinet are painted black internally for absorbing the solar radiation transmitted through the plastic or glass cover. A relatively high temperature, of the order of 80°C, was recorded in the cabinet dryer. The products to be dried are kept in simple aluminum trays, having wire mesh or perforations at the bottom. The trays are placed a few centimeters above the bottom in the assembly, so that the product can receive the solar radiation directly. This also helps some air easily to flow from the bottom of the trays through the product. Holes are provided near the base and the top of the rear vertical side (a few centimeters below the cover) to permit exit of the air by natural convection. The ambient air enters the cabinet through holes at the bottom, passes through the product placed on the wire mesh and escapes with moisture vapors through the top holes provided on the rear vertical side.

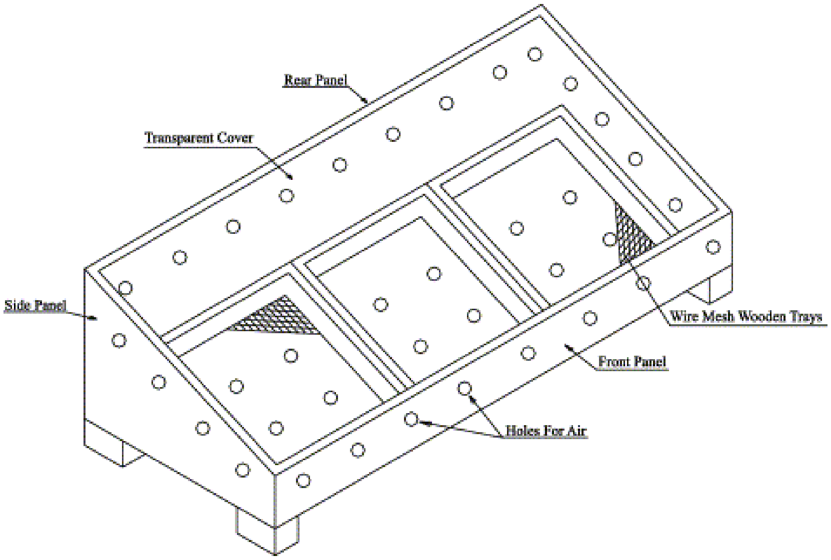


Figure 2.4: Solar cabinet dryer (*Reference No. 5*)

Initial low cost and easy maintenance are the main features of the cabinet dryer. The cabinet dryer can, at least, halve the drying period in comparison to open sun drying.

Improved product quality is, of course, an additional benefit. The main disadvantages of the cabinet dryer are (i) the required drying time is large because of low heat and moisture transfer coefficients due to natural convective air flow and (ii) the efficiency is low because part of the solar energy input is used to induce air flow, and the product itself acts as an absorber, which may not be a good absorber of solar radiation (Pangavhane and Sawhney, 2000).

2.4 Dryer with Biomass Integration Methods

A lot of researched has been done in order to understand how biomass burner works together with the solar dryer in order to is to reduce the moisture content of the crops or biomass waste. From the research, several attempts have been made to overcome the problem of intermittent drying in natural convection solar drying. This research is utilized to ensure the applicability of the project. Below are some reviews of recent solar dryers that being studied and developed by a number of researchers. Basically, the study of the used of burner as a back up heater is based on the combination of certain concepts and criteria used in the research model below:

2.4.1 Solar dryer with thermal storage and biomass-backup heater

Madhlopa and Ngwalo (2005) have come out with an indirect type natural convection solar dryer with integrated collector-storage solar and biomass backup heaters. The major components of the drier are biomass burner (with rectangular duct and flue gas chimney), collector-storage thermal mass and drying chamber (with a conventional solar chimney). The thermal mass was placed in the top part of the biomass burner enclosure and works as a storing part of the absorbed solar energy and heat from the burner. The dryer was fabricated using simple materials, tools and skills, and it was tested in three modes of operation (solar, biomass and solar–biomass) by drying twelve batches of fresh pineapple (Ananas comosus), with each batch weighing about 20 kg. The average values of the final-day moisture pickup efficiency were 15%, 11% and 13% in the solar, biomass and solar–biomass modes of operation respectively.

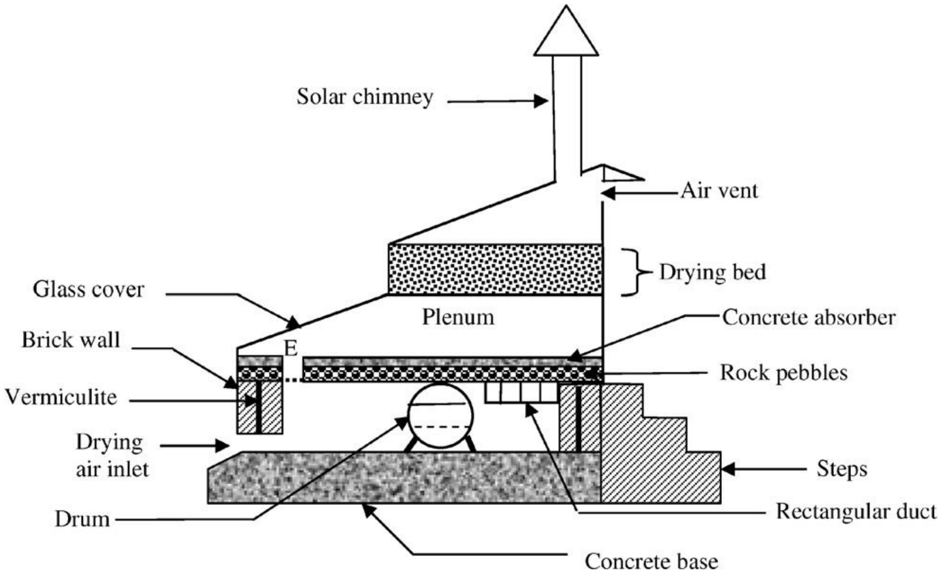


Figure 2.5: Cross-sectional view of the solar dryer through the burner, collector, drying chamber and solar chimney (*Reference No. 2*)

2.4.2 Natural convection solar dryer with biomass back-up heater

Bena and Fuller (2002) designed a direct solar dryer with and integrated biomass backup heater. The dryer consists of a drying cabinet mounted on top of a brick chamber that encloses a simple biomass burner. There are three drying trays, each with a wire mesh base, and in total these provide an effective drying area. The top surface is in inclined condition to maximize the capture of solar radiation. The drying trays slide on timber rails on the inside of the cabinet so that they can be removed from the dryer for loading, unloading and cleaning. An aluminium mesh is fitted to the underside of the dryer to prevent insects reaching the crop through the brick chamber air inlets. The biomass burner, designed primarily for fuel wood. The burner grate was constructed from a perforated tray, supported on rails riveted to the inside walls of the drum. In order to lengthen the flow path of the combustion gases and maximize the transfer of heat to the drum walls, a metal baffle was inserted above the grate and below the exhaust gas exit. The drying cabinet was fixed to the chamber with metal strapping mortared into the top layer of brickwork, and any gaps were sealed with mortar.

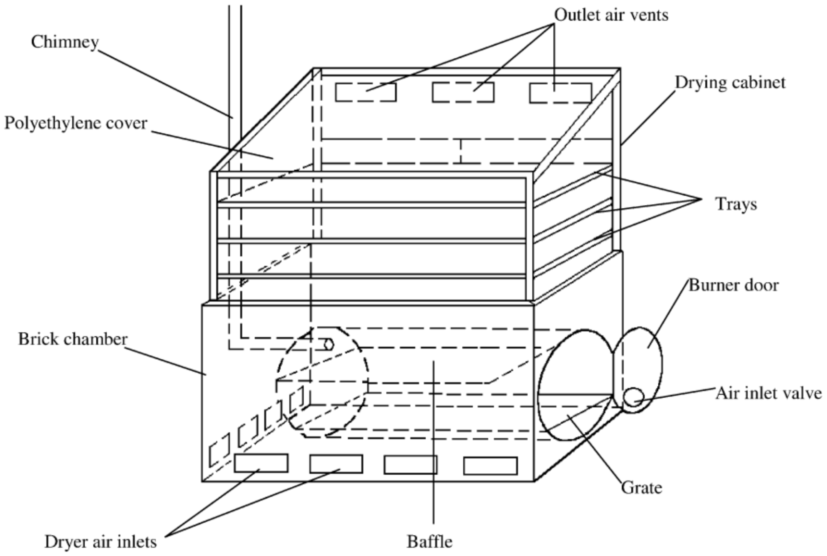


Figure 2.6: Natural convection solar dryer with biomass back-up heater

(*Reference No. 14*)

2.4.3 A mixed-mode natural convection solar dryer with biomass burner and heat storage back-up heater

Tarigan and Tekasakul (2005) was constructed solar dryer at department of Mechanical Engineering, Faculty of Engineering, Prince of Songkla University, Thailand. The main parts of the dryer are solar collector system, biomass burner, and drying chambers. Solar collector system consists of absorber, single glass cover, back plate, and insulation. The system is framed with the aluminum logs. Absorber is made of black painted of metal (zinc) plate with thickness of 0.05 cm. In operation, air flows through the space between absorber and back plate that set just above the bottom/back insulation. For back up heating system for the solar collector, a biomass burner was constructed from concrete as the wall, and filled up with bricks as heat storage. In the biomass burner, a free space was occupied, including extruded wall to out side of the burner, for space for burning fuels. A door was set up at front side of the extruding wall for the way of feeding fuel. A hole at bottom edge of the door was made for fresh air inlet to burner during burning fuels. The bricks, for the heat storage, were arranged so in the burner that the exhausts gas and smoke from burning fuel can pass through them. This is to maximize the heat stored from burning fuel.

