DESIGN AND DEVELOPMENT OF A SOLAR COOKER

By

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the requirements for the
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CERTIFICATION OF APPROVAL

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Approved by,

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UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

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CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

MUHAMMAD KHAIRIL ANUAR BIN MOKHTAR

ABSTRACT

Solar cooker is popular in developing country such as Africa and India since most of the regions received more heat by solar radiation from the sun. The main focus of the project is to design and development of a solar cooker for cooking and determine the best materials for the insulation. The project is proceed with the experiment to find the lowest thermal conductivity of selected materials followed by calculation of insulation thickness. The material for the solar cooker is chosen based on the several criteria such as material properties, locally available, and cost. After the fabrication of the solar cooker is done, the stagnation test is carried to monitor and record the solar cooker performance by measure the temperatures inside the cooking chamber. Through the experiment and calculations, the value of thermal conductivity of selected insulation is determined. The thickness of the rice straw and glass fiber for the solar cooker is 26.76 mm and 28.9 mm respectively to achieve 100 ºC on the absorber plate. Results of thermal performance test for the absorber plate average temperatures from 12 pm to 1 pm is 120.9 ºC and 102.3 ºC by using rice straw and glass fiber insulation in place respectively. The thermal conductivity of rice straw by experimentally is 7.97% less than glass fiber. The efficiency of the solar cooker by using rice straw is increased 12.7 % compared to glass fiber as insulation. The performance of the cooker with rice straw as insulation was improved compared to the glass fiber.

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I would like to extend my thanks to all technical staffs within Mechanical Engineering Department especially to Mr. Zailan Alang Ahmad and Mr. Muhammad Hazri Ahmad Shahpin who have been very co-operative in helping me through out his project.

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Finally, I dedicate this work to my parents for their support, encouragement and understanding until completion of this dissertation report. Wassalam.

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NOMENCLATURE

I	Incident solar radiation (W/m^2)
T	Temperature (ºC)
h	Convection heat transfer coefficient (W/m^{2}·K)
Nu	Nuselt Number (-)
Ra	Raleigh Number
k	Conductivity of materials (W/m.K)
Pr	Prandtl Number (-)
v	Kinematic Viscosity (m^2/s)
g	Gravitational Acceleration (m/s^2)
L	Gap between glass plate (m)

Greek symbols

Δ	Difference
η	Efficiency
ε	Emissivity (-)
β	Coefficient of Volume Expansion (K^{-1})
σ	Stefan-Boltzman Constant (5.67 x 10^{-8} W/m^2.K^4)
α	Absortivity of materials (-)
α_m	Reflector angle form zenith axis (º)
θ	Latitude (º)

Subscripts

amb	ambient
avg	average
conv	convection
f	food
rad	radiation
pl	plywood
p	pot or absorber plate
l	loss
u	useful
t	top
g1	lower glass
g2	upper glass
sur	surrounding
s	surface
m	mirror
ins	insulator
w	water

CHAPTER 1
INTRODUCTION

1.1 Background of Study

Solar energy is used for cooking and drying food, vegetables, fish etc. in developing country to getting out from expensive technology which use fuel for cooking and heating element for drying. The drying process is done by exposed the direct and diffuse solar beam to evaporate water contains in the food. The process is usually done during summer day light at afternoon since the direct solar radiation is maximum at that time. The maximum of solar radiation for a solar cooker is depend on latitude, ambient temperature, wind speed, properties of absorber, type of cooker, number of glazing, insulation properties, effectiveness of booster system (reflector), types of food and number of cooking vessel.

The first solar cooking made by a European naturalist Horace de Saussure after the usage of the glass to trap the was increased during eighteenth century. He is discovered how effectively the glass trap the heat from solar energy. Later experiments is done by many researchers until now to bring new technologies to make very efficient and cheap solar cooker to conserve the energy from solar radiation to cook the food.

The principle working of solar cooker is to heat the food or pasteurize the water to eat and drink by absorbed and trap the heat until the food is cooked. There are many types of solar cooker which is parabolic type, hot-box type , panel type and advanced type.

1.2 Problem Statement

Wood is widely used for cook in rural area and for camping. But when the rain fall or humid season, the firewood will wet so that it can not burn to cook their food. So this project will help them to cook their food while waiting the wood become dry for the next days by develop a solar cooker. The impact of burning the wood is seriously for peoples if they inhale the smoke during cooking using firewood which normally happened in developed country. Furthermore the environment will pollute because the excessive of smoke during burning. Some of the villagers also cook their food by firewood in their house, this can contribute fire incident if they did not take care awareness during cooking. But they are still refuse to use the solar cooker because several factor which is (a) the product is expensive to buy, (b) cannot cooking indoors, (c) the material are not locally available, (d) cannot cook in cloudy weather, (d) cooking can only done in the direct sun too complicated to handle, (e) can not cooking at night, (f) incompatible with traditional practices, etc. All the reason above is only can overcome by continuous program of introduction, education and training, and involvement of women folk to make it successful. Determine the type of the solar cooker design is the first step to solve the problem.

1.3 Objectives

The main objective of this project is to design and build a solar cooker which can use for Malaysia environment. Several objective is stated below, which there are:-

a. To determine the best design of solar cooker by compare the design criteria's.
b. To determine type and thickness of insulation
c. Performance monitoring by using one liter of water as test load.

1.4 Scope of Study

1.4.1 Finding the best design of solar cooker

Three type of solar cooker is compared to select which design has good criteria in term of performance, material locally available and cost. The types of solar cooker are Parabolic type, Hot Box type and Advance solar cooker.

1.4.2 To determine type and thickness of insulation

This analysis is done by compare several materials by measure the value of conductivity of materials by using thermal conductivity of building and insulating testing unit. The best result of selected materials is chosen for insulation for solar cooker. The major study from this analysis is also to determine how much heat loss through the top cover and floor of cooking chamber. The result obtained of this analysis will be the guideline to select the best thickness of the wall and top of glass cooking chamber to save the material cost but hold the best performance.

1.4.2 Performance monitoring by using one liter of water as test load.

Thermal performance of the solar cooker is monitored by using one liter of water as test load. Optimization of solar cooker is done by add more reflector to increase the temperature inside the cooking chamber by experimentally. The comparison of the additional reflector is transferred to a graph to determine the effect of additional reflector.

CHAPTER 2
LITERATURE REVIEW

Solar Cooker types

There numerous of solar cooker types existing in the world but different design and shape. There are no standard design to make the solar cooker. The initial concept of the solar cooker was built is to pasteurize the water so that the water is safe to drink. The bacteria such as E.coli in the water found died after temperature of the water up to 65ºC. According to Robert, the temperature level is a moderate method to kill pathogenic microbes which is a carrier agent for malaria and hepatitis A. The solar cooker is also found able to cook food and boil the water.

Many research is conducted until nowadays is to heat the pot to cooked and pasteur water. In order to select the best selection of the solar cookers, several characteristic evaluated by choose which the best design that can use in equatorial region especially Malaysia. According to H. Huseyin Ozturk (2006), “The energy output of the Solar Box Cooker (SBC) ranged from 8.2 to 60.2 W, whereas it was varied between 20.9 and 73.5 W for the Solar Parabolic Cookers (SPC) for the same time interval”. This experiment show that the parabolic-type is higher performance than box-type since the parabolic is used to concentrated the heat form solar radiation. Furthermore, the higher temperature inside the cooking chamber can be achieve for Solar Parabolic Cooker by using the vacuum cooker.

The characteristic of good solar cooker is based on maximum temperature can be achieved, cheap material, light, and easy to setup and stored. Even the Solar Parabolic Cookers (SPC) is can give high temperature on the pot but the other parameter such as cost, material available should be consider in order to get attention for rural folks to buy the solar cooker or teach them how to do it. Mark Aalfs (2007) says that solar parabolic cookers can cook food, but when compared to the solar box approach, they are more difficult to build, require specialized materials, need constant refocusing and may burn food when solar radiation is maximum.

2.2 Testing the solar cooker

Some of the previous solar cooker made technical practitioners, they do 'stagnation test' where cookers temperature is measured without load. Copper-Constantan thermocouples is used for the temperature measurements. During the experiment, the ambient temperature, wind speed and solar radiation is recorded simultaneously. According to K. S. Malhotra (1981) "A rubber gasket at the boundary of the door is to prevent the leakage of hot air, thus increasing the pressure in the cooking chamber. The efficiency of the cooker found to be 41.2 percent". H.P Garg (2007) says that there are many test procedure for thermal rating of flat-plate collectors in different countries and the most widely accepted and used procedure is ASHRAE[13] standard 93-97, yet there is no standard test procedure for a solar cooker.

2.3 Reflector of the solar cooker

Solar cooker will perform better if more reflector attach to because more insolation will bias to the cooking chamber thus increase the temperature. The solar cooker which is non-tracking type have to design properly to get the maximum solar radiation since the position is not change automatically based on the direction of the beam radiation. The existing of the reflector is also known as booster.

2.4 Insulation

In order for the box to reach interior temperatures high enough for cooking, the walls and the bottom of the box must have good insulation. So, it is important to choose right insulator and their thickness of the materials. The common insulating materials include: aluminum foil, fiberglass mat, cellulose, foam, rice hulls, wool, straw, and crumpled newspaper.

According to Mark Aalfs, 2007, when building a solar cooker, it is important that the insulation materials surround the interior cooking cavity of the solar box on all sides except for the glazed side (usually the top). Insulating materials should be installed so that they allow minimal conduction of heat from the inner box structural materials to the outer box structural materials. The lower the box heat loss, the higher the cooking temperatures.

2.5 Solar Radiation

Solar radiation is divided by two components which is direct radiation also known beam radiation and diffuse radiation. Direct radiation is the highest energy since it has high density of solar radiation per unit area because its the sun angle perpendicular to the object. According to Gilani, 2007, diffuse radiation is the solar radiation received from the sun after its direction has been changed by scattering by atmosphere.

2.6 Cooking Chamber

According to Malholtra, 1983 the temperature inside the solar cooker is increased when the volume is reduced. It is a proved of the gas law where the temperature is increased proportionally with reducing of the volume and pressure of the gas of any substance.

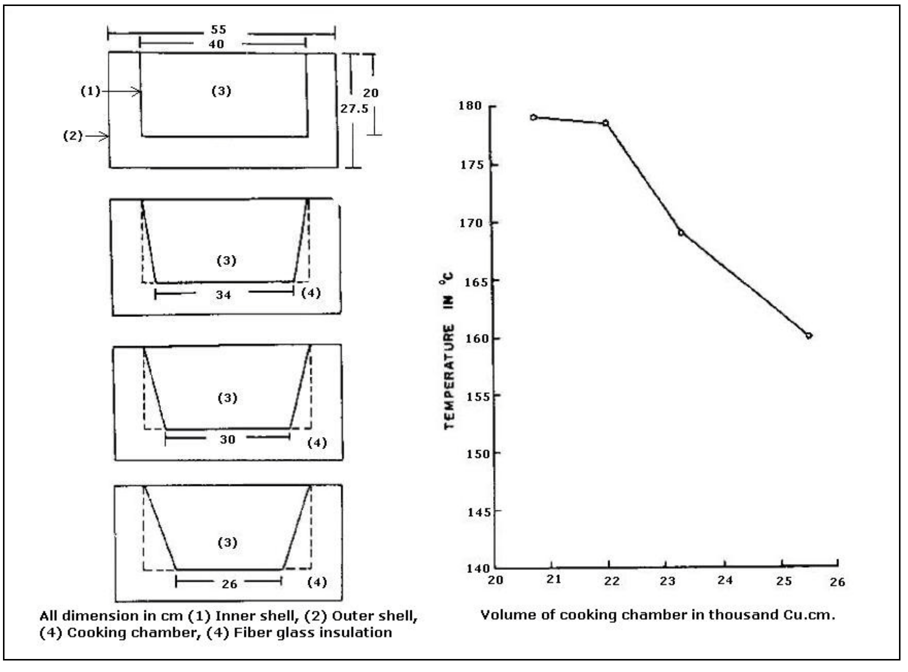


Figure 2.1 : Effect of cooking chamber volume on the air temperature inside.

Source : Malholtra, 1983, http://solarcooking.org/research/fi/pics/310.gif

CHAPTER 3
METHODOLOGY

The best type solar cooker is selected by evaluation and comparison process. The parameters used to compare the different types of solar cooker is performance, material, and cost.

The approximation for the calculation of the reflector angle,α is done to get the optimum solar angle, so that maximum solar radiation can be achieve. Thus, the performance of solar cooker increased with several parameters such as declination of the sun, hour angle, latitude, azimuth angle, zenith angle and elevation.

