A Comprehensive Study of Convective and Radiation Heat Transfer in the Flat Plate Absorber Region of a Solar Dryer

By

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Dissertation submitted in partial fulfilment

of the requirement for the

Bachelor of Engineering (Hons)

(Mechanical)

May 2014

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CERTIFICATION OF APPROVAL

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(MECHANICAL ENGINEERING)

Approved by,

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(Dr. Khairul Habib)

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
MAY 2014

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 acknowledgments, and that the original work contained herein have not been undertaken nor done unspecified sources or persons.

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Mohd Hazman Bin Mahli

Abstract

In this project, a study on the flat plate solar collector for solar dryer was done to determine the factors that affect its performance and type of material that can be used to achieve the optimal performance of the solar collector. The model was developed using MATLAB software and simulation was done to identify the parameters that are involved in the performance of the solar collector. In determining the performance of the solar collector, heat energy balance equation was used to calculate the heat loss coefficient and the outlet temperature of the transfer fluid. The tropical weather data of Malaysia was used during the simulation of this study. Despite that system performance achieved, there is need to establish the study through experimentation techniques.

Acknowledgment

I would like to express my deepest appreciation to all those who provided me the possibility to complete this report. A special gratitude to my final year project supervisor, **Dr. Khairul Habib**, suggestions and encouragement, had helped me to achieve the targets of my project especially during the period of writing this report.

Furthermore I would also like to acknowledge with much appreciation to my mentor **Mr. M.W. Kareem**, who provide necessary guidance to me in completing this project. Special thanks go to my family and friends, who always keep on giving me strength and encouragement for me to keep on going in completing this project.

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Nomenclature

Notations

S_2 : solar radiation absorbed by absorber plate (W/m^2)

U_t: top heat loss coefficient (W/m^2K)

U_b: bottom heat loss coefficient (W/m^2K)

U_f: air velocity in the collector (m/s)

T_f: mean fluid temperature (K)

$h_{1,2}$: convection heat transfer coefficients (W/m^2K)

h_r: radiative heat transfer coefficient (W/m^2K)

h_w: convection heat transfer coefficient of wind ($W/m^2.K$)

h_{rs}: radiative heat transfer coefficient of glass cover to sky ($W/m^2.K$)

$\alpha_{1,2}$: absorptivity of glass cover and absorber plate

$\varepsilon_{1,2}$: emissivity of glass cover and absorber plate

τ: transmittance of glass cover

k_i: thermal conductivity of the insulation (W/m.K)

k: thermal conductivity of the air (W/m.K)

x: thickness of insulation (m)

$T_{1,2}$: mean temperatures of surfaces (K)

Q_u: useful heat gain (W)

CHAPTER 1

INTRODUCTION

1.1 Background

Solar energy is one of the most popular renewable energy sources for the past few decades. It is proven that solar energy produced can sustain the global energy demand including the heavy industries. Solar energy has been considered as one of the most prospective source of energy. Hence, it is referred to as energy of the present and the future. The development of the technology in producing renewable energy using solar radiation is continuously done by many scientists around the world in order to reduce the reliance on fossil fuels as dominant source of energy.

Solar energy is mostly used to generate heat and electricity which serves as source of power to domestic appliances and for running of heavy industrial machines and equipment. Over the years, scientist had done a lot of experiments and researches in order to develop a solar system that will work at a very high efficiency so that solar energy can be economically utilized.

Solar energy is energy that is produced by the solar radiation obtained from the sun. The solar radiation from the sun is absorbed by the solar collector in the form of heat energy. Then, the heat energy is going to be utilised directly or going to be converted to heat or other forms of energy depending on the application. The applications of the solar energy can be divided into three;

1. Solar thermal energy: the solar radiation from the sun is converted into heat energy that could be used to heat water or for drying purposes [1].
2. Solar photovoltaic energy: Photovoltaic cells could be used to convert the solar radiation from the sun to electricity [1].
3. Solar photovoltaic-thermal energy: Combination of both solar thermal energy and solar photovoltaic energy whereby heat energy as well as electricity will be produced simultaneously [2].

A successful renewable energy is energy that is not just economically feasible but the most importantly is that it must be able to sustain a continuous human demand and eco-friendly [3]. Average daily solar energy radiation is very large in magnitude and sufficient to satisfy human energy needs [4].

Heat absorption process in the solar collector region involves two specific processes; convection and radiation. Convection heat transfer is the transfer of heat from one point to another point by the means of movement of the fluids such as air and water. Bobes-Jesus et al. [5] defined convection as process of thermal transfer between a solid surface and a fluid in motion.

However, radiation heat transfer is the transfer of heat in a vacuum space. It is defined as the process of transfer heat from an object with higher temperature to another object at lower temperature through electromagnetic waves [6].

1.2 Problem Statement

Nowadays, the price of the solar collector is still considered high due to its high cost of manufacturing process until production stage, this is due to the cost of material used to build the solar collector is expensive. Moreover, a lot of the previous experimentation processes were done under steady-state condition whereby a lot of external factor is excluded. Solutions are needed in order to overcome this problem.