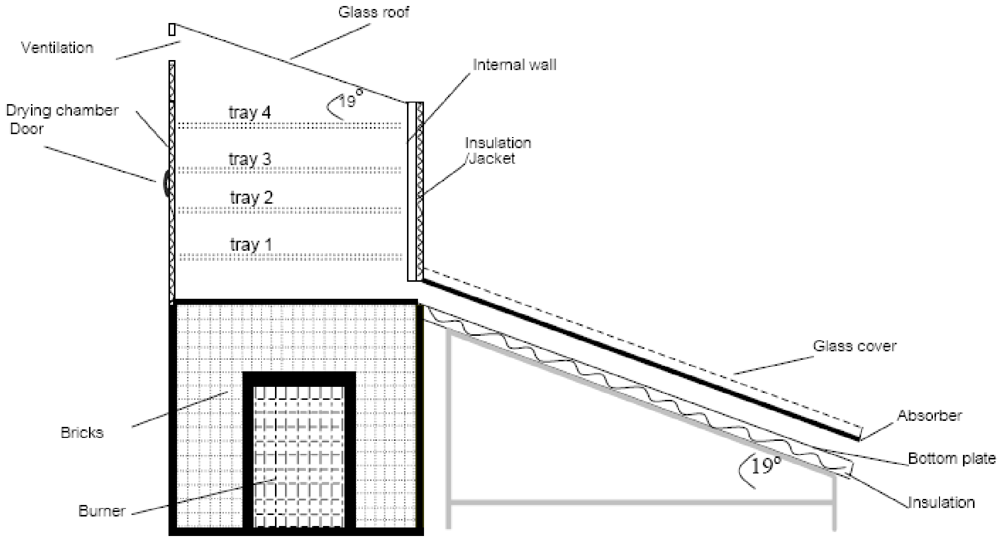


Figure 2.7: Side view of the mixed-mode natural convection solar dryer with biomass burner and heat storage back-up heater (*Reference No. 15*)

CHAPTER 3

METHODOLOGY

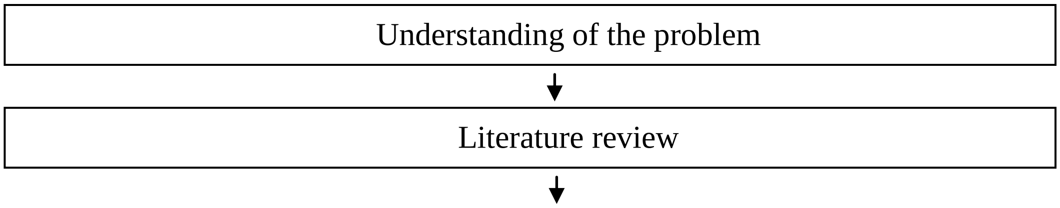
3.1 Analysis Techniques

After the design and fabrication process, the model performance and characteristics need to be investigated. This is important in order to measure the effectiveness of the model. The study was carried out by two analysis techniques:

a. Experimental modeling with measurement.
b. Analytical.

3.2 Procedure Identification

The project begins with the research work on previous journals and books that been published for the references through out the project. Most of the objectives much more related to the design criteria, material selection and the effectiveness of the hybrid solar dryer with biomass burner as a back up heater. Experimentation is conducted on 3 modes as shown in the methodology followed by analysis of the results and recommendation. This report also come out with the governmental equation (analytical) of the solar dryer and biomass burner which obeys the mass and thermal energy balance.



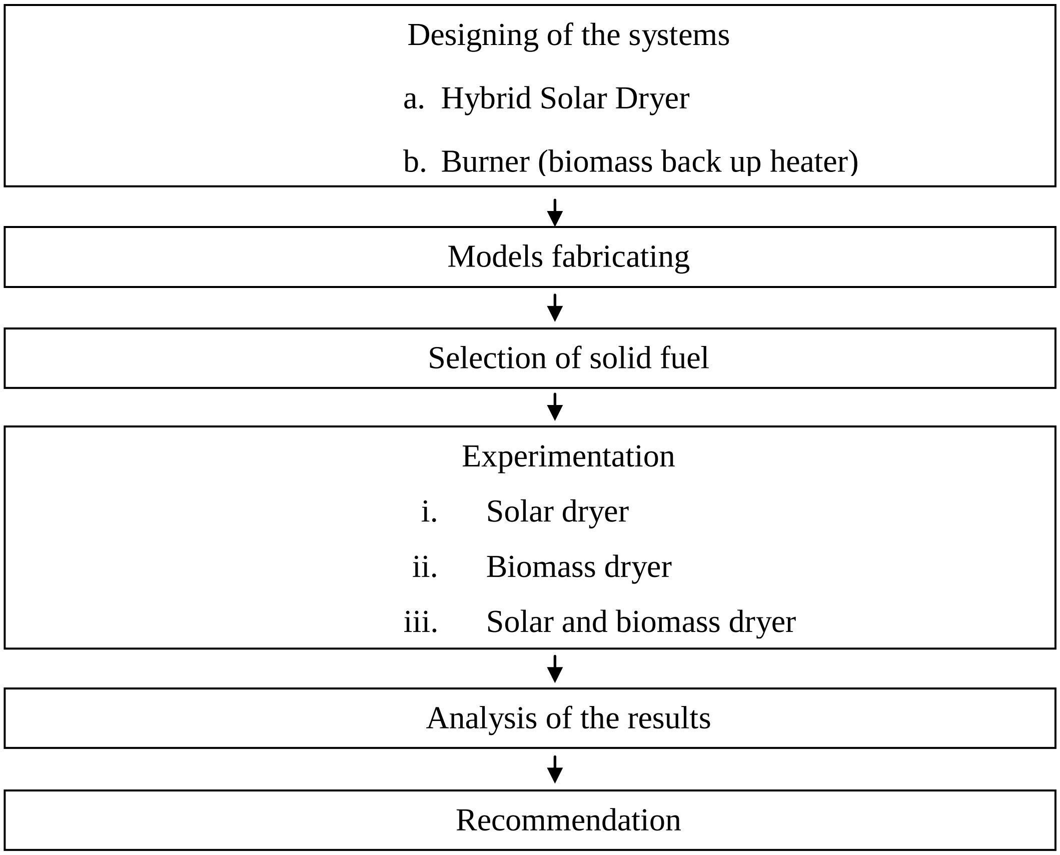


Figure 3.1: Project Work Flow

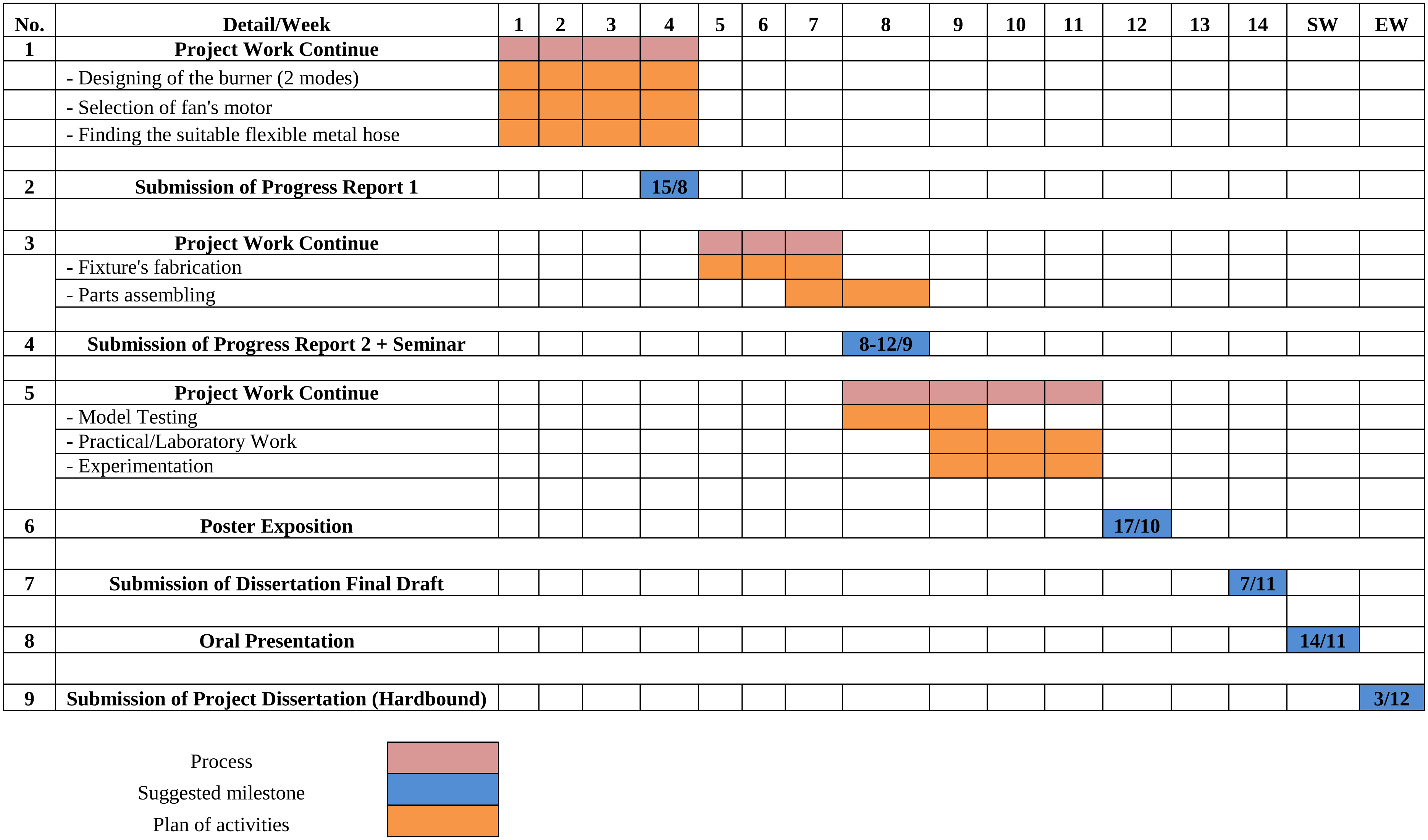
3.3 Gantt Chart

The Gantt chart of this project is divided into two since this project was started since the last semester. It is important in order to ensure the flow movement of this project run smoothly. Besides, since the Final Year Project (FYP) is only conducted in two semesters, a detailed schedule must be done to avoid time constraint and to ensure that the project will be finished on time. The Gantt chart for the first and second semester is shown below.