Experimental of the several material for insulation is done to investigate what material and thickness is the to make the best solar cooker. The result of the experiment is applied into the solar cooker. The thermal performance testing of the solar cooker is done by measure the temperature of one liter of water as a test load to know how much the time is needed to boil the water. The test is done from 11.30 a.m. to 2 p.m. during clear blue sky and bright sunshine. During the test, additional reflectors is attached to the solar cooker to monitor and differentiate the performance between one reflector and three reflectors.

This project will involve the design and development activities as state below.

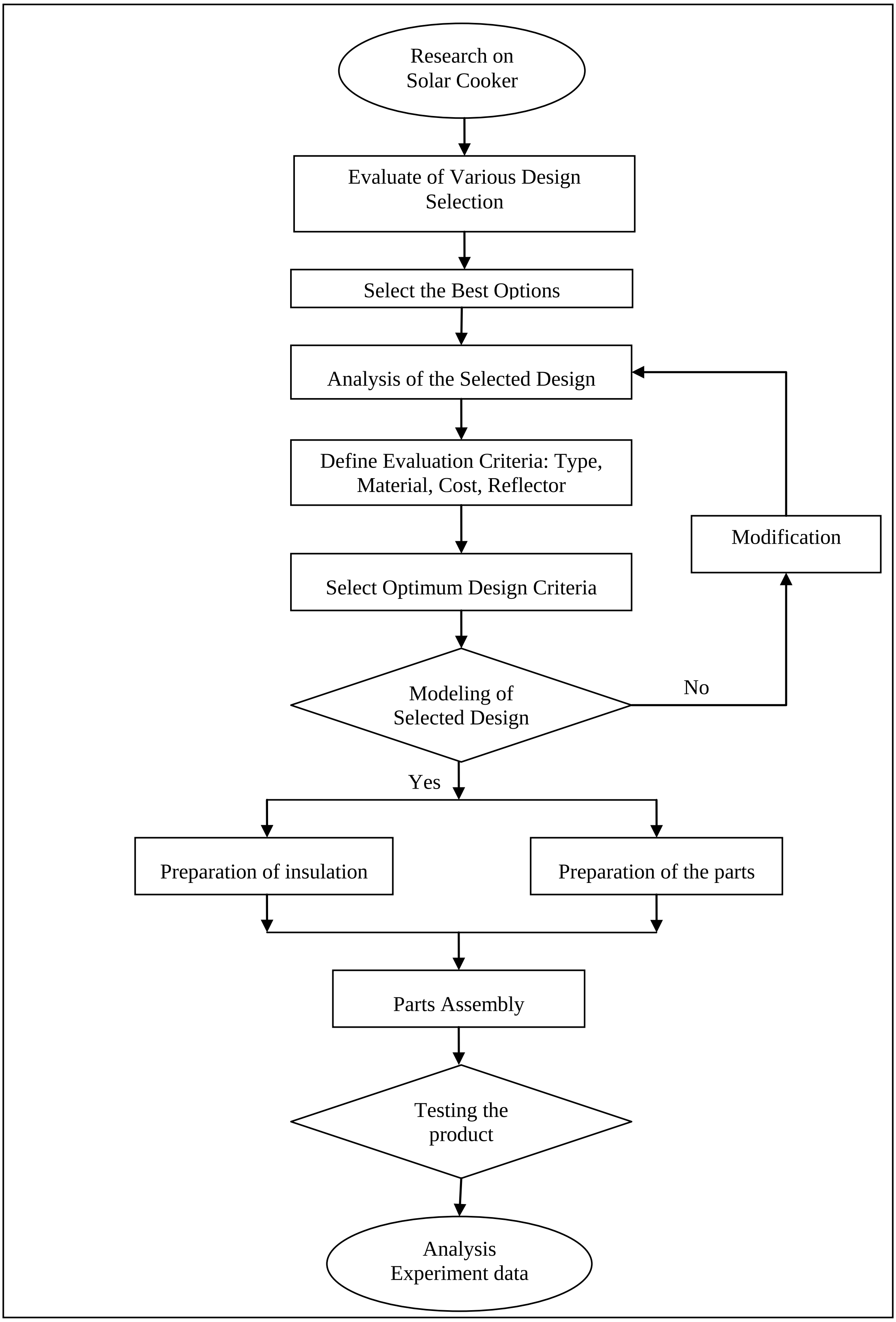
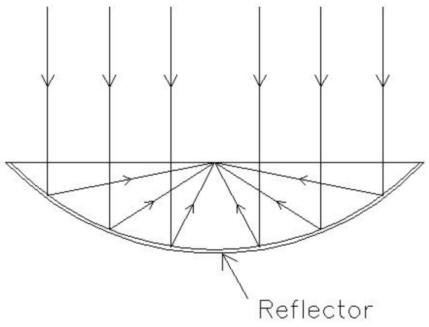
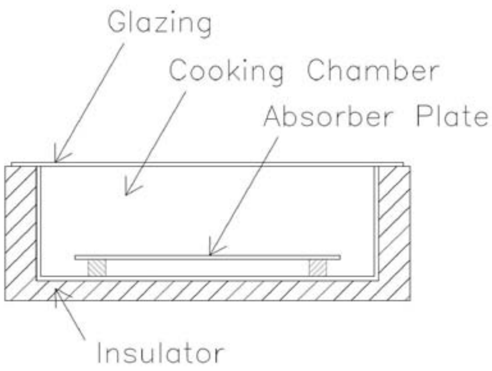
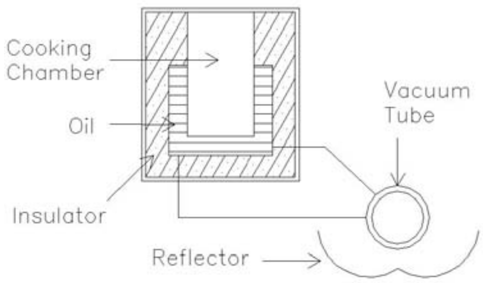


Figure 3.1 : Design and Development Process

3.1 Evaluation of Design Selections

Table 3.1 : Description of different types of solar cooker

Types of Solar Cooker	**Descriptions**
1. Parabolic type 	The beam radiation is reflected by parabolic reflector to heat the focal point where a cooking pot is located. The reflector usually made by aluminum foil or anodized aluminum sheet. This is also known as *passive cooker*.
2. Hot box type 	The sun's rays are received in an insulated box with a transparent lid which lets in the sun's rays. Inside the box, this sunshine turns to heat which is trapped in the box. Then the heat will transfer to the cooking pot. The absorber plate is used to absorb more heat and transfer to the cooking chamber.
3. Advance type 	A medium usually is used to transfer the heat to the insulated box by natural convection. The polished aluminum parabolic reflector focus on the tube to heat the oil inside. The reservoir which is located inside cooking chamber always kept at a higher position than oil tube to help in the natural convection of oil.

3.2 Selection the Best Design

The criteria chosen to design the solar cooker is stated below :-

- **Performance –** The highest temperature of the is the main criteria but the total cost of the solar cooker have to consider to select the best option since the main
- **Material cost** – Is there any cheaper material can give the solar cooker good in performance.
- **Manufacturing Cost** – How much the labor wage to make this prototype?
- **Material available –** Is it the materials for solar cooker have to imported from outside.
- **Easy to Carry –** The solar cooker is considered to used at remote area. Can solar cooker able to use at remote area?
- **Easy to manufacture –** Does it easy to manufacture? What is the tool and machine needed to make the solar cooker?

Table 3.2 : Decision Matrix for Comparison of Solar Cooker Types

Decision Criterion	**Weight**	Alternatives					
		Parabolic type		Hot Box type		Advance type	
		Rating	Score	Rating	Score	Rating	Score
Performance (high temp.)	3	4	12	3	9	3	9
Material Cost (Cheap)	3	3	9	2	6	1	3
Manufacturing Cost	3	3	9	3	9	2	6
Material available	2	1	2	4	8	1	2
Easy to Carry	2	2	4	4	8	1	2
Easy to Manufacture	2	2	4	3	6	1	2
TOTAL	15	15	**40**	19	**46**	9	**24**

Score = Rating * Weight

Rating	**Description**
4	High
3	Good
2	Moderate
1	Low Satisfaction

0	No Good

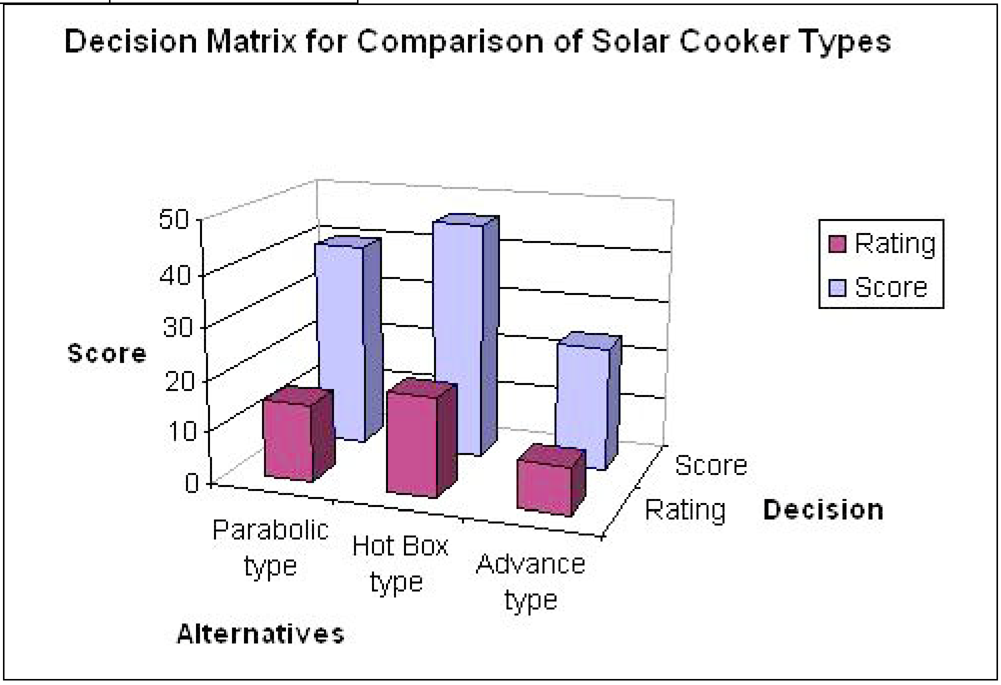


Figure 3.2 : Decision Matrix for Comparison of Solar Cooker Types

Refer to graph above, the hot box type is most valuable compare with others by using Decision Matrix Selection. According to the selection method, the hot box type is the final decision and the actual prototype is carried out to prove the solar cooker performances.

3.3 Analysis of the Selected Design

Once the hot box type is selected, the design analysis is done to increase performance analytically and experimentally.

3.3.1 Design Options

Several sketch of different design was selected to identify which is the best in performance and easy to manufacture. First design (Figure 3.3) is available in market today and for the second design (Figure 3.4) is combine with parabolic reflector. Since the parabolic reflector is not locally available, another design is made. The third design (Figure 3.5) is the final decision because it has an air gap between absorber plate and base of the cooking chamber which able to reduce the heat loss by conduction.