1.3 Objective

To overcome the problem, a general objective is specified that is to investigate the thermal transfer around a solar collector for drying application. This objective can be further divided into three sub-objectives:

1. To develop solar collector model using partial differential equation (PDE) technique.
2. To identify the factors affecting the performance efficiency of the solar collector.

3. To determine the economical and efficient material for a solar collector in drying application.

1.4 Scope of study

This study will focus on the heat transfer involved around the solar collector. The reduction of heat loss that happens around the solar collector due to the heat convection and radiation would be the main focus of the study. A flat plate solar collector made of aluminium would be considered in this study. Among the parameters to be focused in this study are the temperature, size of the solar collector, wind velocity, ambient temperature, temperature of the absorber plate and solar radiation.

CHAPTER 2

LITERATURE REVIEW

2.1 Solar Collector

Solar energy is one of the most common alternative energy that is available today. A lot of technologies have been developed in order to convert solar radiation to energy. Nowadays, solar collector is the most common technology in converting solar radiation to useful energy such as heat energy. A solar collector captured the solar irradiance which would be converted to heat energy [7]. This would in turn transfer to the flowing working fluid.

In a solar system, solar collector is the main component and it is divided into two types, a non-concentrating solar collector and concentrating solar collector [8]. Example of non-concentrating solar collector is flat plate solar collector (FPSC). M.Hamed et al [8] states that a solar collector consists of five main parts;

1. Transparent cover: glass or other material that act as cover to transmit the solar radiation to the absorber plate.
2. Tubes: Medium for working fluid.
3. Absorber plate: plate that act as the medium in changing the solar radiation to heat.
4. Insulation: material that can reduce the amount of heat loss at the back side of the collector.
5. Casings: Enclosure for the whole solar collector as to keep all the components in its place.

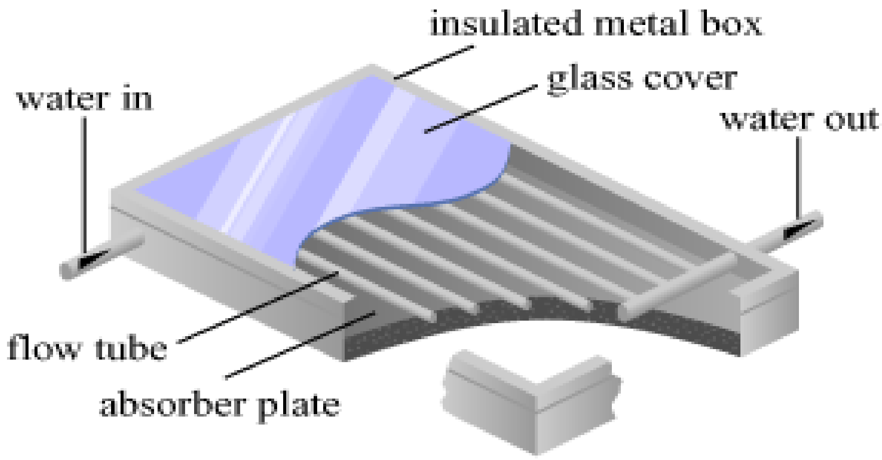

Figure 2.1: Flat plate solar collector [21].

The focus of this study would be centred on the flat plate solar collector (FPSC). Flat plate solar collector (FPSC) can be divided into 2 categories; glazed flat plate solar collector and unglazed flat plate solar collector [9]. Glazed flat plat solar collector is collector with a transparent cover which will be the focus of this study.

In the design of a solar collector; there are few criteria that must be considered such as the cost, lifetime, durability, maintenance and ease of installation [8]. The flat plate solar collector differs depends on its application, most of the flat plate solar collector used for water heating. One of the famous of the flat plate solar thermal collector is drying systems. In this study, concentration would be on the flat plate solar air collector for solar dryer. Solar air collector can be divided into two types; single pass solar collector and double pass collector. A single pass solar air collector is a collector whereby the air that goes directly into the solar collector without the air being preheated.

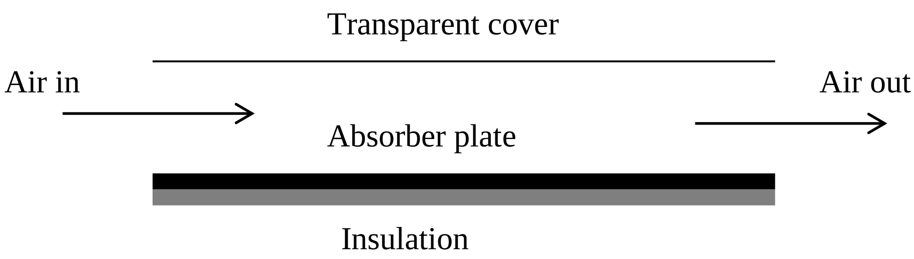

Figure 2.2: Single pass solar air collector [2].

A double pass solar air collector is a collector whereby the air is naturally or forced to flow into the collector by passing the front glass cover (preheated) before being heated again during the flow passing the absorber plate [9].