No.	Detail/Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	**Selection of Project Topic**	🟥	🟥						Mid-Semester Break							
2	**Preliminary Research Work**		🟥	🟥	🟥											
	Understanding of the problem		🟧	🟧	🟧	🟧	🟧	🟧								
	Literature review		🟧	🟧	🟧	🟧	🟧	🟧		🟧	🟧	🟧	🟧	🟧		
3	**Submission of Preliminary Report**				**15/2**											
	Designing of the system				🟧	🟧	🟧	🟧								
	Fabricating										🟧	🟧	🟧	🟧	🟧	🟧
4	**Seminar 1 (optional)**															
5	**Project Work**					🟥	🟥	🟥								
	Computational Simulation									🟧	🟧	🟧	🟧	🟧	🟧	🟧
	Selection of solid fuel from palm oil waste												🟧	🟧	🟧	🟧
	Experimentation															
6	**Submission of Progress Report**									**21/3**						
7	**Seminar 2 (compulsory)**										**24/3**					
8	**Preparation of Interim Report Final Draft**													🟥		
9	**Submission of Interim Report**														**25/4**	
10	**Oral Presentation**															**28/4**

Process 🟥
Suggested milestone 🟦
Plan of activities 🟧

Figure 3.2: FYP 1 Gantt Chart



No.	Detail/Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	SW	EW
1	**Project Work Continue**	🟥	🟥	🟥	🟥												
	- Designing of the burner (2 modes)	🟧	🟧	🟧	🟧												
	- Selection of fan's motor	🟧	🟧	🟧	🟧												
	- Finding the suitable flexible metal hose	🟧	🟧	🟧	🟧												
2	**Submission of Progress Report 1**				🟦 **15/8**												
3	**Project Work Continue**					🟥	🟥	🟥									
	- Fixture's fabrication					🟧	🟧	🟧									
	- Parts assembling							🟧	🟧								
4	**Submission of Progress Report 2 + Seminar**								🟦 **8-12/9**								
5	**Project Work Continue**								🟥	🟥	🟥	🟥					
	- Model Testing								🟧	🟧							
	- Practical/Laboratory Work									🟧	🟧	🟧					
	- Experimentation									🟧	🟧	🟧					
6	**Poster Exposition**												🟦 **17/10**				
7	**Submission of Dissertation Final Draft**														🟦 **7/11**		
8	**Oral Presentation**															🟦 **14/11**	
9	**Submission of Project Dissertation (Hardbound)**																🟦 **3/12**

Process	🟥
Suggested milestone	🟦
Plan of activities	🟧

Figure 3.3: FYP 2 Gantt Chart

3.4 Instrumentation for the Dryer Evaluation

The software required in this project for the documentation and design software was Microsoft Office and Autodesk AutoCAD. The dryer performance was tested with four separate trials with both loaded and unloaded condition. In the drying experiments, EFB were used as the test samples in the dryer. The experimentation was conducted with 3 different modes which are solar dryer, biomass dryer and the mixed mode of the dryers. During the trials the parameters measured were: temperatures, solar radiation, mass of EFB dried and the charcoal burnt, relative humidities and speed of the airflow through the dryer. The relative humidity and temperature inside the chamber was measured using digital hygrometer/psychrometer (NPI 597), solar radiation was measured with solar meter and airflow velocities were measured with anemometer (Testo 435). The mass of EFB and charcoal was measured using electronic balances (max 16 kg) and the absorber temperature was measured using thermocouple (Hanna Instruments). Refer to *Appendix-B* to *F* for the equipment used and how the measurement/data was taken.

CHAPTER 4
ANALYTICAL ANALYSIS

4.1 Boundary Condition

The boundary condition of the dryer was set based on the properties the types of material that was used to dry. In this project, EFB was dried. The properties of EFB were collected from the research of literature review as listed below. The psychrometric chart is used based on the boundary condition given.

Table 4.1: Condition or assumption data of EFB

No	Items	Condition/Assumption
1	Initial moisture content, M_i	67% w.b
2	Final moisture content, M_f	8% w.b
3	Ambient air temperature, T_{am}	29.5°C
4	Outlet temperature, T_{out}	35°C
5	Ambient relative humidity, RH_{amb}	71.2%
6	Ambient relative humidity, RH_f	53%
6	Drying time, t_d	28 800 s (8 hours)
7	Average incident solar radiation, I	400 m^2/day
8	Initial mass of product, m_p	1 kg
9	Average mass of water evaporate, m_{evap}	0.636 kg
10	Specific heat of air, C_P	1.004 kJ/kg.K
11	Water-vapor saturation enthalphy, h_{fg} at 50°C	2382.75 kJ/kg
12	Solar collector flat surface area	0.414 m^2

4.2 The Governing Equations

Material balances (mass balances) are based on the fundamental “law of conservation of mass”. The law of conservation of mass states that mass cannot be created or destroyed [20]. The total mass balance equation in the dryer can be written as:

(Total mass entering – (Total mass leaving = (Net change in mass
the system) the system) within system)

or

$$m_{in} - m_{out} = \Delta m_{system} \qquad (1)$$

In solar dryer application, the mass balance is as follow:

$$\dot{m}_p M_f - \dot{m}_p M_i = m_w \qquad (2)$$

Energy balance is a systematic presentation of energy flows and transformations in a system. Theoretical basis for an energy balance is the first law of thermodynamics according to which energy cannot be created or destroyed. The net change (increase or decrease) in the total energy of the system during a process is equal to the difference between the total energy entering and total energy leaving the system during the process [20]. The energy balance is described as follow:

(Total energy entering - (Total energy leaving = (Change in the total energy
the system) the system) of the system)

or

$$E_{in} - E_{out} = \Delta E_{system} \qquad (3)$$

In solar dryer application, the energy balance is as follow:

$$\dot{Q} = \dot{m}_p (h_{out} - h_{in}) \tag{4}$$

The amount of moisture to be removed from the product is calculated using this formula:

$$m_w = m_p (M_i - M_f) / (100 - M_f) \tag{5}$$

From the result, the average mass of water evaporates calculated is 0.636 kg. The specific mass is given by:

$$\dot{m}_{evap} = \frac{m_{evap}}{t_{dr}} \tag{6}$$

Based on the specific mass of water evaporates, the specific mass of air can be calculated using the following equation:

$$\dot{m}_{evap} * h_{fg} = \dot{m}_{air} * C_P * (T_{out} - T_{amb}) \tag{7}$$

where;

$$\dot{m}_{air} = \frac{\dot{m}_{evap} * h_{fg}}{C_P * (T_{out} - T_{amb})} \tag{8}$$

The total heat energy, E (kJ) required to evaporate water was calculated as follows:

$$E = \dot{m}_{air} * (h_f - h_i) * t_{dr} \tag{9}$$

The efficiency of the solar dryer is given by this equation:

$$\eta = \frac{E}{A_c * I * t_{dr}} \tag{10}$$

The area of the corrugated solar collector is as shown below:

$$A_c = 0.5\pi * \text{ flat surface area} \qquad (11)$$

Table 4.2: The result of calculation

No	Items	Value	Data/Equation used
1	Initial humidity ratio, w_i	0.0188 kg water/ kg dry air	T_{am} and RH_{am}
2	Initial enthalphy, h_i	78 kJ/kg	T_{am} and RH_{am}
3	Final enthalphy, h_f	85 kJ/kg	T_{out} and RH_f
4	Mass of water evaporated, m_w	$5.905*10^{-3}$ kg	Equation (5)
5	Specific mass of water evaporated, $\dot{m}_{evap}$	$2.208*10^{-5}$ kg/s	Equation (6)
6	Specific mass of air, $\dot{m}_{air}$	$9.529*10^{-3}$ kg/s	Equation (8)
7	Total useful energy, E	1921.043 kJ	Equation (9)
8	Corrugated solar collector area, A_c	0.650 m^2	Equation (11)
9	Efficiency of solar dryer, η	25.65%	Equation (10)

From the design calculation, the efficiency of solar dryer is approximately 27%.

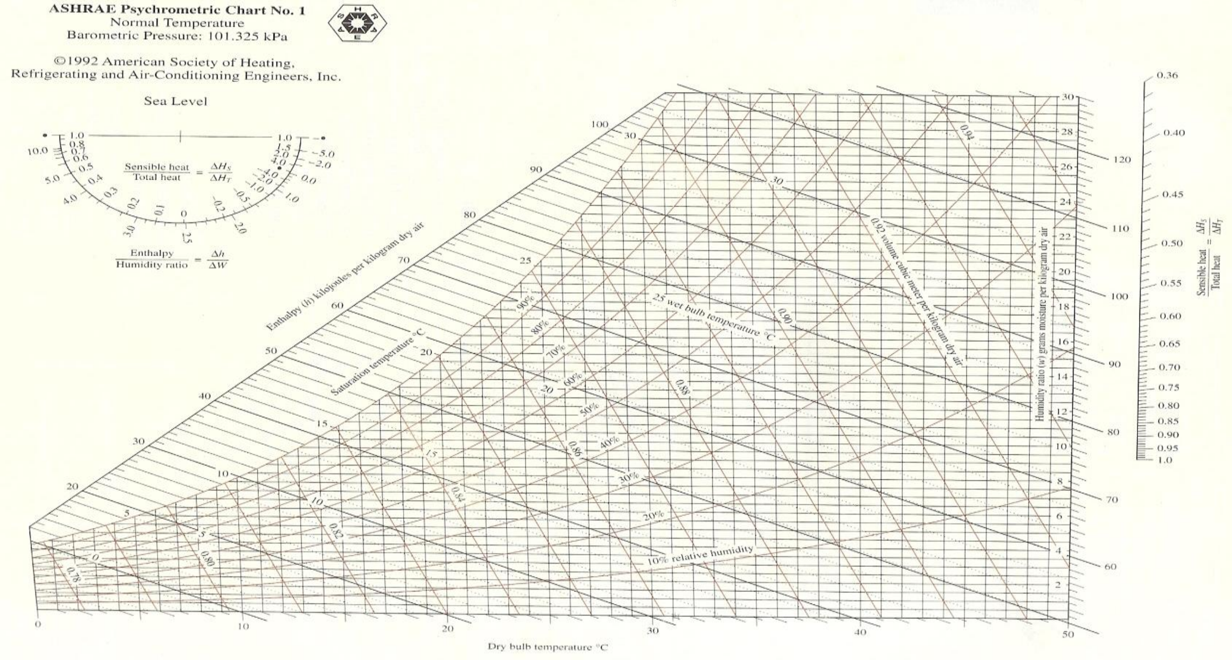


Figure 4.1: Psychrometric Chart

4.3 Thermal Calculation

Area of corrugated collector, $A_c = 0.650\text{m}^2$

Area of trays, $A_2 = [(0.892\text{m}*0.292\text{m}) – (0.5\text{m}*0.05\text{m}*2)]*2 + [(0.892\text{m}*0.292\text{m}) – (0.5\text{m}*0.05\text{m})]*3$