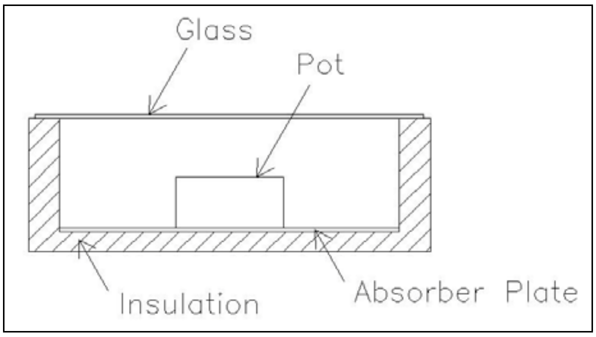


Figure 3.3 : First Design

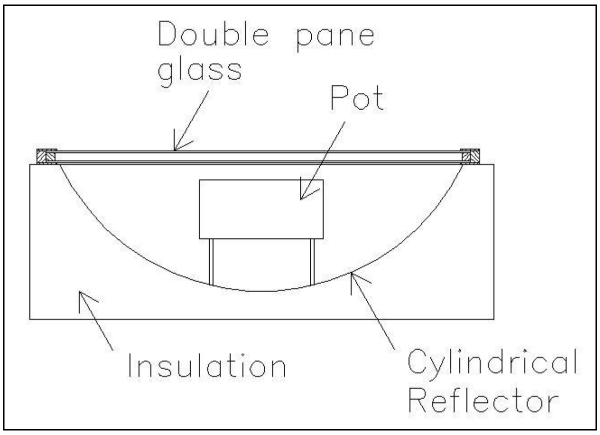


Figure 3.4 : Second Design

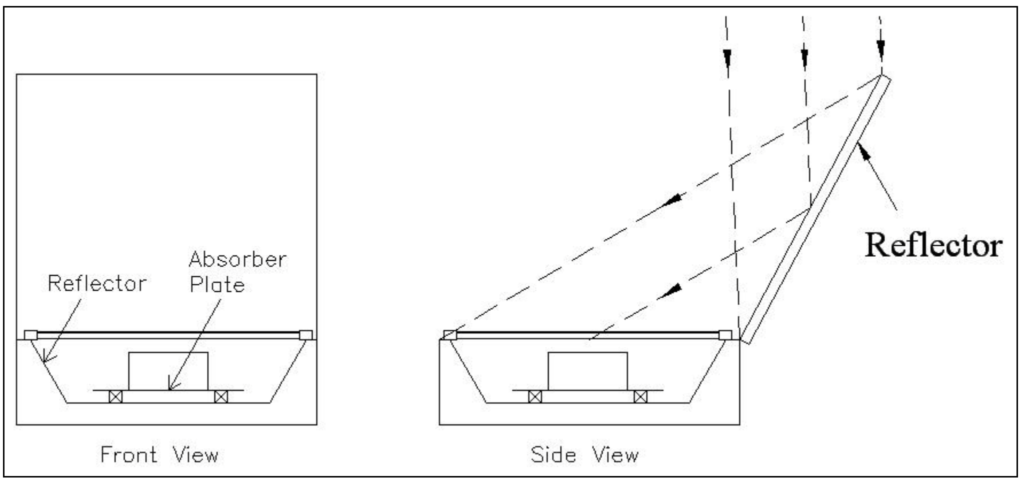


Figure 3.5 : Third Design (Final Decision)

3.3.2 Main Components in Hot Box Solar Cooker

3.3.2.1 Cover

Solar energy from the sun is formed of short radiation. After the energy reached to the earth's surface. It will re-radiated into surrounding or deep space as long wave radiation. According to Godfrey Boyle, the most important property of glass is transparent to visible light and short-wave infrared radiation, but opaque to long wave infrared re-radiated from a solar absorber plate or material behind it. So, glass is used for glazing because the ability to allow the short wave radiation and retain the long wave radiation in the cooking chamber because long wave radiation cannot penetrate the glass. Others characteristic to select the cover is based on cost, non-degradability, durability, specific heat. Calculation for the selection of the number of glazing is done to compare which design is lowest heat loss.

Table 3.3 : Absorptivity, emissivity and transmittance for different types of glass

Type of Glass	Absorptivity, α	Emissivity, ε	Transmitance, τ	Effective transmittance-absorptance, $\tau\alpha$	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

Source : Radiative heat transfer, MODEST, MICHAEL, Amsterdam : Academic Press, 2003 and Godfrey Boyle, 2004. Renewable Energy, Oxford Universiti Press

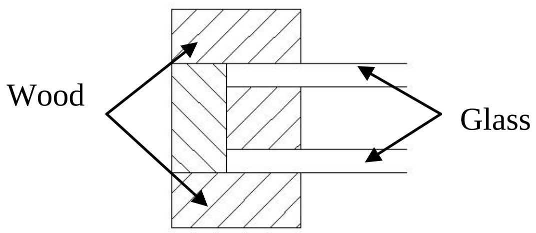


Figure 3.6 : Initial design of the glazing

Figure 3.6 shows that the double pane glass spaced by 11 mm of wood is used to reduce heat loss from the cooking chamber to the environment. Standard manufacture size of wood (11 mm x 11 mm) is used for the spacer between two glasses. The assembly of the wood is done with the nails. Final design decision is made to reduce the thickness of the glazing assembly by used the plywood instead of wood (refer Figure 3.7).

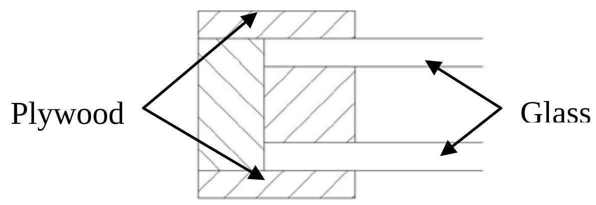


Figure 3.7 : Final design decision of the glazing assembly

3.3.2.2 Absorber Plate

Absorber plate is used to absorb heat from the solar radiation to increase the temperature of the cooking chamber since it has high thermal conductivity than other material being used in solar cooker. Aluminum (k= 237 W/m.K) with matt black painted as absorber plate is chosen because it is cheap compare to copper (k= 401 W/m.K) even copper has good thermal conductivity. The price for aluminum also is less than copper. The absorber plate is roughed by sand paper to produce rough surface because more surface area can be develop, thus increase the absorbtivity.

Table 3.4 : Thermal conductivity of selected materials for absorber

Materials	Density, ρ (kg/m³)	Specific Heat, C (J/kg.K)	Thermal conductivity, k (W/m.K)
Aluminum 1100	2379	903	237
Copper	8933	385	401
Carbon Steel	7832	434	60.5
Tin	7310	227	66.6

Source : Frank P. Incropera and DeWitt, Introduction to Heat Transfer, 5th ed. (Asia : John Wiley & Sons, 2007). p A1-A8.

3.3.2.3 Insulation

Selection of the insulation is based on the lowest thermal conductivity and the material cost. Selected materials that can be use for the solar cooker as stated in Table 3.5.

Table 3.5 : Thermal conductivity of selected materials for insulation

Materials	Thermal conductivity, k (W/m.K)
Rigid foam	0.026
Glass Fiber	0.043
Blanket	0.038
Cotton	0.06
Sawdust	0.06
Straw	0.09
Paper	0.18
Plaster / gypsum	0.48

Extracted from : Incropera, DeWit, 2007. *Introduction to Heat Transfer 5th Edition*, John Willey and Sons. and <http://www.engineeringtoolbox.com/thermal-conductivity-d_429.html>

3.3.2.4 Reflector

Reflector is use as a booster to solar cooker to cook the food. The material for the reflector should have high emissivity,ε to reflect the heat energy from the solar radiation. When the reflector of the solar cooker is adjusted for certain angle, in can maximize the flux arriving the target. The reflector for the solar cooker is not tracking type where the angle of the solar reflector should be adjusted over the time. The reflector are made of 2 mm thick of glass mirror which is suitable in term of cost and material locally available.

Table 3.6 : Emissivity and absorptivity for selected materials

Materials	Absorptivity,α	Emissivity, ε
Mirror	0.13	0.83
Aluminum (Polished)	0.09	0.03
Aluminum Foil	0.15	0.05
Aluminum, soft anodized, Reflectal alloy	0.23	0.79

Extracted from : Modest and Michael, 2003. Radiative heat transfer, Amsterdam : Academic Press and Yunus A. Cengel, 2003. Heat Transfer : A Practical Approach, Mc. Graw Hill.

Aluminum foil has low emissivity but it is cheap compare to the glass mirror. The characteristic of glass mirror because it is capable to reflect more incident radiation due to high emissivity. The main mirror reflector is facing to the south at 28.33º angle from zenith axis because the solar angle is not changed but the hour angle is changed 15º per hour due to rotation of the earth. Additional of solar reflector which also from glass mirror is attached to plywood to increase the concentration ratio. The concentration ratio is the effective aperture area divided by absorber area. The higher concentration ratio resulting the higher heat gain is absorbed by absorber. According to U.S. Mirdha and S.R. Dhariwal, the position of the reflector obtained from following equation :-

$$\text{Reflector angle (from zenith axis)}, \alpha = \frac{1}{3}\left(2\theta + \beta - \frac{\pi}{2}\right)$$

Latitude for Malaysia, θ = 2.5ºN

Angle of absorber or cover plate, β = 0º

$\therefore$ Reflector angle (from zenith axis), α_m = -28.33º

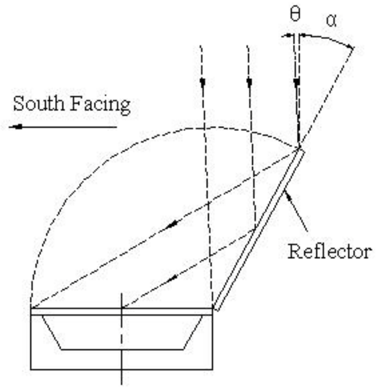


Figure 3.8 : Reflector position of the solar cooker

3.3.2.4 Selective Coatings

The characteristic of coating that should select for absorber plate is determined by solar absorptance,α and emittance,ε of the material. According to Gilani, 2007, the objective to select coating for absorber plate is to achieve maximum absorptance,α and minimum re-emittance,ε so that the ratio of performance factor, α/ε is a maximum. The Flat Black paint is selected for coating because it is locally available and cheap compare to Black Nickel or Black Chrome plating.

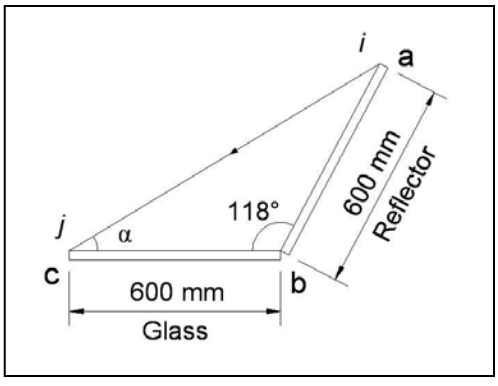
Table 3.7 : Performance ratio for selected coatings

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
Flat black paint	0.97	0.86	1.13
Gray paint	0.75	0.95	0.79

Source : W. Shepherd and D.W. Shepherd, 1998. *Energy Studies*, Imperial College Press, p293.

3.3.2.5 View Factor

According to Incropera, the view factor is defined as the fraction of the solar radiation leaving between any two surfaces. The equation of view factor for two-dimensional of the solar cooker is stated below :-



$$F_{ij} = 1 - \sin\left(\frac{\alpha}{2}\right)$$

$$= 1 - \sin\left(\frac{30.85°}{2}\right)$$

$$= 0.734$$

Figure 3.9 : View factor of two-dimensional solar cooker

3.4 Experimental of thermal conductivity of insulation

Figure 3.10 : Equipment used to determine thermal conductivity of materials

Experiment to determine the thermal conductivity of materials is done by record the temperature of the hot plate and cold plate inside the testing chamber. The size of the specimen is 300 mm x 300 mm. The set point, SP 1 for the heater plate is 40ºC and the thickness of the samples is 50mm for all type of materials. The reading is taken after is 30 minute due to achieve steady state conditions. Thermal conductivity is determined by using calibration constants (k_1 to k_6) supplied with the tester unit. The temperature for the cold plate is not set according to manual lab. The temperature for hot plate and cold plate is needed for calculation.

Thermal conductivity,

$$k = \frac{l * \left[\left(k_1 + \left(k_2 * \overline{T}\right)\right) + \left(\left(k_3 + \left(k_4 * \overline{T}\right)\right) * HFM\right) + \left(\left(k_5 + \left(k_6 * \overline{T}\right)\right) * HFM^2\right)\right]}{dT}$$

Where :

l = Sample thickness

Temperature different, $dT = T_1 - T_2$

Average Temperature, $\overline{T} = \frac{T_1 + T_2}{2}$

k_1 = -5.4636	k_4 = 0.0499
k_2 = 0.0983	k_5 = 0.0644
k_3 = 2.6335	k_2 = -0.0002

Source : Lab Manual, *Thermal conductivity of Building and Insulating Materials Unit B40*, P.A. Hilton Ltd.

3.5 Calculations

Three main parts of calculation for the solar cooker which are heat transfer from solar incident radiation, heat useful from pot to food and heat loss through cover and insulator.

The following assumption is used to make the model of the solar cooker :

- The solar cooker is considered as a flat plate solar collector operating under steady state condition.
- Constant thermal conductivity
- Ambient temperature is constant, $T_{amb} = 30^{o}C$
- The mass of air in oven is neglected
- Heat loss through the wall is neglected. Heat loss through the base and top cover is calculated.
- Pot temperature is assumed same as absorber plate.
- Previous experiment (Emad H. Amer, 2002) that the temperature of lower glass, T_{g1} of the cover is greater than upper glass, T_{g2}.
- Natural convection and radiation inside enclosure is exchanged in between absorber plate - lower cover and lower cover - upper cover.
- Combination of natural, forced convection and radiation heat transfer is assumed on outer glazing.
- Heat convection coefficient in cooking chamber is assumed h_{cc}=3 W/m²K since there is no air flow inside the cooking chamber.
- Incropera (2007) says the view factor is introduced to calculate the heat transfer by solar radiation on tilted and horizontal surface due to sun angle from zenith axis.