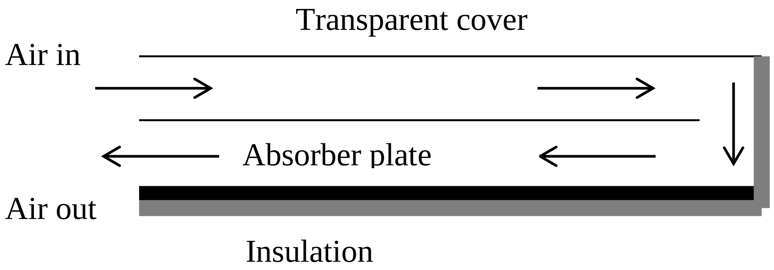

Figure 2.3: Double pass solar collector [2].

In terms of thermal efficiency, a double pass solar air collector has a higher efficiency compare to the single pass solar air collector [10]. Although a double pass solar air collector has a higher efficiency, the double pass design causes the path taken by the air to increase hence causing a higher pressure drop across the solar air collector, hence a fan or pump need to be used in order to keep the flow rate at optimum level [11]. To further increase the thermal efficiency of the solar air collector, K. Sopian et al [9] stated that a porous media can be added into the double pass solar air collector design it will increase the efficiency of the solar air collector to maximum 70%. To develop a solar air collector with a high thermal efficiency, every method can be used such as the additional of porous media.

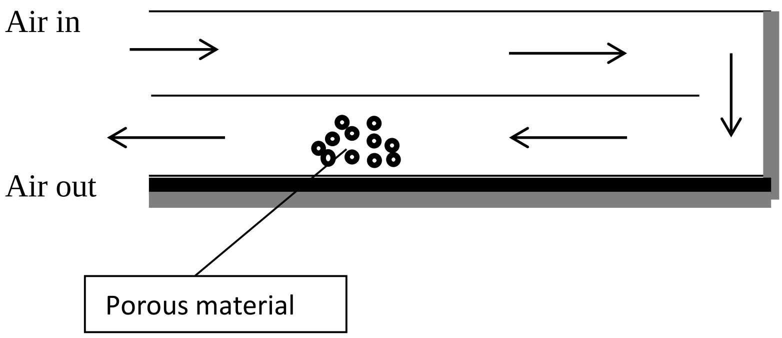

Figure 2.4: Double pass solar air collector with porous media [9].

To further increase the overall performance of the solar air collector, heat exchanger can be added into the design of the collector. Three type of heat exchanger design had already been experimented to test whether the thermal efficiency of the solar air collector can be increased or not.

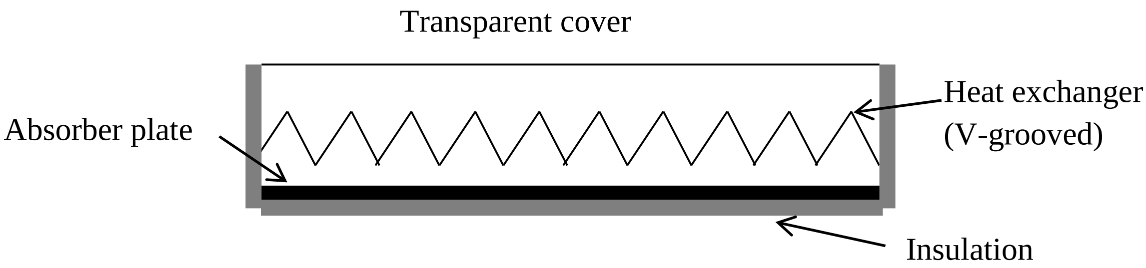

Figure 2.5: Solar collector with V-grooved heat exchanger [12].

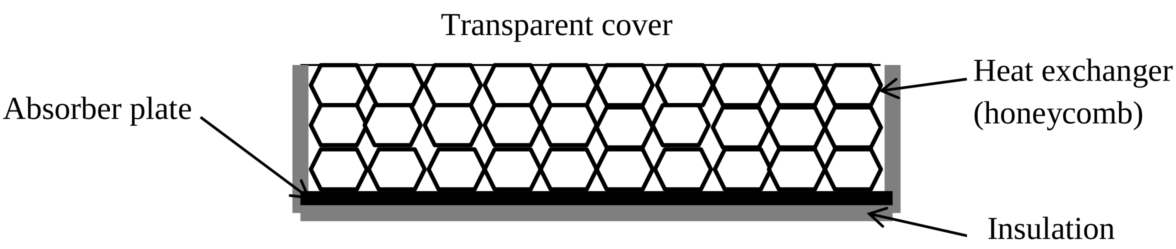

Figure 2.6: Solar collector with honeycomb heat exchanger [12].

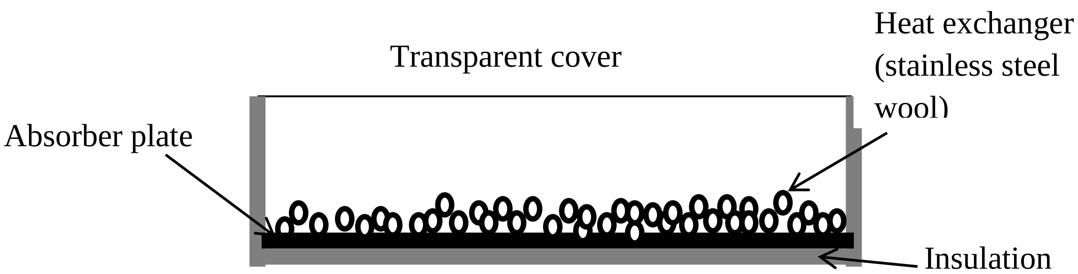

Figure 2.7: Solar collector with stainless steel wool heat exchanger [12].