$= 0.421\text{m}^2 + 0.706\text{m}^2$

$= 1.127\text{m}^2$

Average solar radiation in Malaysia, $I = 460 \text{ W/ m}^2$

EFB absorptance, $\alpha = 0.7$

Glass transmittance, $\tau = 0.84$

Average inlet temperature = 29.5°C~30°C

h_{fg} at 50°C = 2382.75 kJ/kg

Safety factor, $f = 0.75$

The amount of heat absorbed by the collector, Q_1 is:

$Q_1 = A_1 * \alpha * \tau * I$

$= 0.650 \text{ m}^2 * 0.7 * 0.84 * 460 \text{ W/ m}^2$

$= 175.812 \text{ W}$

The amount of heat absorbed through the trays, Q_2 is:

$Q_2 = A_2 * \alpha * \tau * I * f$

$= 1.127 \text{ m}^2 * 0.7 * 0.84 * 460 \text{ W/ m}^2 * 0.75$

$= 228.623 \text{ W}$

$Q_{total} = Q_1 + Q_2$

$= 175.812 \text{ W} + 228.623 \text{ W}$

$= 404.435 \text{ W}$

The amount of heat evaporated to dry 1kg of EFB to about 60% reduction of moisture content is:

$$Q_{evaporated} = m_{water\ evaporated} * h_{fg}$$

$$= \frac{(635.75 * 10^{-3})\ \text{kg} * (2382.75 * 10^{3})\ \text{J/kg}}{(8 * 60 * 60)\ \text{s}}$$

$$= 52.6\ \text{W}$$

CHAPTER 5
DESIGNS AND FABRICATION

A lot of studies need to be made in order to come out with a good design of the hybrid solar dryer and biomass burner. The operation, the characteristics of each fixtures design and also the types of material used are needed to be investigated.

5.1 The Biomass Back Up Heater

Biomass, particularly fuelwood, is the most common source of energy in rural areas of developing countries, and provided unsustainable pressure is not placed on the local resource, fuelwood can be a greenhouse gas neutral source of energy, if usage is balanced by new plantings. It is currently often burned inefficiently and so there is need for simple, affordable combustion devices, which can be used to complement appropriate solar technologies. The biomass burner was designed mainly to complement the solar dryer, and to sustain the drying process even during cloudy weather. However, it can also be used to extend the period of drying beyond sunshine hours, and perhaps during night as well, while drying high value addition crops. The description on how biomass burner works together with the solar dryer is as shown on the next page.

5.2 The Operation

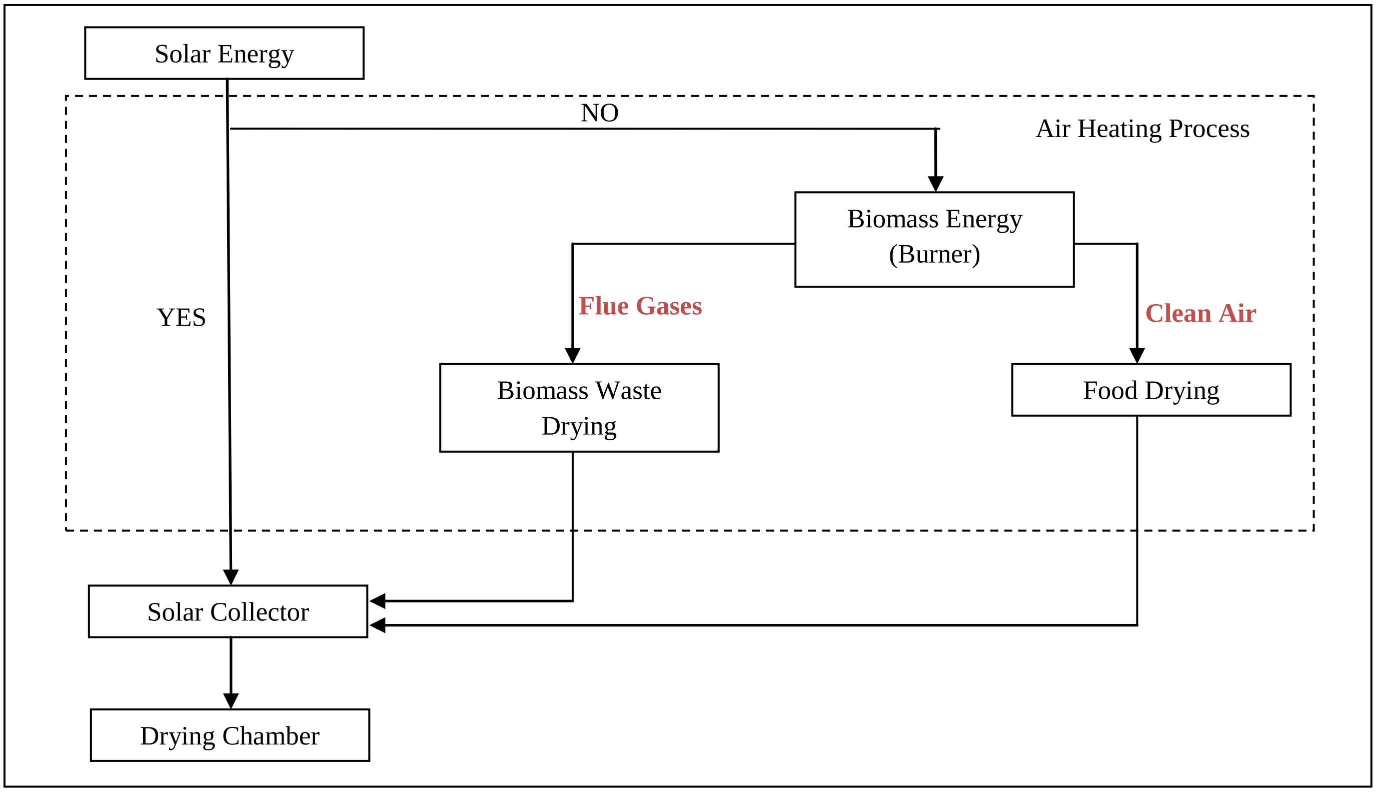


Figure 5.1: Solar dryer with biomass integration flow diagram

The dryer is designed to operate with solar radiation as the main source of energy. The back up heater which is the biomass burner is used when radiation is inadequate and at night so that continuous drying is possible and it is also can be used to extend the period of drying beyond sunshine hours. When the dryer is operated using solar dryer, radiation enters through the transparent cover, is absorbed by the black painted Aluminum solar collector and by the crops, and is converted into heat. The heated surfaces warm the surrounding air, which rises by natural convection, passing through the drying trays and picking up the moisture. The moist are finally exits the dryer through the vents on the upper side. This action reduces the pressure inside the solar dryer and ambient air is drowning into the dryer through the inlet holes at the side of solar dryer. A continuous flow of air is thus established.

During periods of low or zero solar radiation, the back-up heater is used to supply heat energy. To dry food, the combustion gases heat up the galvanized iron plate. Here, the smoke is being separated from clean air; the smoke will directly flow to the chimney, while the clean air flow trough the baffle and moves over to the solar collector and drying chamber. For the biomass waste drying, the smokes flow directly into the solar dryer. The warm air rises up into the drying chamber, evaporating and picking up crop moisture as it passes through the trays, and then escapes through the top vents as before. To test the efficiency of the models, experimentation will be carried out using 3 modes, which are solar dryer, biomass dryer and finally solar-biomass dryer.

5.3 Hybrid Solar Dryer Design Criteria

Design process is very important where the design enable the specified properties of the product to be obtained. From the research that has been done, several methods the mixed mode of solar drying was taken into consideration which are glass roof solar dryer, solar dryer with natural ventilation and solar cabinet dryer. For the biomass integration, a connection is made between solar dryer and biomass source so that both systems can function together. The details regarding the design’s features are as discussed below:

5.3.1 Walls and Roof

The roof is designed with some angle or slope to make sure the evaporated water can easily flow in contact with the roof’s surface without touching or dropping onto the sample. At both sides of the roof were elongate to prevent rain or outside water drop from entering the outflow holes. Small holes were made at the bottom side wall of the dryer. The purpose of these holes is to allow the in flow of the air. The ambient air enters hybrid solar dryer through holes at the bottom, passes through the product placed on the wire mesh and escapes with moisture vapors through the solar chimney at the top of solar dryer.