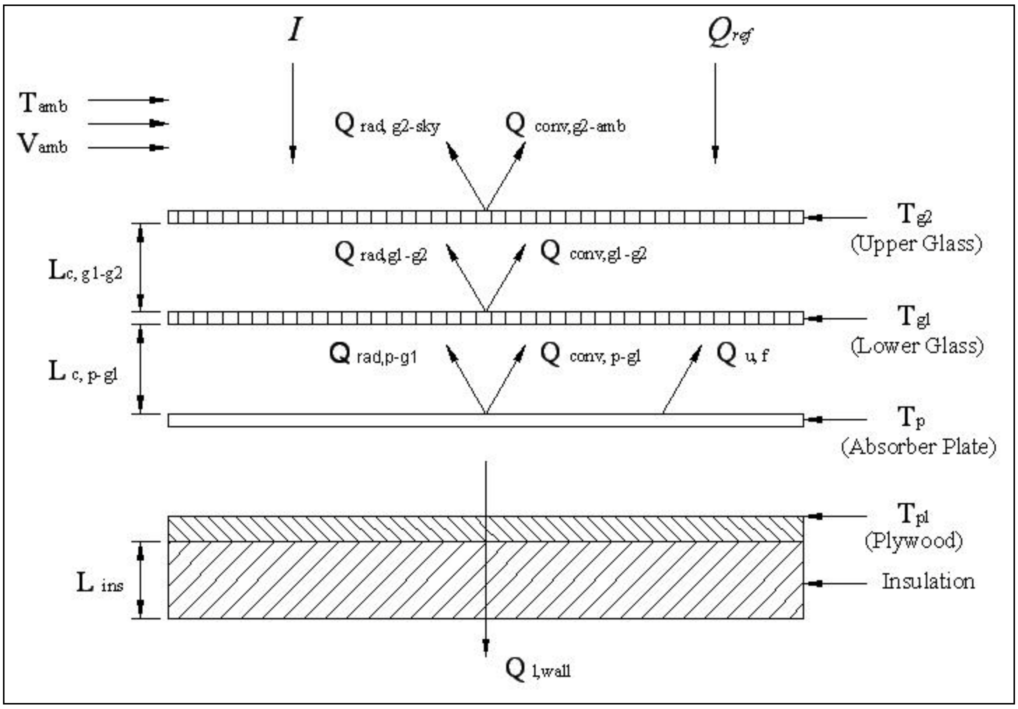


Figure 3.11 : Schematic representation of heat flows in a box-type solar cooker

The energy balance on solar cooker under steady state is :

$$\mathbf{IA_g(\tau_g\alpha_g) \;+\; \alpha_g Q_{ref} \;=\; Q_{u,f} \;+\; Q_{loss}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

Where :

$$Q_{loss} = Q_{l,wall} + Q_{l,,t} + Q_{l,g} + Q_{l,,p\text{-}g1}$$

The equation (1) become :

$$\mathbf{IA_g(\tau_g\alpha_g) + \alpha_g(F_{ref\text{-}g2}\,A_{ref}\,I) = Q_{u,f} + Q_{l,wall} + Q_{l,,t} + Q_{l,g} + Q_{l,,p\text{-}g1}} \quad \ldots..(2)$$

Where :

a) <u>Heat useful to cook a food, $Q_{u,f}$</u>

$$Q_{u,f} = \frac{mC_p(T_p - T_f)}{\Delta t} = \frac{(1\,\text{kg})(4200\,\text{J/kg.K})(100-30)}{4800\,\text{s}} = \mathbf{61.25\ W} \quad \ldots..(3)$$

b) <u>Heat loss through wall, $Q_{l,wall}$</u>

$$R_{total} = R_{conv,p} + R_{pl} + R_{ins} + R_{conv,a}$$

$$= \frac{1}{h_{cc}A_p} + \frac{L_{pl}}{k_{pl}A_{pl}} + \frac{L_{ins}}{k_{ins}A_{ins}} + \frac{1}{h_{amb}A_{ins}}$$

$$= \frac{1}{3(0.3\times0.3)} + \frac{0.003}{1.4(0.4\times0.4)} + \frac{L_{ins}}{0.12(0.4\times0.4)} + \frac{1}{5(0.4\times0.4)}$$

$$Q_{l,wall} = \frac{T_{pl} - T_{amb}}{R_{Total}}$$

$$= \frac{80-30}{\frac{1}{3(0.3\times0.3)} + \frac{0.003}{0.12(0.4\times0.4)} + \frac{L_{ins}}{0.0464(0.4\times0.4)} + \frac{1}{5(0.4\times0.4)}} \quad .....(4)$$

c) <u>Heat loss (Top), $Q_{l,t}$ (between upper cover and sky)</u>

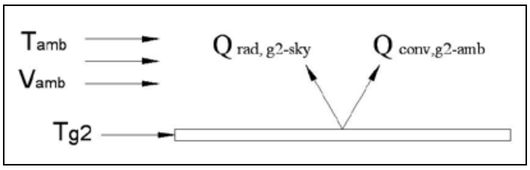


Figure 3.12 : Heat loss from upper glass to environment.

Assumption :

- Upper glass temperatureT_{g2} = 35 ºC
- Sky temperature, T_{amb} = 30 ºC
- Sky temperature, T_{sky} = $T_{amb} - 6$ = 24 ºC
- Wind velocity, V_{amb} = 2.05 m/s
- Characteristic length, L_c = $\frac{A_g}{p}$ = $\frac{(0.54x0.54)}{4 \text{ x } 0.54}$ = 0.135 m
- Average temperature, T_f = $(T_s + T_{amb})/2$ = 32.5 ºC
- Properties of air at 32.5 ºC :-
  - k = 0.02607 W/mk ; - Pr = 0.7275 ;

$- \ v = 1.6315x\ 10^{-5}$; $\beta = 1/T_f = 1/(32.5 + 273) = 3.2733x10^{-3}$;

$$Re = \frac{V_{amb} L_c}{\nu} = \frac{(2.05)(0.135)}{1.6315x10^{-5}} = 1.705x10^4$$

$$Nu = \frac{h.L_c}{k} = 0.664 Re_L^{0.5} Pr^{1/3}$$

$$h = 3.763\ W/m^2$$

$$Q_{l,t} = hA_s(T_{g2} - T_{amb}) + \sigma\varepsilon_g A_g(T_{g2}^4 - T_{sky}^4)$$
$$= (3.763)(0.54x0.54)(35\text{-}30) + (5.67x10^{-8})(0.83)\ )(0.54x0.54)\ (308^4 - 297^4)$$
$$= 5.487 + 16.719$$
$$= \mathbf{22.206\ W} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(5)$$

d) Heat loss from absorber plate, $Q_{l,\ p\text{-}g1}$

Heat loss occurred from absorber plate to lower glass is assumed as heat transfer between two enclosure.

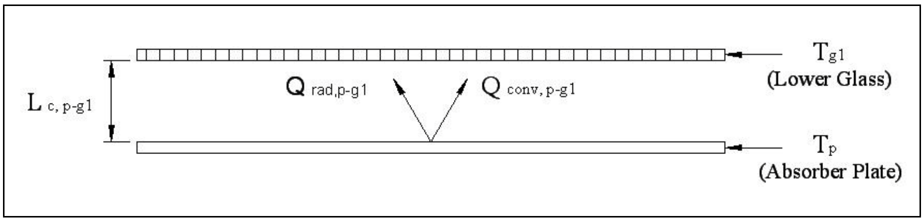


Figure 3.13 : Heat loss from absorber plate to lower glass (first glass)

Assumption :

- Pot temperature, T_p = 100 ºC
- Lower glass temperature, T_{g1} = 80 ºC

$$Q_{l,\ p\text{-}g1} = Q_{conv,p\text{-}g1} + Q_{rad,p\text{-}g1}$$
$$= h_p A_{ref}(T_p - T_{g1}) + \sigma\varepsilon_p A_p(T_p^4 - T_{g1}^4)$$

$$= \frac{Nu\, k_{air}(T_p - T_{g1})}{L_c} + \frac{\sigma A_p (T_p^{\,4} - T_{g1}^{\,4})}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1}$$

$$= \frac{(6.583)(0.03024)(100 - 80)}{0.1} + \frac{(5.67x10^{-8})(0.3x0.3)(373^4 - 353^4)}{\frac{1}{0.09} + \frac{1}{0.83} - 1}$$

$$= 39.812 + 1.727$$

$$= \mathbf{41.539\ W} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(6)$$

Subsitute (3), (4), (5) and (6) into equation (2) :-

$$\mathbf{IA_g(\tau_g\alpha_g) + \alpha_g(F_{ref\text{-}g2}\, A_{ref}\, I) = Q_{u,f} + Q_{l,wall} + Q_{l,,t} + Q_{l,g} + Q_{l,,p\text{-}g1}} \quad \ldots..(2)$$

(700)(0.2916)(0.91x0.13) + 0.13(0.734x0.36x700) =

$$61.25 + \frac{80 - 30}{\frac{1}{3(0.3\times0.3)} + \frac{0.003}{0.12(0.4\times0.4)} + \frac{L_{ins}}{0.0464(0.4\times0.4)} + \frac{1}{5(0.4\times0.4)}} + 22.206$$

$$+ 56.889 + 41.539$$

$$\therefore \quad L_{ins} = 27.02 \text{ mm of rice straw thickness.}$$

3.5.1 Calculation for the cover to compare single glass and double glass performance

1. Single glazing

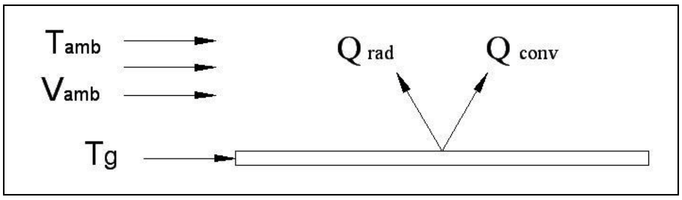


Figure 3.14 : Heat loss through single glass

Assume : T_{amb} = 30 ºC ; V_{amb} = 2.06 m/s ; T_g = 80 ºC ; T_{sky} = T_{amb} -6 ºC = 24 ºC

A_g = 0.54 m x 0.54m

$T_{avg} = (T_g + T_{amb}) / 2 \quad = \quad (80^oC + 33\ ^oC) / 2 \quad = \quad 56.5^oC \quad \approx \quad 329.5\ K$

Charecteristic Length, $L_C = \dfrac{A_g}{P}$

Reynold Number, $Re = \dfrac{V_{amb} L_C}{\nu}$ Re < 5 x 10^5 : Laminar

$Nu = h.L_C/k$

$Nu = 0.664\ Re^{0.5}\ Pr^{1/3}$ (Equation 7.21, Cengel, Yunus)

$\therefore \quad h = Nu*k / L_C$

Heat Transfer by convection, $Q_{conv} = hA_g(T_g - T_{amb}) = 58.476$ W

Heat Transfer by radiation, $Q_{rad} = \sigma\varepsilon_m A_g(T_g^{\ 4} - T_{sky}^{\ 4}) = 102.405$ W

$\therefore$ Total heat loss for single glazing is :

$Q_{l,g} \quad = Q_{conv,g} + Q_{rad,g}$

$= 54.476 + 102.405$

= 160.881 W

2. Double Glazing

1. Natural Convection Inside Enclosure, Q_{conv}

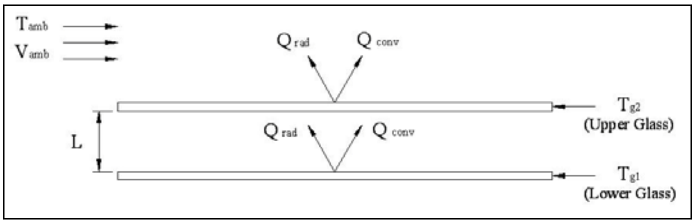


Figure 3.15 : Heat loss through double pane glass

Assume : $T_{g1} = 80^oC$ and $T_{g2} = 35\ ^oC$

$T_{avg} = (T_{g1} + T_{g2}) / 2 = (80^oC + 33\ ^oC) / 2 = 56.5^oC \approx 329.5\ K$

Properties at T = 56.5 ºC :