Theoretically, the larger the surface area of the heat exchanger the higher the rate of heat transfer to the working fluid [13]. Othman et al. [12], stated that the honeycomb and stainless steel wool heat exchanger design have a higher thermal efficiency compare to the V-grooved heat exchanger design; honeycomb heat exchanger (87%), stainless steel wool heat exchanger (86%) and V-grooved heat exchanger (71%). V-grooved solar air collector is the most suitable collector for the purpose of drying agricultural product [14].

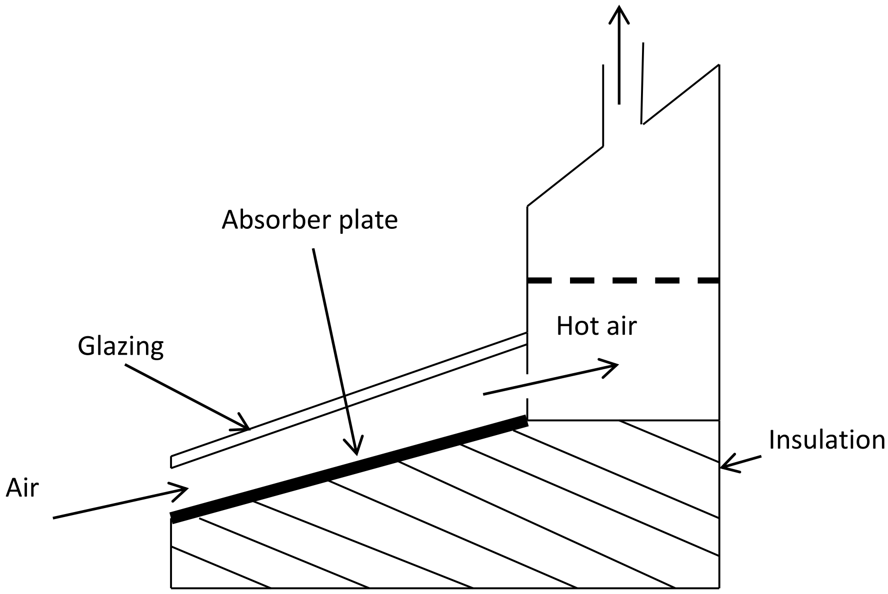

Figure 2.8: Solar dryer [15].

2.2 Factors affecting solar collector's efficiency

To design a high efficient solar collector, the heat loss during the heat transfer process must be reduced as much as possible. The heat loss happens due to the convection and radiation that happens during the heat transfer process [16].

In reducing the heat loss, several factors had to be considered such as absorber plate design, selective coatings, thermal insulation, tilt angle of collector, working fluids, the ambient temperature, the size of the collector, wind velocity, specific geometric design, etc. [17]. Aboltins et al. [18] stated that the performance of solar collector is based on meteorological parameters such as direct and diffuse radiation, ambient temperature, wind speed, design parameters; type of collector, collector material and flow parameters; air flow rate and mode of flow.

To capture the maximum amount of solar radiation, the solar collector must move in accordance to the movement earth around the sun. Furthermore, solar radiation varies according to its location and on the season [18]. Every part of the earth receive different amount of solar radiation. Based on Sudhakar et al. [19] the concentration of solar radiation varies according to many factors such as location latitude, declination angle, tilt angle, the sunrise angle and azimuth angle. This study will be based on solar radiation in tropical region of Malaysia.

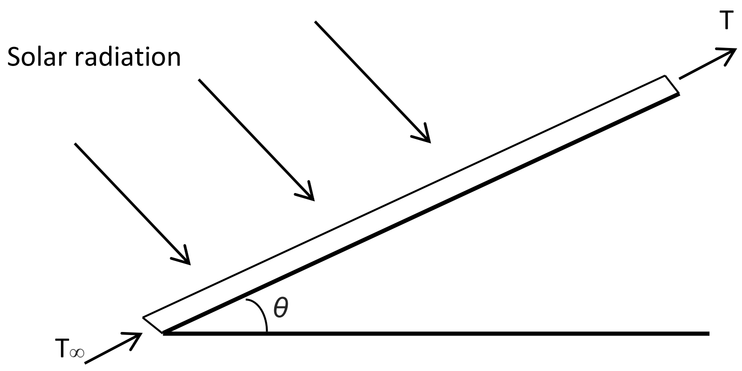

Figure 2.9: Tilt angle of a solar collector [18].

Based on Figure 2.9, the angle, θ is the factor that might increase or decrease the amount of solar radiation captured. Idowu et al. [20] stated that for every latitude and time of the year are vital parameters in determining the optimum tilt angle of the solar collector to capture the maximum solar radiation.