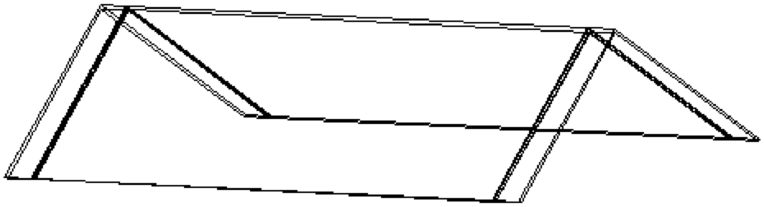


Figure 5.2: The Roof

5.3.2 Floor

The base of the hybrid solar dryer is very important in order to increase the stability of the model so that it will not easily shake. The floor is designed with some angle or slope to make sure the evaporated water can flow smoothly. Some gap is provided at the middle of the floor to ensure easiness of removing the evaporated water. 2 holes were made at the side of solar dryer to connect it with biomass source. The holes were design at the bottom of the absorber to guarantee distribution of the heat. It will heat the absorber and some of heat will flow through small space and escape through the holes at roof. Thus, even when biomass source being used, the theory of the heat flow is just the same as when using solar itself. The thin bending Aluminum supporter was screwed around the border of solar dryer so that it will become more rigid and reduce the shaking part.

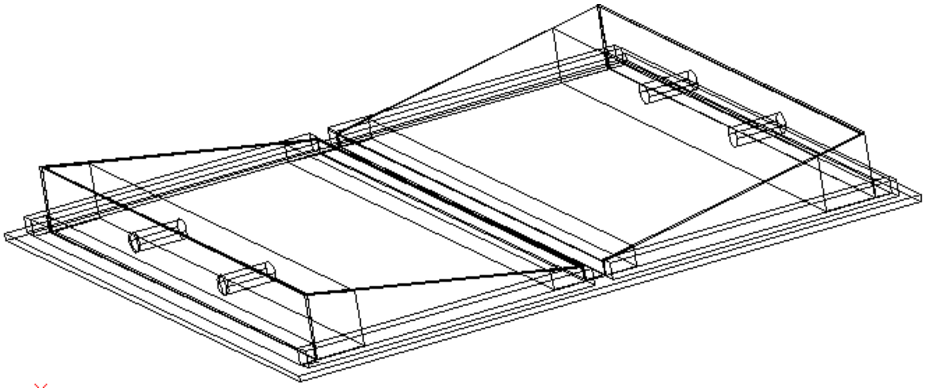


Figure 5.3: Floor, or base structure

5.3.3 Racks

The design was included with five racks. The racks are designed with some space between each other for ventilation process and it is also designed with rectangular hole to allow the warm air especially sourced or released from the black painted Aluminium. Warm air will go through the alternating rectangular hole. This is to ensure that the heat can be accumulated or spread uniformly inside that area, and same amount of heat will be received by the samples at all layers. Wire mesh is used to prevent the crops from dropping through the rectangular hole. This also helps some air easily flow from the bottom of the racks through the crops.

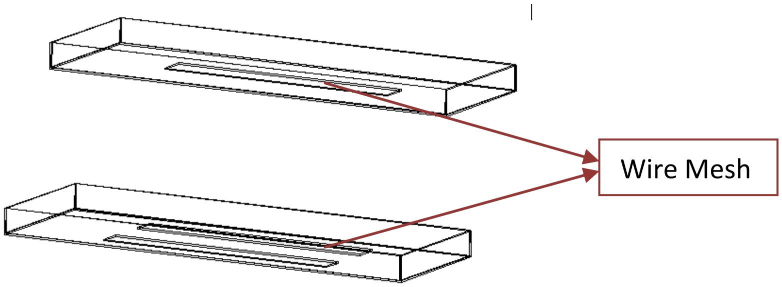


Figure 5.4: The racks

5.3.4 Other Features

Beside the basic features of the model as discussed above, some other features are also included, which is wheels and front door. Four wheels were attached to the prototype to make sure that the model can be moved easily from one location to another. The door is needed to insert the racks with crops into drying chamber easily and to dry crops in a closed area. Fan was used to enhance the flow of moving air so that drying process becomes more effective. Refer to *Appendix-G* and *H* for 3-dimensioning view and the complete model of solar dryer.

5.4 Biomass Burner Design

Biomass burner or also known as heating fluids generation is used as a back up heating system. The burner is already available but some modification has to be made so that it can be operated in two ways. For biomass waste drying, the burner can directly flow the smoke into the solar dryer. But to dry food or vegetables, the poisonous smoke is needed to be sieved or remove and to prevent any contamination by just let only clean warm air enters into the solar dryer. 2 fixtures has been made to the burner in order to separate between the smoke and clean air. Refer to Appendix C and D for complete view of the biomass burner model. For the experimentation, since waste is being dried, thus only fixture 2 has been tested. The sketches of the design of 2 mode burner system are as shown below:

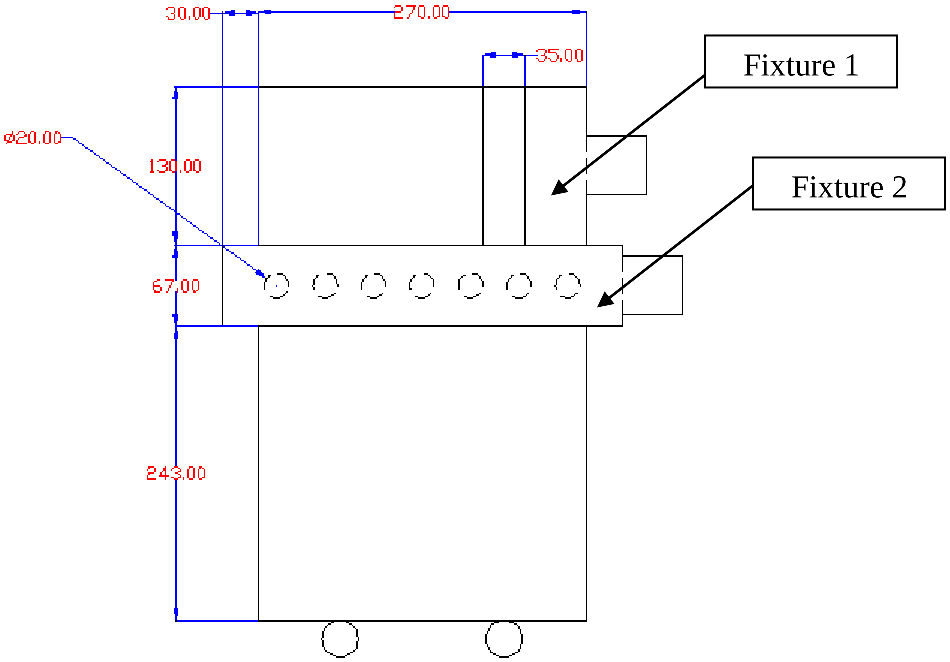
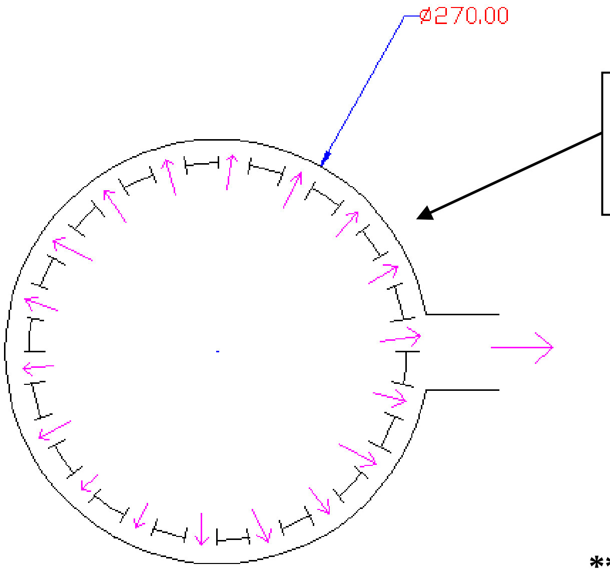


Figure 5.5: Biomass burner with combine fixtures

**** All dimensions are in mm**

5.4.1 Direct Smoke

For direct smoke system, the burner is directly connected with the solar dryer. Here the smokes are not separated and it will let to circulate into solar dryer. The main focus here is just to get the heat from the smoke. During fuels burning, the smoke will directly flow through the flexible metal hose which is connected with the solar dryer. Fixture 1 is used to store up all the smoke and as the pressure increases, the smoke will flow through the metal hose, solar dryer and finally lost through the solar chimney. In the solar dryer, the smoke will heat the solar collector or absorber; some escapes from the corrugated area and the heat will flow passing each rack and at the same time dry out moisture from the biomass waste.



Smokes being collected into Fixture 2 through the small holes

Direct smoke is connected directly to the solar dryer

**** Arrow = Flowing smoke**

Figure 5.6: The top view of direct smoke fixture (Fixture 1)

5.4.2 Clean Warm Air

For clean warm air, the smoke from inside the burner will be blocked by the galvanized iron plate. Only clean warm air is allowed to enter into the solar dryer. Fixture 2 is used where the heat that pass by the galvanized iron plate, mix with the air which flows to the inside through the air inlet (refer Figure 15) and the mix air is heated through the baffle at the top of the biomass burner. Baffle is used in order to lengthen the flow path of the combustion gases and maximize the transfer of heat to the solar dryer. As it gets heated, pressure inside the fixture 2 increases and the clean warm air will flow to the solar dryer through the flexible metal hose which is different connection with the direct smoke. Refer to *Appendix-I* for the complete model of the biomass burner.