$k = 0.02782$ W/m ºC $\quad v = 1.862e\text{-}5\ m^2/s$

$Pr = 0.7211 \quad \beta = 1/ T_{avg} = 1/329.5\ K = 3.035e\text{-}3$

$\varepsilon_1 = \varepsilon_2 = 0.9$ $\quad$ L = 10 mm (0.01m)

The Raleigh Number, Ra for the enclosure is determined from :

$$\text{Ra} = \frac{g\,\beta(T_1 - T_2)L^3\,\text{Pr}}{v^2} \quad = \quad 2.911 \times 10^3$$

Nusselt Number for horizontal plate :

Based on experiment with air, Hollands et al (1976) recommend this correlation for enclosure,

$$Nu = 1 + 1.44\left[1 - \frac{1708}{Ra_L}\right]^{+} + \left[\frac{Ra_L^{1/3}}{18} - 1\right] \qquad \text{Ra} < 10^8 \qquad \text{(Cengel, Yunus)}$$

Nu = 1.388

$\therefore$ Heat Transfer by convection, $Q_{conv} = hA_s(T_1 - T_2) = \dfrac{k\,Nu\,As\,(T_{g1} - T_{g2})}{L}$

= 56.375 W

2. Radiation heat transfer between two parallel plates, Q_{rad}

$$Q_{rad} = \frac{\sigma A(T_{g1}{}^4 - T_{g2}{}^4)}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1} = \mathbf{0.514\ W}$$

$\therefore$ Total heat loss in the glazing, $Q_{l,g}$:

$Q_{l,g} = Q_{conv} + Q_{rad}$

= 56.375 W + 0.514 W

= 56.899 W

The results of the analytical solution shows that the maximum heat loss occur at single glass application compare to double glass since heat transfer by convection and radiation removed the heat on the glass surface. The gap of air between double glass causing to reduced the heat loss thus increased the performance of the solar cooker. The comparison of heat loss between single glass and double glass is shown in Figure 3.16. The temperature different between outer glass and ambient for single glass and between lower glass and upper glass for double glass application is assumed 20 ºC. Figure 3.16 shows that total heat loss occur in single glazing is larger than double glazing. So, the double glass is selected to make the glazing for the solar cooker.

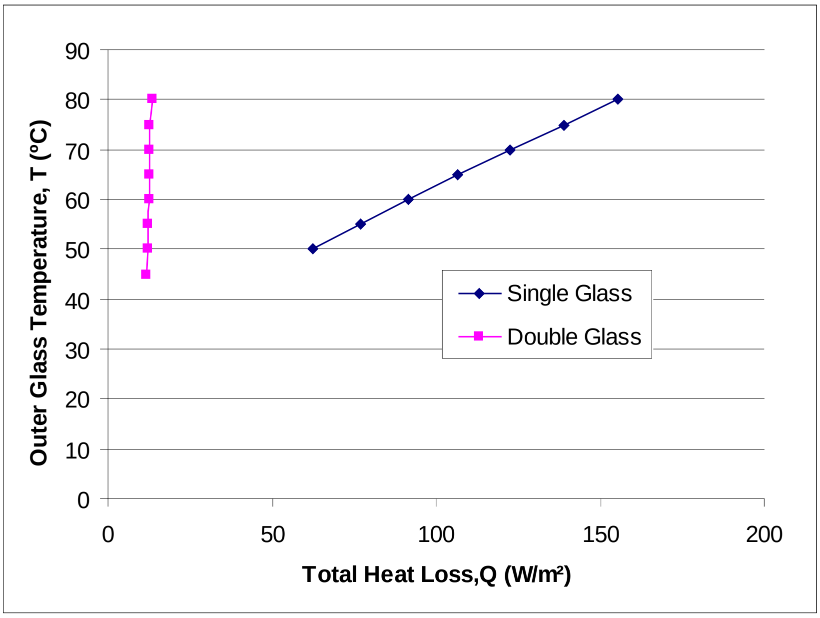


Figure 3.16 : Heat loss through single cover and double cover.

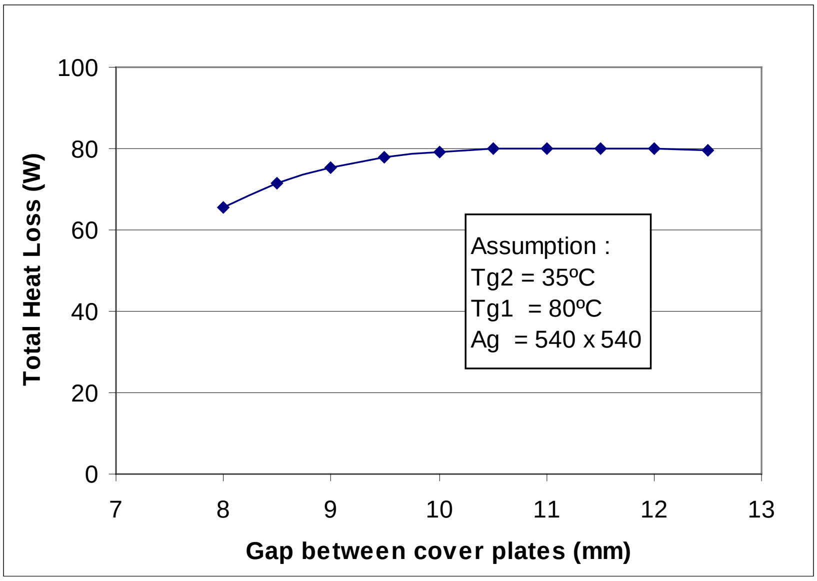


Figure 3.17 : Total heat loss occur in double pane glass with different air space.

Figure 3.17 shows that the analytical result of spacing between glasses where total heat is lowest for the small gap instead of larger gap space. But since the standard size of lumber for 8 mm is not available, the size of 11 mm x 11 mm is selected and put between the glasses.

3.6 Fabrication of Solar Cooker

Three main parts is divided to make the solar cooker which is main frame, cooking chamber, cooker covers and glazing. All assembly is combined with the nails and screws. Support wood is designed to make the solar cooker more rigid. A set of mirrors is placed on the inclined wall to keep solar radiation bouncing to the pot and absorber plate.

Figure 3.18 : Assembly of main frame with cooking chamber of solar cooker

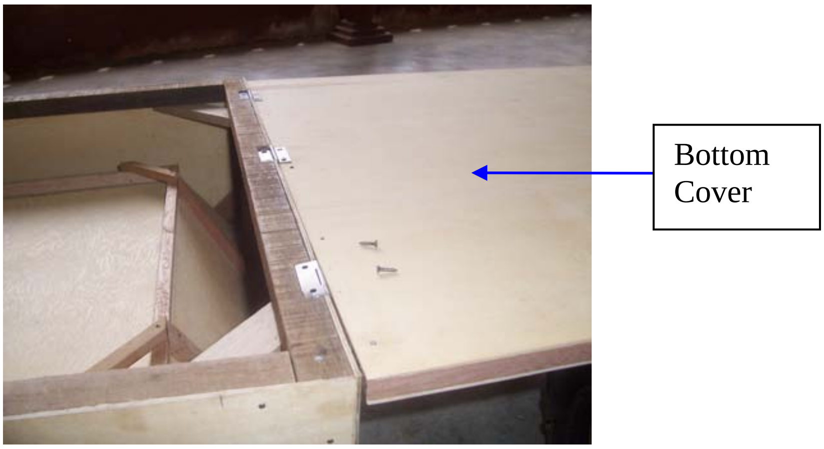


Figure 3.19 : Bottom cover is attached to the base of solar cooker

3.7 Testing of Solar Cooker

Direct radiation from the sun is measured using a solarimeter, while the velocity of wind and temperatures of the solar cooker is measured by anemometer and Copper-Constantan thermocouples with data logger. The solarimeter probe is inclined 2.5º (according to latitude of Malaysia) to the southward from horizontal surface. The thermocouples is attached to several position in solar cooker which is absorber plate, both surface of double glazing and inside of the pot. The purpose of placement of thermocouples at different location in solar cooker is to study the behavior inside the solar cooker experimentally and to compare assumption made by analytically.

Figure 3.20 : Performance testing of a box type solar cooker.

Figure 3.21 : Thermocouple is submerged in water inside the cooking pot.

According to “Standard of Testing and Reporting Solar Cooker Performance, American Society of Agricultural Engineers, the thermocouple junction should be immersed in the water in the cooking vessel and secured 10 mm above the bottom, at the center. A piece of wood or stone is put between plywood and absorber plate because to prevent the plywood thermal expansion during cooking. During the experiment, temperatures of the cooker, ambient temperature and solar radiation is recorded simultaneously for every 10 minutes from 11.30 a.m. to 2 p.m. Wind speed is taken for once only because to simplify the test method. According to http://www.ask.com/weather, the average wind speed in Malaysia is 7.4 km/h (2.06 m/s).

CHAPTER 4

RESULT AND DISCUSSION

4.1 Experimental result of thermal conductivity of insulation

There are four possible material to be used as insulation, namely : Glass fiber, Coconut husk, Rice straw and Bushes straw. To decide the thermal conductivity of each material respectively, the result of the experiment as follows :-

Material : Glass fiber
Date : 14 February 2008 (Thursday)
Thickness : 50 mm

	Samples				
	1	2	3	4	
SP 1(ºC)	40.0	40.0	40.0	40.0	
l (mm)	0.05	0.05	0.05	0.05	
T1 (ºC)	40.1	40.2	40.1	40.1	
T2 (ºC)	26.8	27.7	28.3	29.4	
Tavg (ºC)	33.45	33.95	34.2	34.75	
HFM (mV)	1.62	1.05	4.32	4.9	Average
k (W/mK)	**0.0186**	**0.0099**	**0.0751**	**0.0969**	**0.0501**

Material : Coconut husk
Date : 14 February 2008 (Thursday)
Thickness : 50 mm

	Samples				
	1	2	3	4	
SP 1(ºC)	40.0	40.0	40.0	40.0	
l (mm)	0.05	0.05	0.05	0.05	
T1 (ºC)	40.1	40.2	40.4	40.4	
T2 (ºC)	25.6	27.3	27.1	27.4	
Tavg (ºC)	32.85	33.75	33.75	33.9	
HFM (mV)	6.19	6.79	8.05	8.73	Average
k (W/mK)	**0.0911**	**0.1156**	**0.1366**	**0.1539**	**0.1243**

Material : Rice Straw
Date : 19 February 2008 (Tuesday)
Thickness : 50 mm

	Samples				
	1	2	3	4	
SP 1(ºC)	40.0	40.0	40.0	40.0	
I (mm)	0.05	0.05	0.05	0.05	
T1 (ºC)	39.9	40	40.2	40.3	
T2 (ºC)	26.7	26	26.7	27.4	
Tavg (ºC)	33.3	33	33.45	33.85	
HFM (mV)	0.9	4.86	3.79	3.46	Average
k (W/mK)	**0.0065**	**0.0712**	**0.0554**	**0.0524**	**0.0464**

Material : Bushes Straw
Date : 20 February 2008 (Wednesday)
Thickness : 50 mm

	Time (minute)				
	30	60	90	120	
SP 1(ºC)	40.0	40.0	40.0	40.0	
I (mm)	0.05	0.05	0.05	0.05	
T1 (ºC)	40.1	40.1	40	40.1	
T2 (ºC)	25.7	26.6	27.6	28.1	
Tavg (ºC)	32.9	33.35	33.8	34.1	
HFM (mV)	1.49	0.84	5.2	8.03	Average
k (W/mK)	**0.0148**	**0.0054**	**0.0882**	**0.1517**	**0.0651**

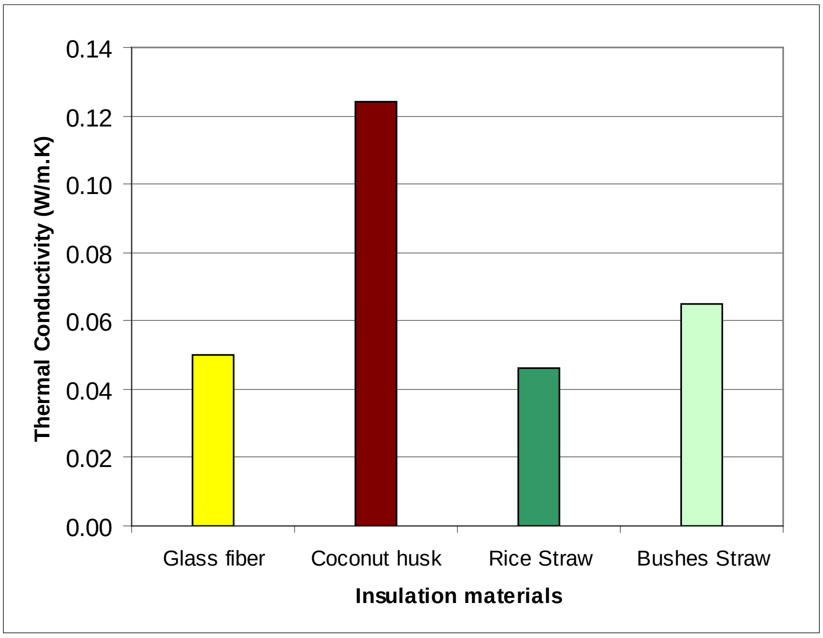


Figure 4.1 : Experiment result for finding an insulator material for the cooker.