The optimum tilt angle is stated to be $\theta \pm 15^{o}$ [21]. Pavlovic et al. [22] stated that for tropical region (South East Asia) the optimum tilt angle is $\theta \pm 8^{o}$ for monsoon season and $\theta \pm 5^{o}$ for dry season.

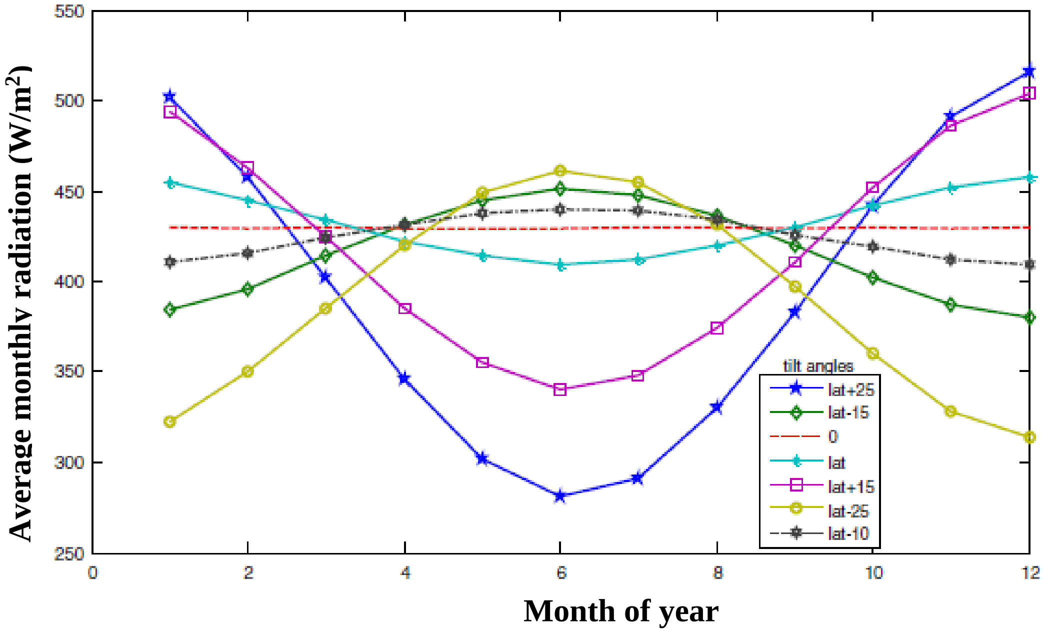

Figure 3.0: Average monthly solar intensity on tilted solar collector at tropical region [20].

In Malaysia, the global solar radiation differs due to the changing of season. Average annual global solar radiation in Malaysia is around 4.21–5.56 kWh/m^2 with 2200 of sunshine hours [23]. In Perak, the average global solar radiation measured is 4.54 KWh/m^2 [24].

The main element of a solar collector is absorber plate. It acts as a receiver for a large portion of heat energy from solar radiation that later will be transferred to the working fluid [25]. Three main functions of absorber plate are to absorb the solar radiation from the sun, transfer the heat energy absorb to the working fluids and lose a very minimal amount of heat to the surrounding [26].

To be able to transfer the heat energy to the working fluid, the absorber plate must have a very good thermal conductivity since the thermal efficiency of the collector increases as the thermal conductivity of the plate increase [27]. Hence, in choosing a material for absorber plate a very high thermal conductivity is needed in order to ensure a high thermal performance of the collector.

Diamond have the highest thermal conductivity, but its price is too expensive. Economical factor must be taken into consideration in choosing the material for the absorber plate. In this study, aluminium will be used as the material for the absorber plate. Recently, a Finnish company had managed to produced an absorber plate using aluminium that has a high efficiency. A high rate of heat transfer between the aluminium and the solar fluid occurred due to the direct flow of collector efficiency factor has a value of almost 0.97 [28]

In regards of the material for the solar collector, the most common material used for the absorber is usually aluminium, due to its high thermal conductivity. There are a lot of metallic materials and alloys that are suitable for absorber plate.

In choosing the material for the absorber plate, Amrutkar et al. [29] stated that there are factors that one needs to consider such as thermal conductivity, its durability and ease of handling, its availability and cost, and the energy required to produce it.

The solar absorptivity and emissivity of the surface of the plate must also be taken into consideration. The ideal surface to collect solar radiation must have high absorptivity and low emissivity [30]. To increase the absorptivity of the absorber plate, the plate is usually covered with selective coatings. The black paint is usually chosen as the coating for the absorber plate with its absorptivity at the range of 0.92-0.98 [29].

Table 2.1: Absorbtance value of several commonly used colour [12].

Material Colour	Absorbtance (α)
White paint	0.07
White marble	0.46
Red Brick	0.55
Black Tar	0.93
Granite	0.55
Black Paint	0.97

Besides absorber plate, the cover plate or the glazing of the collector can affect the performance of the solar collector [31]. Three properties of the solar collector that can affect its performance are; glazing transmittance, absorptance and reflectance [32].