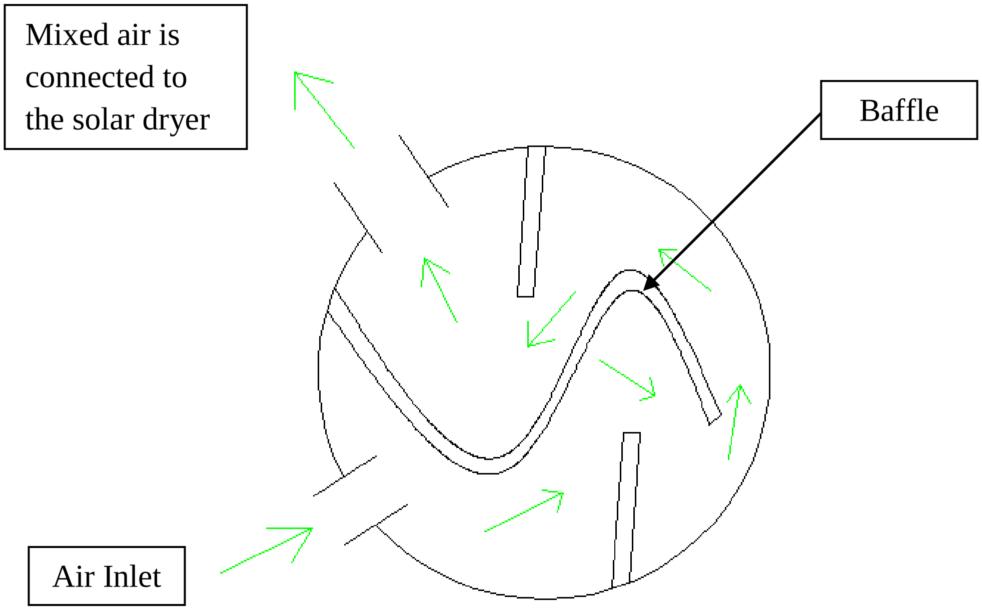


Figure 5.7: The top view of clean air fixture (Fixture 2)

5.5 Material Properties

The performance characteristics of alternative systems have been assessed before the final choice of a dryer type. Almost always some small-scale tests are needed to determine the material's drying characteristics required to predict the way in which the raw material would behave in actual unit. The main parts of the dryer are the body of solar dryer, solar collector, biomass burner and flexible metal hose (Refer to *Appendix-H* to *K*). Materials of the other parts also included as shown in the next page.

5.5.1 The Solar Dryer

The selection of the body is based on cost, non-degradability, durability and specific heat. For the model designed, the first chosen material to be used for the walls, roof and racks is glass. Theoretically, the sunlight can pass through the glass and shine the specimen easily, compared to other materials. Another option is by using Perspex, or also known as acrylic glass. Perspex has the same characteristics as glass, which is transparent and allow solar energy to pass through it, into the interior part. Since the Perspex is easier to be fabricated and lighter than glass, it is decided that Perspex will be used for the model designed.

Table 5.1: Absorptivity, emissivity and transmittance for different types of glass (*Reference No. 21*)

Type of Glass	Absorptivity, α	Emissivity, ε	Transmittance, τ	Effective transmittance-absorptance, τ α	Long-wave infrared transmittance
Crystal Glass	0.13	0.83	0.91	0.1183	0.02
Window Glass	0.13	0.83	0.85	0.1105	0.02
Perspex polymethylmethacrylate (PMMA)	-	-	0.84	-	0.02

5.5.2 Solar Collector

Solar collector also known as absorber plate, with length of 300mm and width 550mm, is made of corrugated black painted of metal (Aluminium) plate with thickness of 1mm. The absorber is used to absorb heat from the incoming solar radiation. The more thermal conductivity, the more it will absorb. It is located in an incline condition at the bottom of solar dryer model basically to ensure drops of water can directly flow to the and also to maximize the capture of solar radiation. The larger the area of absorber, the larger the values of heat absorb. Thus, Aluminium with corrugated surface is being used since it has larger area than the flat Aluminium surface. Besides, Aluminium is cheaper compare to Copper.

Table 5.2: Thermal conductivity of selected materials for absorber (*Reference No. 22*)

Materials	Density, ρ (kg/m^3)	Specific Heat, C (J/kg.K)	Thermal Conductivity, k (W/m.K)
Aluminium 1100	2379	903	237
Copper	8933	385	401
Carbon Steel	7832	434	60.5
Tin	7310	227	66.6

The objective to select black coating for the absorber is to achieve maximum absorptance, α and minimum re-emittance, ε so that the ratio of performance factor, α/ε is a maximum. The black paint is selected for coating because it is locally available and cheap compare to black Nickel or black Chrome plating.

Table 5.3: Performance ration for selected coatings (*Reference No. 21*)

Material	Absorptivity, α	Emissivity, ε	Performance Factor, α/ε
Black chrome on copper	0.95	0.12	7.92
Nonmetallic black surfaces: carbon	0.92	0.94	0.98
Black paint	0.97	0.86	1.13
Gray paint	0.75	0.95	0.79

5.5.3 Biomass Burner

The biomass burner’s fixtures added must capable to extend high temperature. The approximately temperature of the burning fuels is about 300 to 450 °C. The suitable metal to be used is galvanized iron sheet metal since it can sustain up to 2700 °F and it was also selected based on its availability in the market. Galvanized iron has good fire resistance which the main important element as a fixture’s used in burner and fair corrosion resistance as shown in table below:

Table 5.4 Properties of Sheet Metal (*Reference No. 9*)

Material	**Characteristics**	**Principal uses**	**Melting point**	**Coefficient of expansion (per degree F)**	**Method of joining**	**Precautions**
Copper	High corrosion resistance. Tarnishes easily but eventually forms decorative coating called patina. Toxic.	Roofing, gutters, downspouts, flashing, louvers, scuttles, drains, shower pans.	1980 °F	0.0000098	Use caution when welding. Excellent for all other methods.	Water which has been in contact with copper will stain masonry and painted surfaces, and corrode most other metals.
Aluminium	Good corrosion resistance. Light weight. Nontoxic. Good workability. Easily cleaned.	Roofing, siding, trim, flashing, canopies.	1218 °F	0.0000128	Welding requires shield of inert gas. Soldering not recommended. Brazing mechanical fasteners and seaming recommended.	Not recommended for extensive seaming. Highly subject to electrolytic corrosion.
Galvanized iron	Fair corrosion resistance. Good workability. Nontoxic. Good fire resistance.	Roofing, siding, gutters, downspouts, canopies, ventilators.	Coating 786 °F Base sheet 2700°F	0.0000065	Excellent for soldering, seaming and mechanical fasteners. Welding and brazing destroy galvanized surface.	Protective coating (zinc) highly subject to electrolytic corrosion. High temperatures destroy surface.
Black iron	Poor corrosion resistance. Good workability. Excellent resistance to abrasion. High strength.	Floor plates, stair trends, roof decking.	2700 °F	0.0000065	Excellent for all methods of joining and seaming.	Easily damaged by all corrosive elements.
Stainless steel	High corrosion resistance. Good workability. Nontoxic. Easily cleaned. Work hardens rapidly.	Flashing, decorative trim, roofing, gutters, downspouts.	2560 °F	0.0000058 to 0.0000096	Requires additional power for seaming. Inert gas shield not required for welding but recommended to prevent surface damage.	Extra power required for cutting and forming operations. Surface can be contaminated by iron particles, causing rust.
Nickel copper alloy (Monel)	Excellent corrosion resistance. Good workability. Nontoxic. Easily stained. Difficult to clean.	Roofing and drainage components (in highly corrosive atmosphere and salt water areas).	2370 °F	0.0000077	Excellent for all methods. Solder offers no strength.	Surface tarnishes easily and is difficult to clean.

5.5.4 Flexible Metal Hose

There are a lot of criteria that the metal hose should obey. The material used should stand high temperature which is more than 100 °c, flexible which is capable to bend around and no leaking along the joint. Iron metal is being chosen as the hose material based on the availability in the market. Besides it is already come out in the form of flexible hose. Actually, this hose was found in the car workshop and it is actually being used as an exhaust of lorry. In this project the hose also is to be used to flow the smoke from the biomass burner which is the same function as an exhaust. Iron can stand high temperatures as shown in the table below.

Table 5.5: Melting temperatures for various metals and alloys (*Reference No. 9*)

Metal	Melting Temperature	
	°C	°F
Lead	327	620
Tin	232	450
Zinc	420	788
Aluminum	660	1220
Copper	1085	1985
Brass	900	1652
Nickel	1455	2651
Iron	1538	2800
Tungsten	3410	6170

5.5.5 Other Parts

Other parts being used are PVC T-joint and elbow-shape, galvanized iron T-joint and fans. These parts are based on the availability in the market. Basically the T joint is a type of joint produced when two metal parts are perpendicular to each other, forming the shape of the letter "T". The PVC type of T Joint and elbow shape is used to connect the two holes at the bottom side of solar dryer model before being connected with the biomass burner. Galvanized steel T-joint used actually function as a pipe connection. In this project, solar dryer is connected with two flexible hose from the PVC pipe with the biomass burner.

The fans used actually are the 12V PC's fan. Several modifications has been made to the fans so that it can connect easily between the solar chimney and another one is between galvanized steel T joint and flexible metal hose. It is connected with the 12V 7.2 Ah sealed lead-acid rechargeable battery for the power supply.

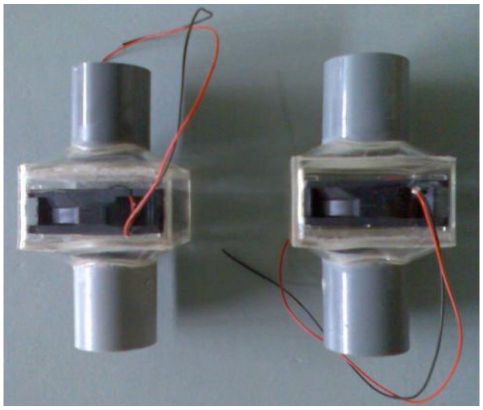


Figure 5.8: The Fans

5.6 Biomass Fuel

The burning fuel used in this project is charcoal. Charcoal is a black substance that resembles coal and is used as a source of fuel. Charcoal is generally made from wood that has been burnt, or charred, while being deprived of oxygen so that what is left is an impure carbon residue. The maximum temperature of charcoal at very high temperature is about 1400-2000 °C. The temperature of carbonization is about 500 °C-600 °C then reduced to a lower temperature at 300 °C (Syred, Griffiths, Beedie and James, 2005). The advantages of using charcoal are as listed below:

1. Charcoal produces a heat that is hotter and burns cleaner than wood.

2. Unlike wood, charcoal is a smokeless fuel. The smoke produced by wood fires in an indoor cooking environment can lead to multiple respiratory illnesses.
3. It can be stored for long periods of time without degradation.
4. Charcoal is inexpensive, harmless, and easily used.