From the graph, the rice straw is the lowest thermal conductivity and the value is almost the same with the glass fiber. Therefore, the straw of rice is selected as insulation of the solar cooker. The thermal conductivity of rice straw is 7.97% less compared to glass fiber.

4.2 Result of the calculations to finding insulation

From the experiment done to determine the value of lowest thermal conductivity, the rice of straw is selected to compare with glass of fiber which is always used for building insulation material. The Figure 4.2 below is based on the energy balance equation (Refer page 20) to find the suitable thickness of insulation for the pot temperature achieved at 100ºC. The insulation is located below surface of the plywood in the solar cooker.

Figure 4.3 shows the result of the thickness for the insulation by using the equation 1 (Refer page 20). From the Figure 4.3, the rice straw is the lowest thermal conductivity compared to glass fiber by experimentally. The result of the existing material which is straw, paper and foam also included in the calculation for comparison purpose. Through the analytically and experimentally, the insulation thickness for the solar cooker by using the rice straw and glass fiber is 26.76 mm and 28.9 mm respectively to achieve 100ºC on the absorber plate or cooking pot.

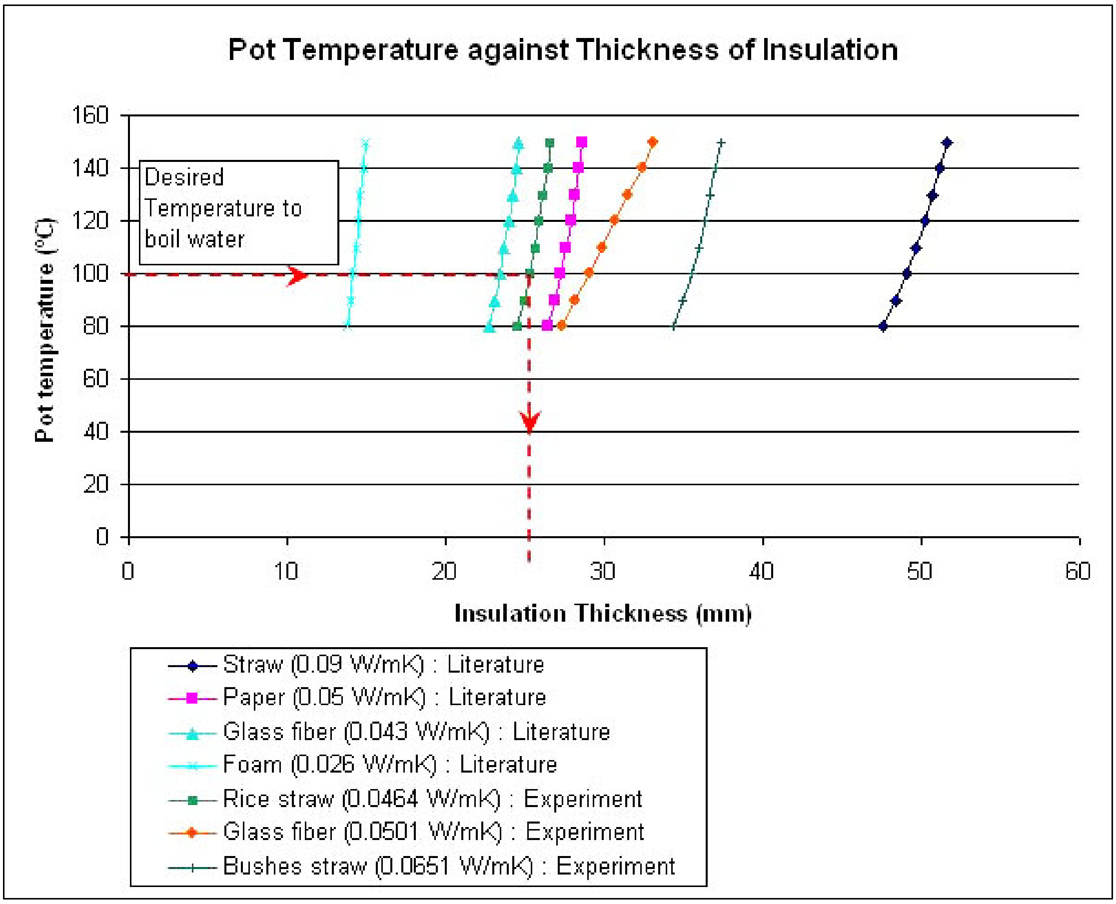


Figure 4.2 : Cooker pot temperature by different type of insulation

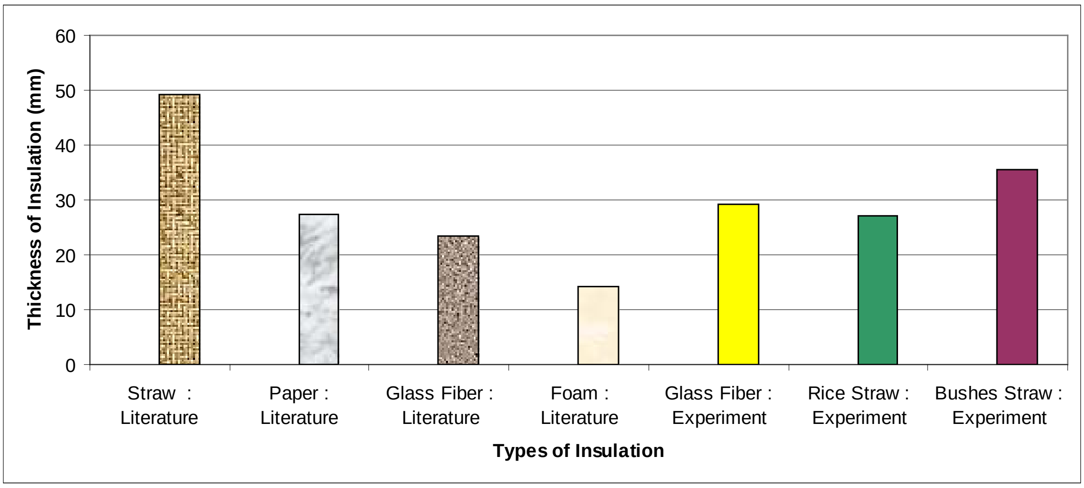


Figure 4.3 : Cooker pot thickness by different type of insulation

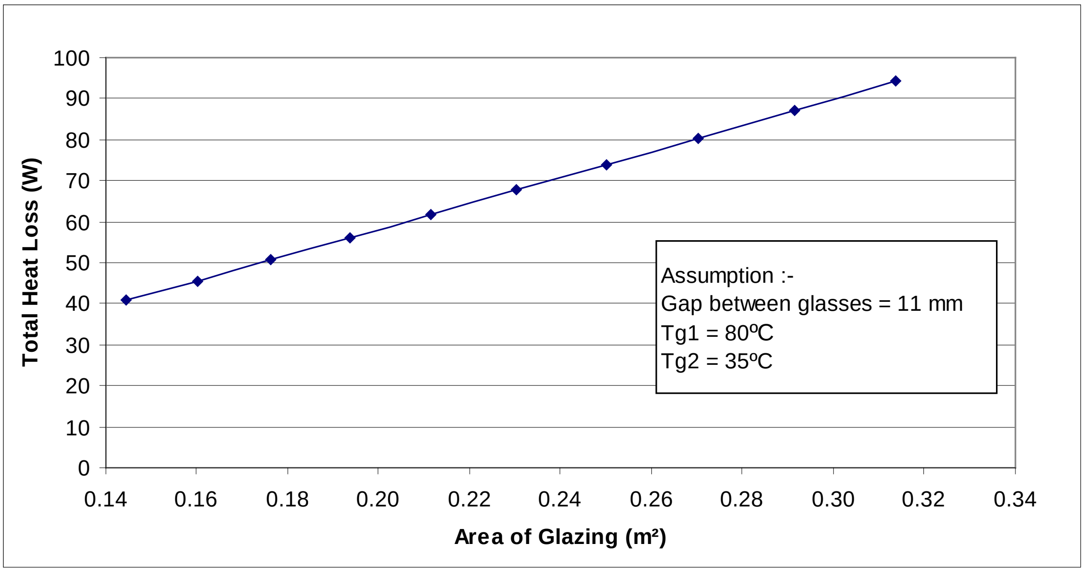


Figure 4.4 : Heat transfer against the area of glazing

In order to determine the size of glazing area, the calculation of different area of glazing was made. Figure 4.4 shows that the heat loss through the glass is increasing proportionally with the area of the glazing. The glazing is the first medium of heat transfer before the solar radiation penetrate into the cooking chamber. The size of the glazing is chosen by measure a piece of standard plywood (4 ft x 8ft) in the market to fit with the size of the solar cooker. So, no additional standard size of plywood required to make the solar cooker because the prototype cost will increase. The larger glazing area, more solar radiation is absorbed into the cooking chamber. The heat loss also increased proportionally with the glazing area because more surface is contact with surrounding air where natural and forced convection may occur. To design the solar cooker with accurate dimension, the design software is used to model the solar cooker. Modeling of the solar cooker (Figure 4.5) is made by using CATIA because it is very beneficial since the inclined wall is need more time to draw by AutoCAD.

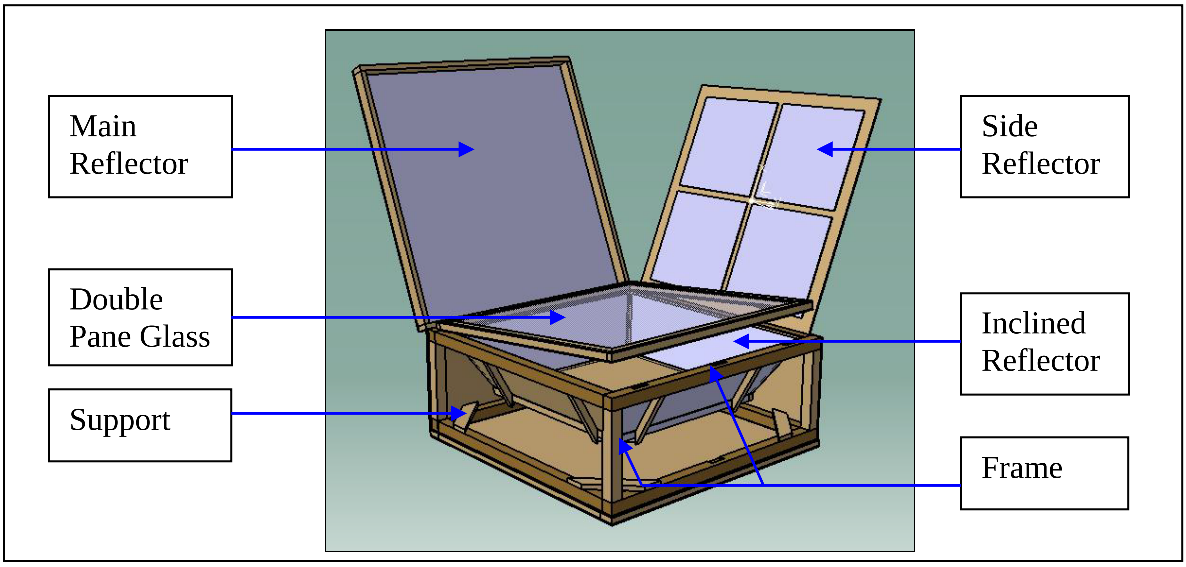


Figure 4.5 : A model of box-type solar cooker using CATIA

4.3 Result of the testing of the solar cooker

Thermal performance result as shown in the Figure 4.6 is the stagnation test where no load condition is put in the cooking chamber. Emad H. Amer (2003) suggest that the stagnation test is the experiment of the solar cooker where the cooker have to exposed to the steady weather under no load condition. The maximum temperature inside the empty cooking pot by using glass fiber in Figure 4.6 is 128 ºC and average solar radiation in Figure 4.7 is 493 W/m^2. The average ambient temperature for the stagnation test is 36 ºC.