It has 3 main working principle; to reduce upward convective and radiant heat loss from the absorber, to maximize the transmission of solar radiation to the absorber plate and to protect the absorber plate from weathering [33]. A lot of different type of glazing settings had been studied in order to find the most efficient setting for the glazing of the solar air collector. The glazing settings is done depending on its applications. T. Koyuncu [34], stated that a single glazed solar air collector is more efficient in terms of its thermal performance compare to the double or triple glazed solar air collector.

Other factors such as strenght of material and durability against the exposure of ultraviolet is important in choosing the material for glazing of the solar collector as it will determine the life span of the solar collector. Another important factor that cannot be neglected in choosing a material for the glazing is the climate of the place where the solar collector will be installed, because the climate will decide the solar irradiance intensity and average temperature that the glazing will be going through [35].

To further increase the performance of the solar collector, insulation is added as to reduce the heat loss at the rear and side of the solar collector. Thickness and thermal conductivity are few of properties that can determine the insulator efficiency [36]. Density malleability, availability and price must also be taken under consideration in choosing a material for insulator. Table 2.4 shows the common materials that are used for solar collector insulation. In order to optimize the energy generated in this study, mineral wool is considered.

Table 2.2: Material density, maximum service temperature and thermal conductivity [19]

Type of Materials	Density, ρ (kg/m^3)	Maximum Service Temperature, T_{max} (^oC)	Thermal Conductivity at 10^oC, k. (W/m.K)
Mineral Wool	160	250	0.040
Foam Glass	100-150	430	0.045
Expanded Polystyrene (EPS)	40	85	0.030
Polyurethane (PUR)	80	110	0.035
Perlite	100-300	100	0.045

Mineral wool is a common material used for insulation of commercial solar collector. It is widely used because of its cheap cost and its high thermal resistance.