5.7 Connection of Solar Dryer with Biomass Burner

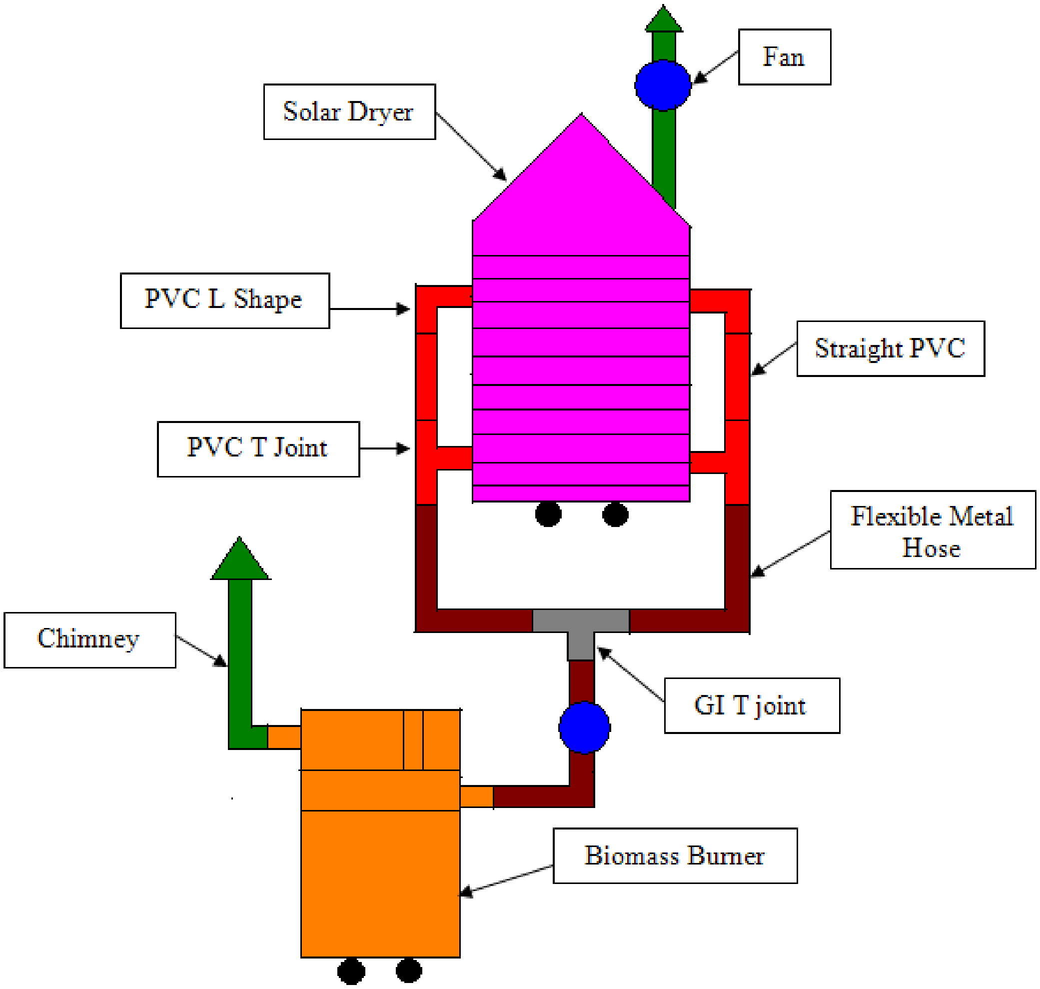


Figure 5.9: Diagram of the connection between hybrid solar dryer with biomass burner

The connection of all the parts of solar dryer and biomass burner as one system is as shown above. The maroon colored is the flexible metal hose. There are 4 holes at the bottom side the dryer which is for the connection of the hose. This hole is being connected to the PVC elbow shaped and T joint before being connected to the hose and biomass burner. Galvanized iron T joint which is grey in color is used to joint the PVC and the hose into one connection. The system consists of 2 PVC elbow shape and T joint. The green colored is the chimney where the smoke and air flow goes out. The fan is blue in color and it is being located into 2 places which are between the biomass burner and the GI T joint and another place is between the solar dryer and the chimney.

Figure 6.0: Complete connection of hybrid solar dryer with biomass integration (experimental setup)

CHAPTER 6

RESULTS AND ANALYSIS

After the fabrication process is completed, the functionability and effectiveness of the model is tested by drying EFB. The rate of moisture reduction for EFB is measured by calculating the weight reduction of the sample used. For all experiments, the initial weight of EFB dried is 200g for each tray. The moisture content reduction for each tray was measured at each hour for solar drying mode and at each 15 minutes for biomass and both drying mode.

6.1 Solar Collector Performance

The average diurnal variation of temperatures for 3 days of the solar collector outlet air (chimney), air inlet/ambient, absorber and solar radiation were plotted. This experiment was conducted with unloaded test to get the solar collector performance. It was observed that the rise in temperature in the collector is sufficient for the purpose of most agricultural products drying even daily solar radiation was relatively low with an average of 350 W/m^2 per day. The inlet/ambient temperature is more or less uniform throughout the day which is around 28 to 31 °C. The maximum air temperature at the dryer absorber was recorded as 85°C at the solar irradiance level of 725 W/m^2. It was observed that the peak hour of temperature rises is at 12pm where typically, the hour angle is defined to be zero at solar noon, when the sun is highest in the sky. Refer to *Appendix-L* for the solar collector performance data.

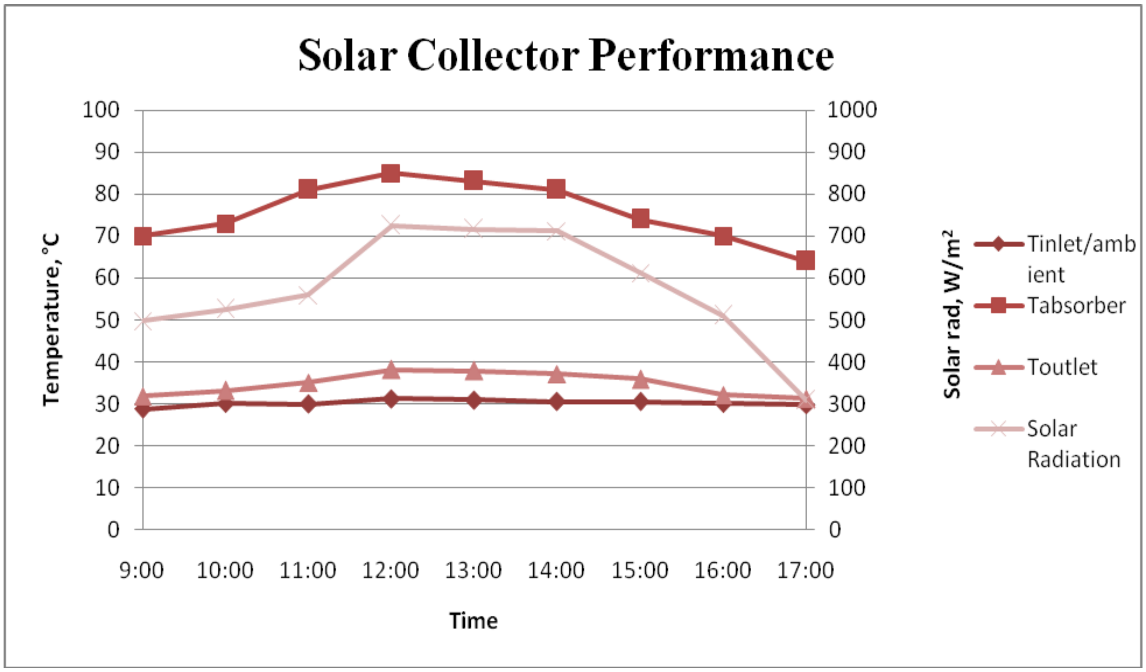


Figure 6.1: Average variation of temperatures at outlet air of collector, absorber, ambient and solar radiation.

6.2 Solar Drying Mode

Solar drying mode operates only by solar radiation source without the use of fan. The initial weight of EFB sample which is dried in the dryer is 200g. The initial condition of EFB contains high percentage of moisture content and the purpose of this experiment is to reduce the moisture content as well as measure the rate of moisture content reduction in the sample of each tray. The sample is weighted for every hour starting from 9am to 5pm. From the graph plotted, the peak hour of moisture content reduction is between 12pm to 1pm. The highest moisture content reduction, 86.08% was in tray 1 because the tray is located at the top of solar dryer. Besides, the area of tray 1 that exposed to the solar radiation is larger compared to the other trays. Refer to *Appendix-M* for the solar drying mode data.