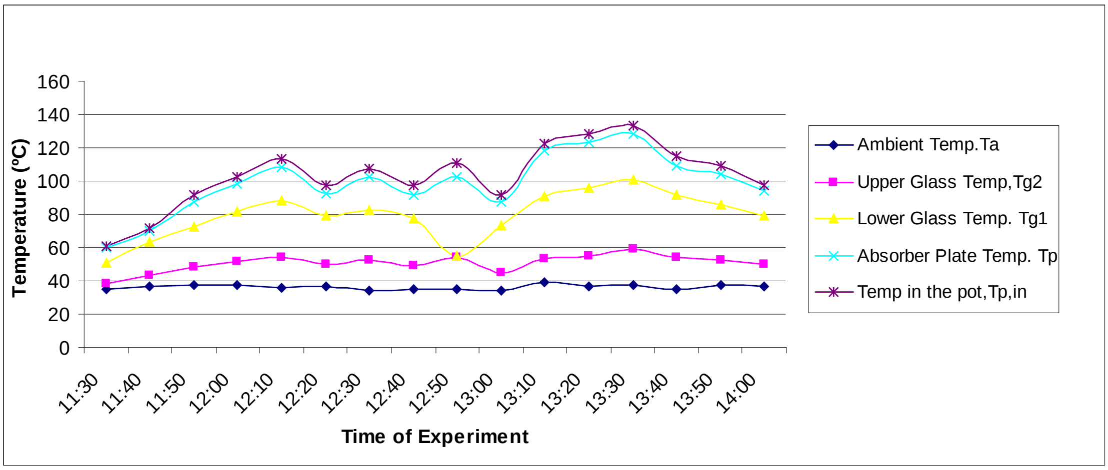


Figure 4.6 : Temperatures variation during stagnation test of the solar cooker by using glass fiber as insulation.

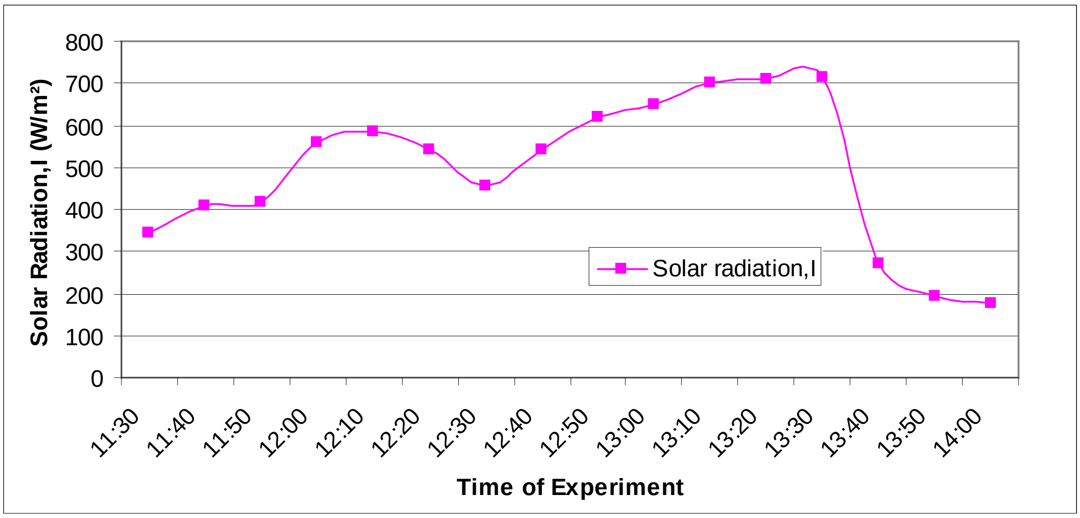


Figure 4.7 : Solar radiation intensity during stagnation test of the solar cooker by using glass fiber as insulation.

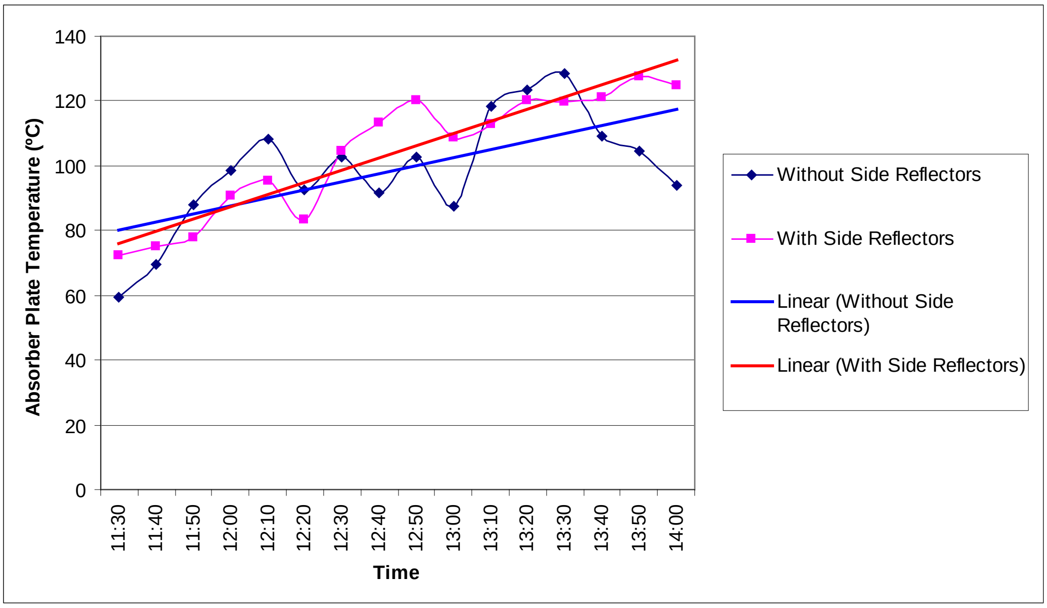


Figure 4.8 : Comparison between absorber plate temperature of the solar cooker with and without side reflector.

The presence of the side reflector shown in Figure 4.8 is resulting of the absorber plate temperature can be increased when the solar reflector is aligned properly. Thermal performance for the cooking test by using glass fiber is shown in Figure 4.8 and Figure 4.9. The maximum temperature achieved for the absorber plate by using rice straw and glass fiber is 151.8 ºC and 127.7 ºC respectively. Efficiency of the solar cooker is highest during noon time (Refer Figure 4.9 and Figure 4.10) due to more solar radiation received by absorber plate.

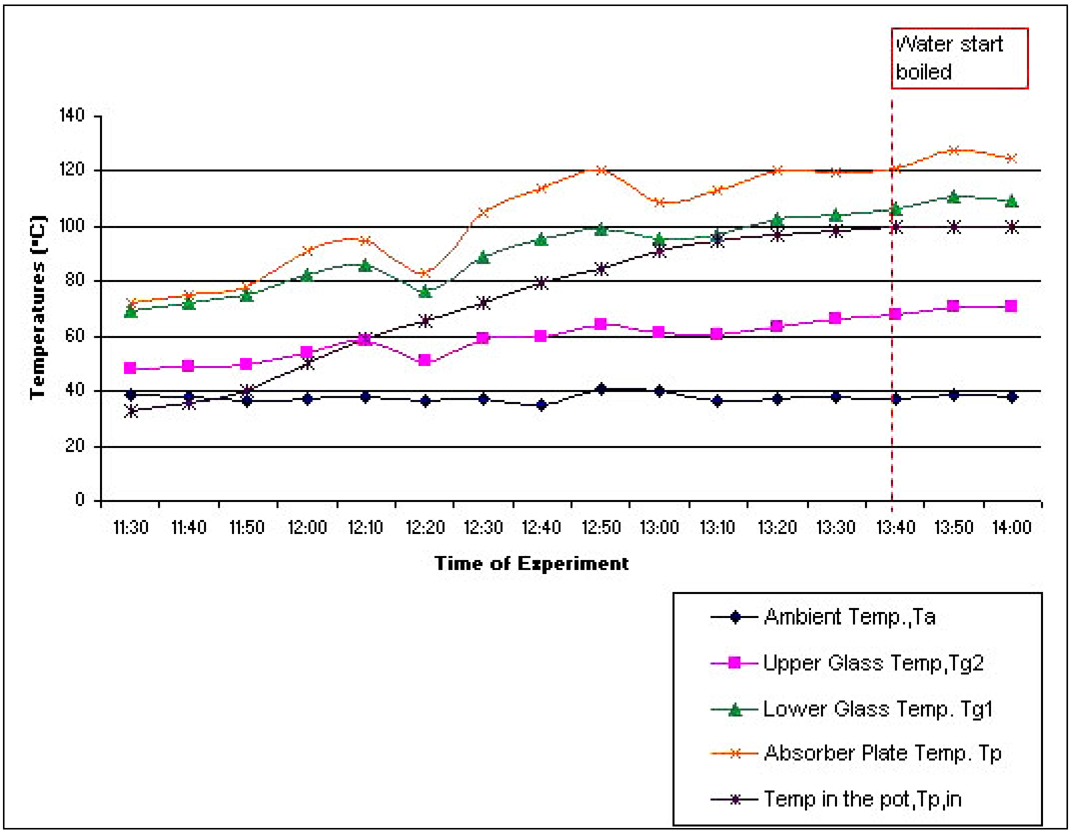


Figure 4.9 : Temperatures variation of the solar cooker by using glass fiber as insulation.

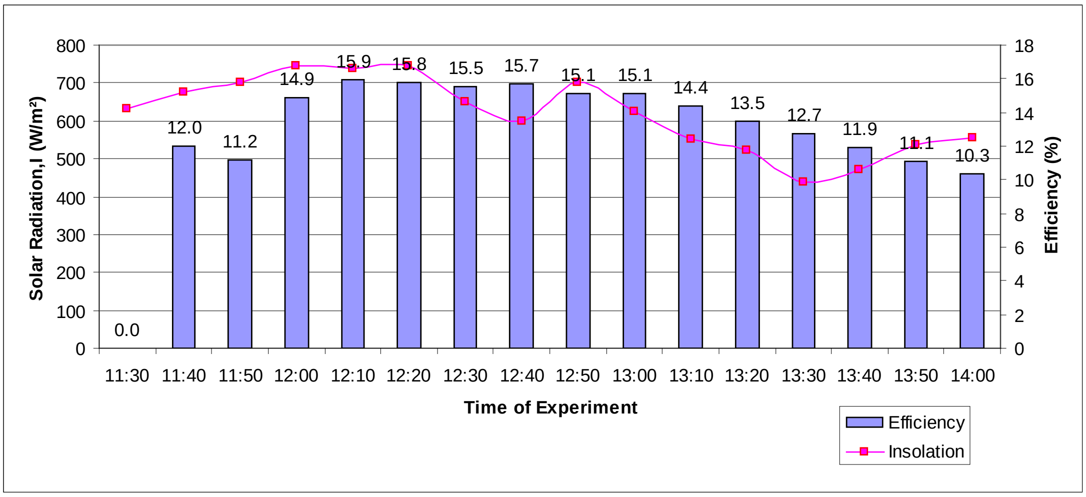


Figure 4.10 : Solar radiation condition and efficiency of the cooker using glass fiber as insulation.