CHAPTER 3

METHODOLOGY

3.1 Project Overall Methodology

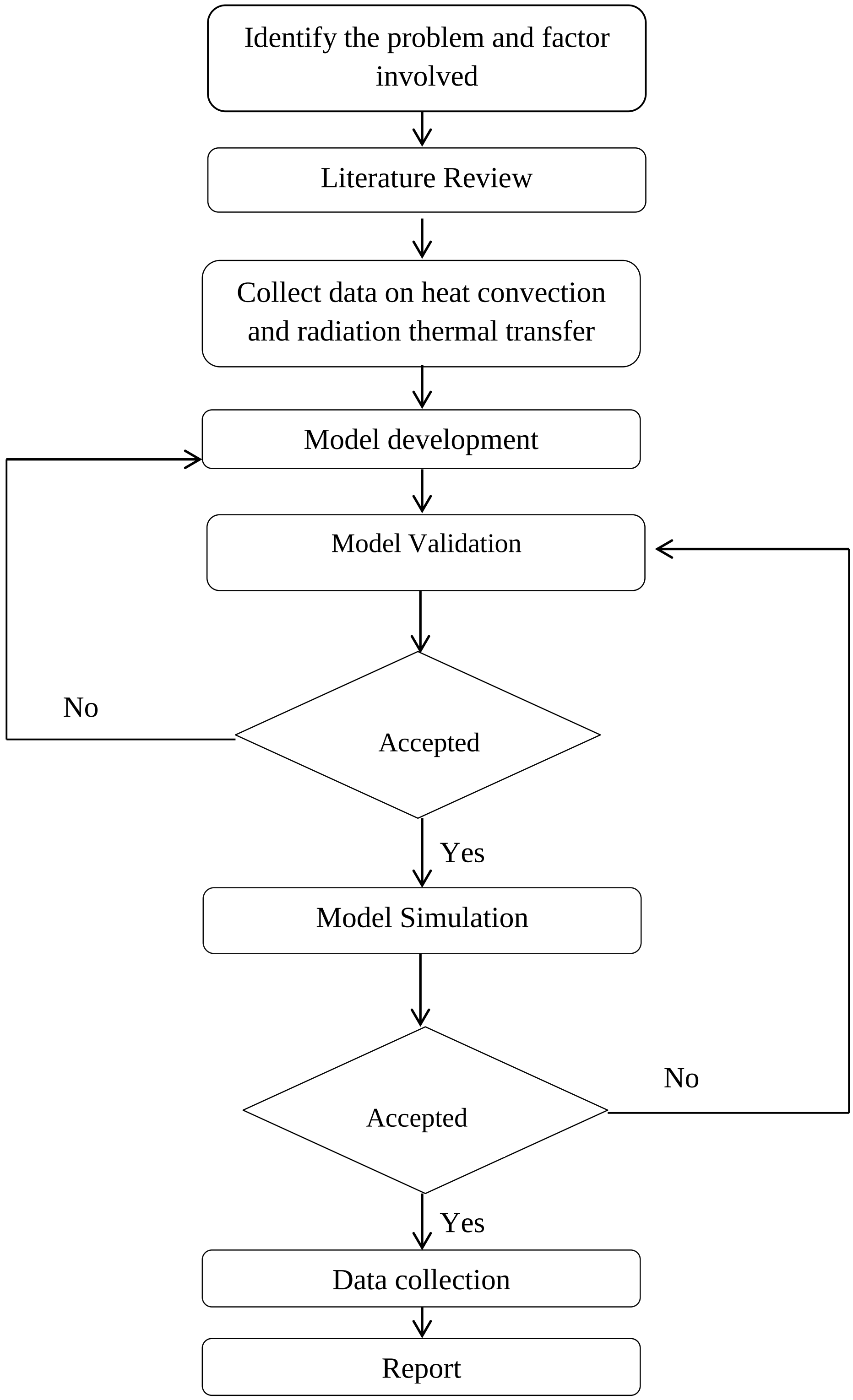

Figure 3.1: Overall project methodology

3.2 Model Computation Flowchart

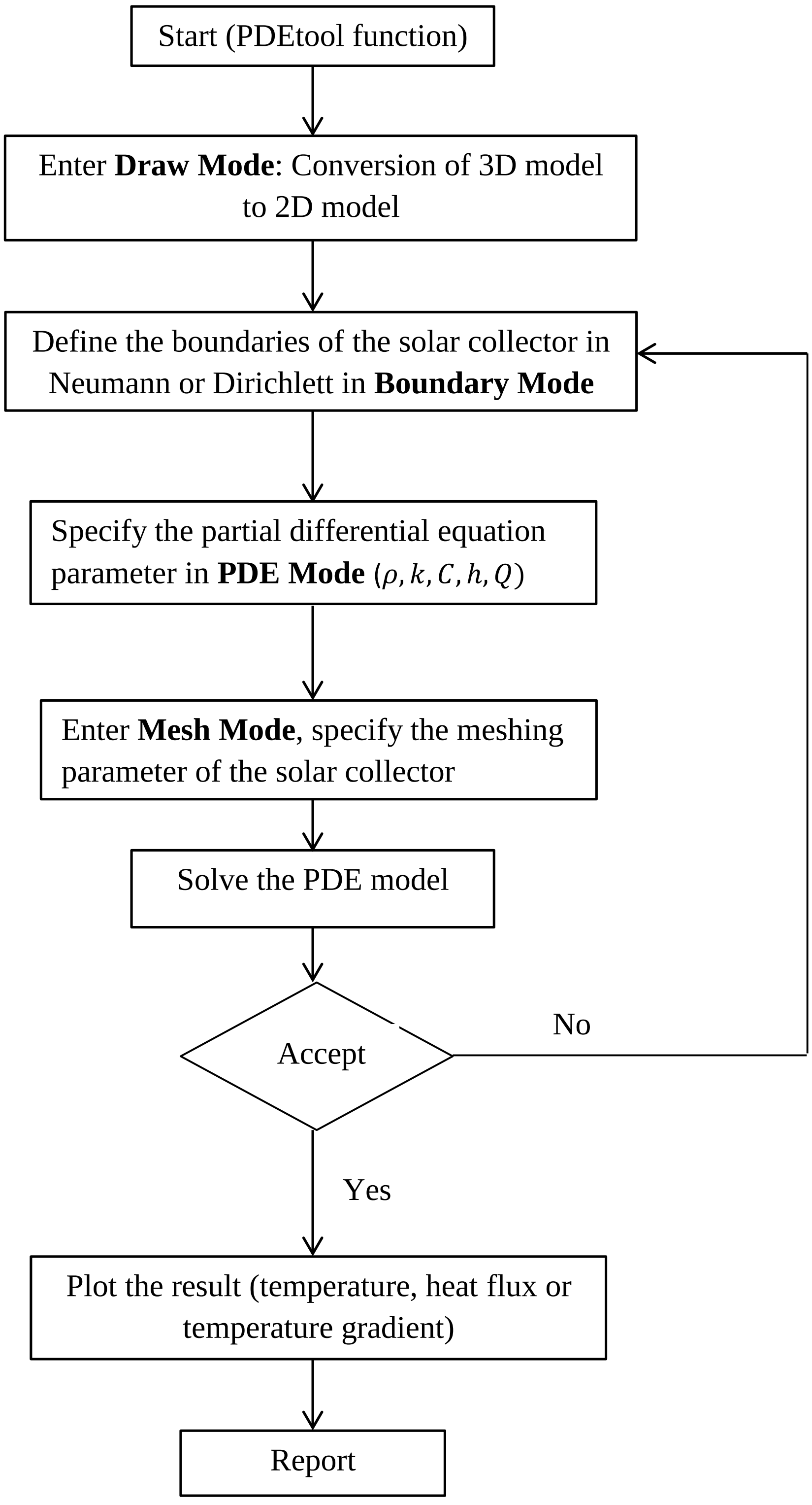

Figure 3.2: Model computation flowchart

3.3 Gantt chart for FYP 1

Task /Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Selection of project topics	■	■												
Conduct preliminary research work			■	■	■									
Prepare extended proposal					■	■								
Submission of extended proposal						■	●							
Preparation for proposal defence							■	■						
Proposal defence presentation									■					
Extensive literature review research				■	■	■	■	■	■	■	■	■	■	
Prepare draft for interim report/Development of model computational flowchart									■	■	■	■	■	■
Submission of interim report														●