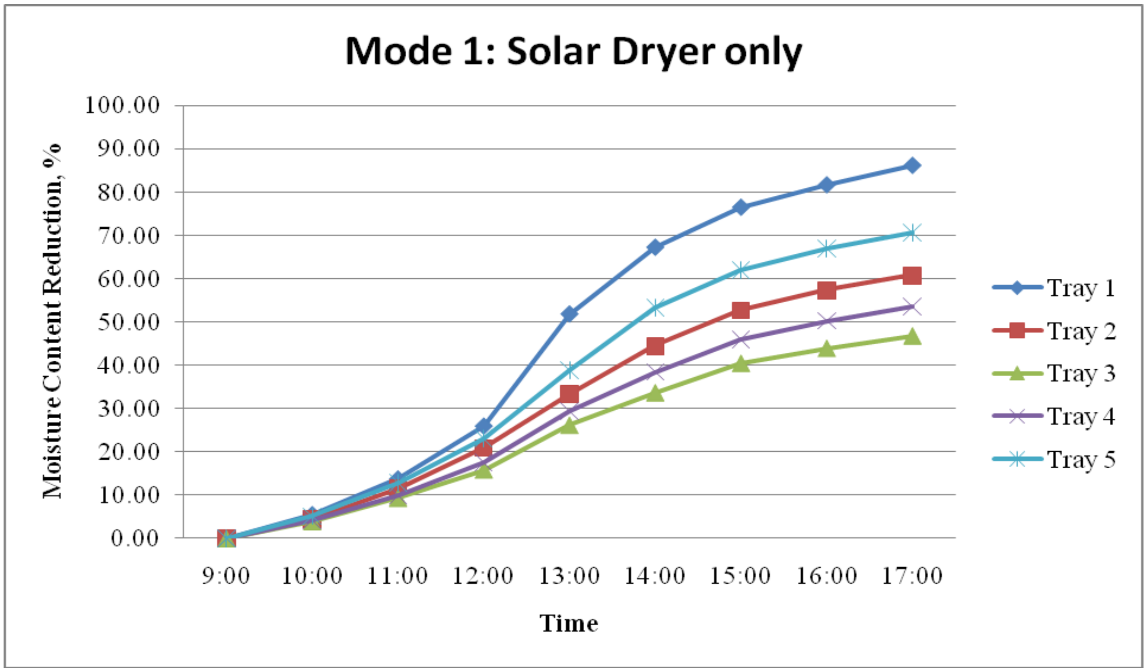


Figure 6.2: Increasing moisture content reduction of EFB for each tray of the dryer

6.3 Biomass Drying Mode

Biomass drying mode used charcoal as the burning fuel and 2 fans, which are located at the chimney and at the hose to enhance the flow hot air. This experiment was conducted in the shade area where there is low or no solar radiation. The initial weight of EFB sample which is dried in the dryer is 200g and the EFB in each tray was weighted for every 15 minutes. This experiment was tested by using 5 charcoals with the total weight of 750g. The experiment was conducted within 2 hours because the approximate hour for 5 charcoals to burn and supplied heat is about 2 hours. It is observed that tray 5 has the highest moisture content reduction because it is located near the absorber, which is at the bottom of solar dryer. Within 2 hours, the moisture content reduction in tray 5 is 33.10%. As compared to solar drying mode, it took 8 hours to reach the highest moisture content reduction in tray 1, thus biomass drying mode took shorter time than solar drying mode. Refer to *Appendix-N* for the biomass drying mode data.

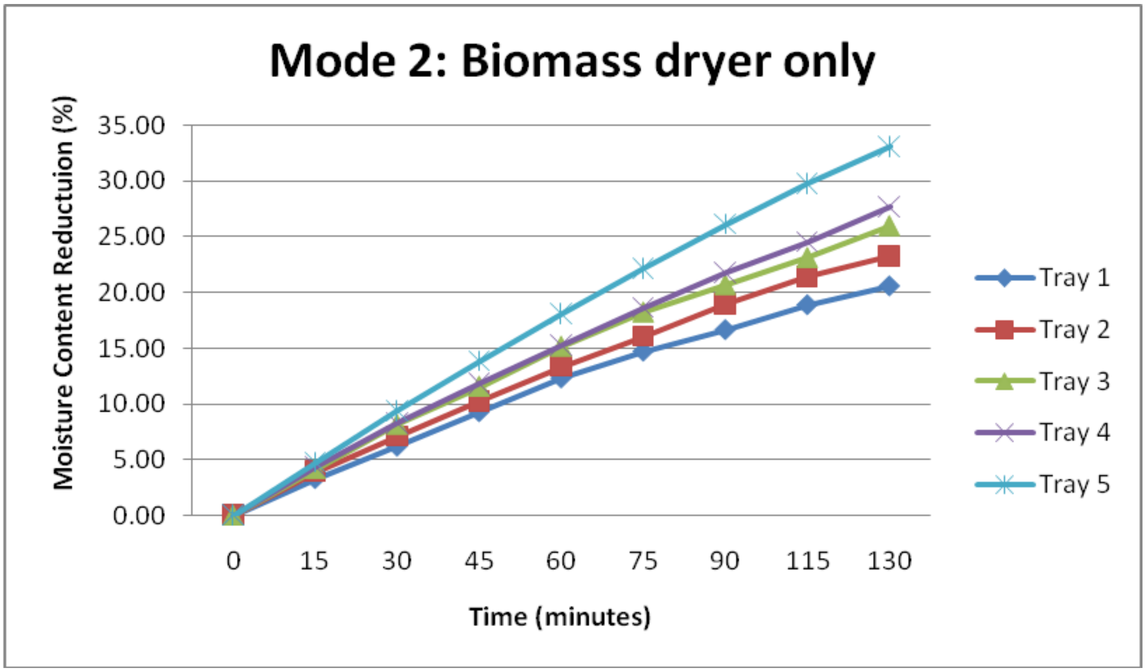


Figure 6.3: Increasing moisture content reduction of EFB for each tray of the dryer

6.4 Combined Drying Mode

In combined drying mode, solar radiation and biomass burner were used as the source of heat. Same like biomass drying mode, 5 charcoals with the total weight of 750g is used and burned inside the burner. The EFB is weighted for every 15 minutes within 2 hours. 2 fans were connected in the system which located at the chimney and the hose to enhance the flow of hot air. From the graph plotted, it is observed that the highest moisture content reduction is in tray 1 with 47.19% followed by tray 5 with 46.37%. The amount of moisture content reduction in these trays is almost the same because tray 1 is located at the top of solar dryer and the area exposed to the solar radiation is larger while tray 5 is located at the bottom of solar dryer which is near the source of heat from the burner. As compared to biomass drying mode, combined drying mode took shorter time to reach the highest moisture content reduction with difference of 14.09%. Thus combined drying is the most effective way of drying process as compared to solar drying and biomass drying mode. Refer to *Appendix-O* for the combined drying mode data.

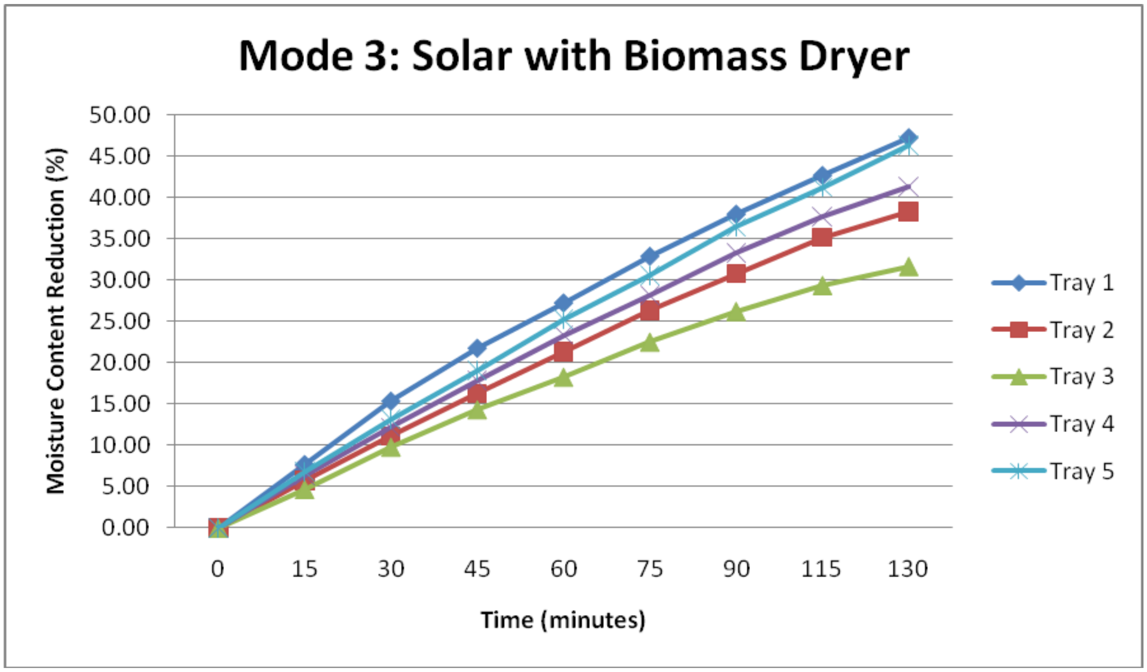


Figure 6.4: Increasing moisture content reduction of EFB for each tray of the dryer

CHAPTER 7
CONCLUSION AND RECOMMENDATION

7.1 Conclusion

The mixed mode of hybrid solar dryer has been designed and constructed with biomass back up heater integration. The system was constructed with easily available materials, tools and skills. The dryer was tested in three modes of operation (solar, biomass and solar-biomass), using EFB. Results show that the combination of hybrid solar dryer with biomass burner as a back up heater is the most effective way for drying process. It is observed that the drying time reduced considerably from solar drying mode followed by biomass drying mode and finally the combination of the dryers' mode.

From the results obtained, the rate of drying was not uniform across the trays. Consequently, there is need for interchanging them during the drying process to achieve uniformly dried products. Besides, the distance between tray 1 and bottom plate of drying chamber can be decreased in order to increase the excessive temperature on the trays, especially during burning fuels. The height of the chimney and the used of fan affects the performance of the dryer. The higher the chimney, the longer of heat air to flow out from the dryer. Thus, the longer the time of heat air to distribute inside the drying chamber. The objectives of the project to validate the used of biomass as a back up heater has been achieved since it the reduction of moisture content of EFB is higher when biomass burner is connected with the solar dryer.

7.2 Recommendation

Certain key design features of the dryer contributed to produce an acceptable thermal efficiency and uniformity of drying temperature across the trays. These features include the gap enclosing the drying chamber and the height of the chimney. However, improvements in the performance of dryer could be achieved through further modifications. Further improvement can be made as listed below:

1. Computational Fluid Dynamics (CFD) can be implemented in order to know the heat distribution.

2. Test the performance of the dryer with repeatability of the measurement using different types of material to be dried since different materials will have different moisture content reduction.

3. Detailed measurement of the velocity, pressure and temperature distribution in order to enhance the design and performance of the dryer.

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APPENDICES

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