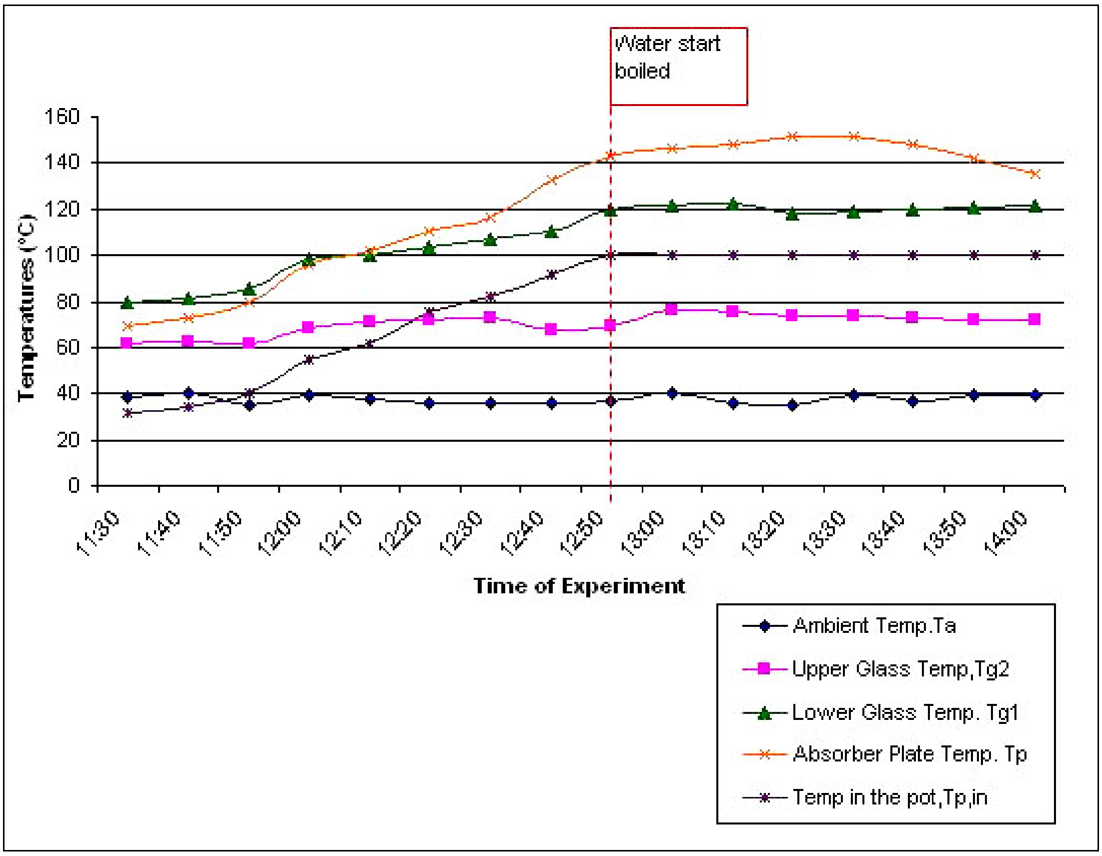


Figure 4.11 : Variation of temperature for the solar cooker using rice straw as insulation.

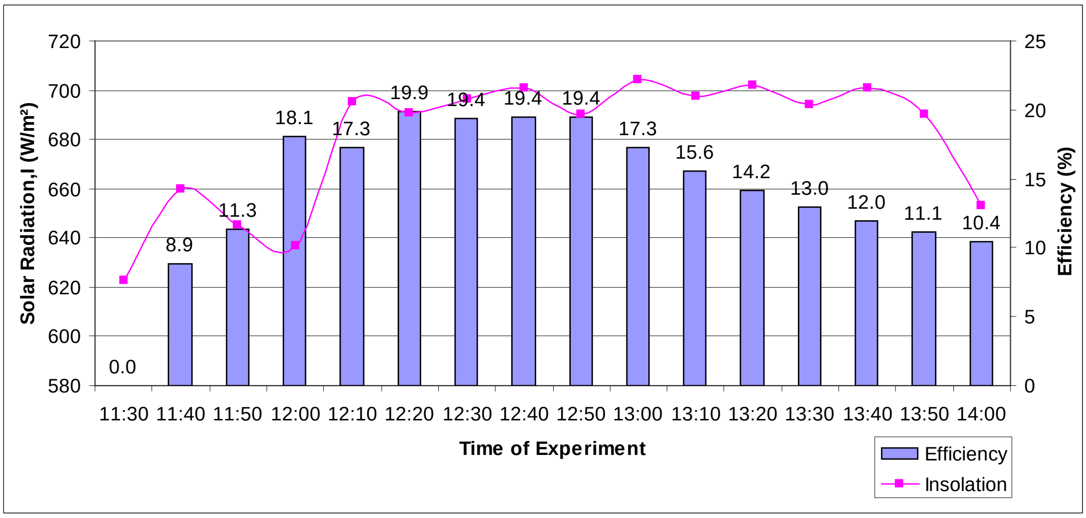


Figure 4.12: Solar radiation condition and efficiency of the rice using rice straw as insulation.

The water temperature was constant after reached 100 ºC because the boiling point for the water at sea level (101.325 kPa) is 99.97 ºC. The water is boiled in 80 minute using straw of rice (Figure 4.6) which is faster compare to 140 minute using glass fiber (Figure 4.5). The performance for both insulation is different due to weather condition. The weather during experiment for rice straw is very clear with less cloud compared to the testing for the glass fiber which is cloudy. For comparison between glass fiber and rice straw as insulation, the data from 12 pm to 1 pm is taken due to the average of the solar radiation is almost same (Refer Appendix 1 and 2). The efficiency of the solar cooker from 12 pm to 1 pm by using rice straw is increased 12.7 % compared to glass fiber as insulation.

4.4 Efficiency of solar cooker

The efficiency of the solar cooker is determined by divide the power output with incoming power from solar radiation. According to Klemen Scwarzer 2006, the incoming power is the solar radiation I in W/m^2 multiplied by the collector surface A in m^2. The power output is the power that required to heat amount of food or water for certain period of time. The highest temperature achieved for the water is 100 ºC and the average ambient temperature is 30 ºC. The time taken to boil the water until 100 ºC is 80 min by using straw of rice as insulation and 120 min by using glass fiber.

The heating-power of the solar cooker :-

$$Q = \frac{m_w . c_p . \Delta T}{\Delta t}$$

Where : m_w = mass of water = 1 kg

c_p = Specific heat capacity at constant pressure = 4200 J/(kg K)

ΔT = Temperature difference ($T_{w,j} - T_{w,i}$) = (100 - 30) = 70 ºC

Δt = The duration of the measurement (s)

Thus, the efficiency of the cooker to boil the water :-

$$\text{Efficiency}, \eta = \frac{Q}{I.A_g}$$

Table 4.1 : Efficiency of insulation for the solar cooker.

Thermal Performance	Type of Insulation	
	Glass Fiber	Rice Straw
Heating Power (W)	35	61.25
Efficiency (%)	20.8	32.35

The efficiency of the material as stated in Table 4.1 is based on temperature of the water inside the pot from 30 ºC to 100 ºC. The time taken to boil the water for the glass fiber and rice straw as insulation is 8400 s (140 min) and 4800 s (80 min) respectively.

Final Design Dimension (Refer to Appendix 4) :

Overall dimension of cooker	(606 x 606 x 282) mm
Main reflector	522 mm x 522 mm
Material for reflector	Glass mirror
Thickness of reflector	2 mm
Absorber plate	400 mm x 400 mm
Material for absorber plate	Aluminum
Material for outer casing of the cooker	Plywood
Material for glazing	Clear glass
Thickness of glass cover	3 mm
Spacing between the glass cover	11 mm (Wood)
Depth of cooking chamber	123 mm
Pot height	67 mm
Pot Diameter	150 mm
Type of insulation	Rice straw

CHAPTER 5
CONCLUSION AND RECOMMENDATION

5.1 Conclusions

The box-type of solar cooker is selected among the other types because the material to make it is cheap, locally available and no special machine is required to build the solar cooker. From the experiment determine the thickness of insulation by finding the value of thermal conductivity, the straw of rice is the best because it is cheap and most available at any place. The small pocket inside the straw of rice is give an advantage to make the insulation since the air trapped air inside the trunk provide no air circulation thus reduce the value of thermal conductivity. The low cost insulation with good performance by using straw of rice is another option for those who does not afford to buy the expensive insulation. The thickness of the rice straw and glass fiber for the solar cooker is 26.76 mm and 28.9 mm respectively to achieve 100 ºC on the absorber plate. Results of thermal performance test for the absorber plate average temperatures from 12 pm to 1 pm is 120.9 ºC and 102.3 ºC by using rice straw and glass fiber insulation in place respectively. The thermal conductivity of rice straw by experimentally is 7.97% less than glass fiber. The efficiency of the solar cooker by using rice straw is increased 12.7 % compared to glass fiber as insulation. The performance of the cooker with rice straw as insulation was improved compared to the glass fiber.

5.2 Recommendations

The recommendations of the design and development of solar cooker is to reduce the dimension and weight so that the product easy to relocate from one place to another place. Beside that, the material of the solar cooker need to study to bring the cheap material but high performance thus increase poor people to build or buy it for themselves. The performance of the design need to simulate by using thermal simulation software such as ANSYS or TRNSYS to optimize the solar cooker performance and reduce calculation error before it manufacture.

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Thermal Performance Study of Solar Cooker with Glass Fiber

Time	Duration (min)	Solar radiation,I	Ambient Temp.,Ta	Upper Glass Temp,Tg2	Lower Glass Temp. Tg1	Absorber Plate Temp. Tp	Temp in the pot,Tp,in	Heating Power	Efficiency
11:30	0	633.0	38.4	47.8	69.1	72.3	33.1	0.00	0.0
11:40	10	677.0	38.1	48.7	71.9	75	35.4	2,268.00	12.0
11:50	20	700.4	36.8	49.7	74.8	77.7	40.1	2,121.00	11.2
12:00	30	745.0	37.1	54.2	82.6	90.9	50.1	2,814.00	14.9
12:10	40	737.0	37.6	58.6	86.3	95.1	58.7	3,013.50	15.9
12:20	50	744.5	36.3	50.8	76.9	83.4	65.6	2,990.40	15.8
12:30	60	650.0	37.2	58.8	88.8	104.7	72	2,940.00	15.5
12:40	70	600.0	34.7	59.5	95.4	113.4	79.5	2,970.00	15.7
12:50	80	700.0	40.8	64.4	99.1	120.1	84.4	2,856.00	15.1
13:00	90	623.2	40.1	61.3	95.3	108.8	91.2	2,856.00	15.1
13:10	100	550.0	36.5	60.5	97.3	113	95	2,730.00	14.4
13:20	110	524.0	37.5	63.4	102.5	120.2	96.9	2,554.36	13.5
13:30	120	438.0	37.8	66.5	104.3	119.7	98.8	2,408.00	12.7
13:40	130	470.0	37.5	67.7	106.4	121.2	99.9	2,258.31	11.9
13:50	140	538.0	38.3	70.7	110.9	127.7	100	2,100.00	11.1
14:00	150	555.3	38	70.7	109.6	124.8	99.9	1,957.20	10.3
Average		617.8	38	60	92	104	75	2427	13
Min		438.0	34.7	47.8	69.1	72.3	33.1	1957.2	10.3
Max		745.0	40.8	70.7	110.9	127.7	100.0	3013.5	15.9
Average (12 pm - 1 pm)		**685.7**	**37.7**	**58.2**	**89.2**	**102.3**	**71.6**	**2920.0**	**15.4**

Thermal Performance Study of Solar Cooker with Rice Straw

Time	Duration (min)	Solar radiation, I	Ambient Temp.Ta	Upper Glass Temp,Tg2	Lower Glass Temp. Tg1	Absorber Plate Temp. Tp	Temp in the pot,Tp,in	Heating Power	Efficiency
11:30	0	623.0	38.6	61.2	79.9	69.6	32	0.00	0.0
11:40	10	660.0	40.1	62.5	81.6	72.6	34	1,680.00	8.9
11:50	20	645.0	35.1	61.4	85.5	79.4	40.2	2,142.00	11.3
12:00	30	637.0	39.1	68.8	98.4	96.1	54.5	3,430.00	18.1
12:10	40	695.0	37.8	70.9	100.5	101.7	61.2	3,276.00	17.3
12:20	50	691.0	36.1	71.8	103.4	110.3	74.9	3,771.60	19.9
12:30	60	696.3	35.9	72.3	106.6	116.5	82.5	3,675.00	19.4
12:40	70	701.1	36	67.9	110.6	132.5	91.3	3,678.00	19.4
12:50	80	690.0	36.4	69.2	119.5	142.9	100.1	3,680.25	19.4
13:00	90	704.4	39.9	75.8	121.9	146.4	100.1	3,271.33	17.3
13:10	100	697.7	36.3	75.5	122.1	147.8	100.2	2,948.40	15.6
13:20	110	701.9	34.9	73.7	118.5	151.1	100.2	2,680.36	14.2
13:30	120	694.3	39.1	73.8	118.6	151.8	100.2	2,457.00	13.0
13:40	130	700.8	37	72.4	119.6	147.9	100.2	2,268.00	12.0
13:50	140	690.0	39.6	71.6	120.5	141.7	100.3	2,109.00	11.1
14:00	150	653.2	39.2	71.7	121.6	135.1	100.3	1,968.40	10.4
Average		680.0	38	70	108	121	80	2690	14
Min		623.0	34.9	61.2	79.9	69.6	32.0	1680.0	8.9
Max		704.4	40.1	75.8	122.1	151.8	100.3	3771.6	19.9
Average (12 pm - 1 pm)		**687.8**	**37.3**	**71.0**	**108.7**	**120.9**	**80.7**	**3540.3**	**18.7**

Appendix 3

Appendix 4

Appendix 4 (Continue)

Appendix 4 (Continue)