■ Process ● Key Milestone

3.4 Gantt chart for FYP 2

Task /Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Development of solar collector model using MATLAB	■	■	■	■	■	■	■							
Experiment to determine the parameters of the solar collector	■	■	■	■	■	■	■							
Preparation of progress report		■	■	■	■	■								
Submission of progress report							●							
Model validation, completion and simulation	■	■	■	■	■	■	■	■	■	■				
Result and Data analysis and documentation							■	■	■	■	■	■		
Prepare draft final report							■	■	■	■	■	■	■	
Submission of dissertation												■		
Viva and submission of final report													■	●

■ Process ● Key Milestone

3.5 Mathematical Modeling

Like many literatures that have used MATLAB in the past, MATLAB is proposed as a tool to be use in studying these problems. A MATLAB model can help in the process of optimization of the solar collector system [39]. The performance efficiency of the collector can be determined. For the mathematical modelling, the energy balance equation will takes place as the governing equation for this study.

The efficiency of the solar collector can be defined as the ratio of useful solar energy, Q_u and the irradiance [40].

For any solar collector that use air as its working fluid, M.A. Karim et al [12] stated that, the focus of the collector will be to increase efficiency on the amount of heat it can absorb into the absorber plate and transfer it to the air in the system. For that purpose, one has to know the amount of effective solar radiation that is absorbed by the absorber plate. The following equations will be used in this study. The energy balance for the top plate [12]:

$$S_2 = h_1 (T_2 - T_f) + h_r (T_2 - T_1) \tag{3.1}$$

Incident solar radiation absorbed by the absorbing plate can be calculated using [12]:

$$S_2 = \tau \alpha_2 I \tag{3.2}$$

Energy balance equations for the glass cover, working fluid, absorber plate and the back plate are developed in order to calculate the performance of the solar collector. Equations used are shown as below:

Energy balance equation for top plate [12]:

$$S_1 + h_r (T_2 - T_1) + h_1 (T_f - T_1) = U_t (T_1 - T_a) \tag{3.3}$$

Energy balance equation for bottom plate [12]:

$$h_1 (T_f - T_2) + h_r (T_2 - T_1) = U_b (T_2 - T_a) \tag{3.4}$$

For working fluids pass [12]:

$$h_1 (T_2 - T_f) = h_1 (T_f - T_1) + Q \tag{3.5}$$

Incident solar radiation absorbed by the glass cover is calculated using [16]:

$$S_1 = \alpha_1 I \quad (3.6)$$

Heat loss coefficient at top plate [12]:

$$Ut = h_{rs} + h_w \quad (3.7)$$

Coefficient of radiation heat transfer between glass cover and absorber plate [40]:

$$h_r = \frac{4\sigma \, {T_f}^3}{\frac{x}{\varepsilon_2} + \frac{1}{\varepsilon_1} - 1} \quad (3.8)$$

Coefficient of radiation heat transfer between glass cover and sky [12]:

$$h_{rs} = \sigma\varepsilon_1 (T_2 + T_1)[(T_2)^2 + (T_1)^2] \frac{(T_1 - T_s)}{(T_1 - T_a)} \quad (3.9)$$

Coefficient of convection heat transfer due to wind [12]:

$$h_w = 5.7 + 3.8\,V \quad (3.10)$$

Heat loss coefficient at bottom plate [12]:

$$U_b = \frac{1}{\frac{x}{k_i} + \frac{1}{h_w}} \quad (3.11)$$

Coefficient of conductive heat transfer [12]:

$$h_1 = \left(Nu \, \frac{k}{D_h}\right)\left(\frac{1}{\sin\left(\frac{\theta}{2}\right)}\right) \quad (3.12)$$

whereby $h_1 = h_2$.

To obtain the Nusselt number, Reynolds number must be calculated first using following formula [12]:

$$Re = \rho \ U_f \frac{D_h}{\mu} \tag{3.13}$$

After obtaining the Reynolds number, the value will be used in the following equation to obtain the Nusselt number [40]:

$$Nu = 0.0158 \times \ Re^{0.8} \tag{3.14}$$

Output temperature of the fluid [12]:

$$T_o = T_i + \frac{Q}{mC_P} \tag{3.15}$$

Efficiency of the collector [12]:

$$\eta = \frac{mC_P(T_o - T_i)}{IA} \tag{3.16}$$

In calculating the radiation heat transfer energy for the solar collector, using formula:

$$q = \varepsilon \sigma T^4 A \tag{3.17}$$

For the convective heat transfer energy, it is calculated using formula:

$$q = hA\Delta T \tag{3.18}$$

As stated before, the main parameters that are involved in determining its efficiency are temperature, collector area and solar irradiance. The heat transfer coefficient also depends on temperature at the around the absorber plate [41].

CHAPTER 4

RESULTS and DISCUSSION

There are few assumptions made in order to simplify the modeling process of the solar collector:

1. Inlet temperature = 30^0C
2. Heat flux of air (natural) = 0.5 kW/m^2
3. Mass flow rate, m = 0.07 kg/s
4. Air velocity = 1.7 ms^{-1}
5. Heat transfer coefficient, h (air) = 25 W/ m^2 K

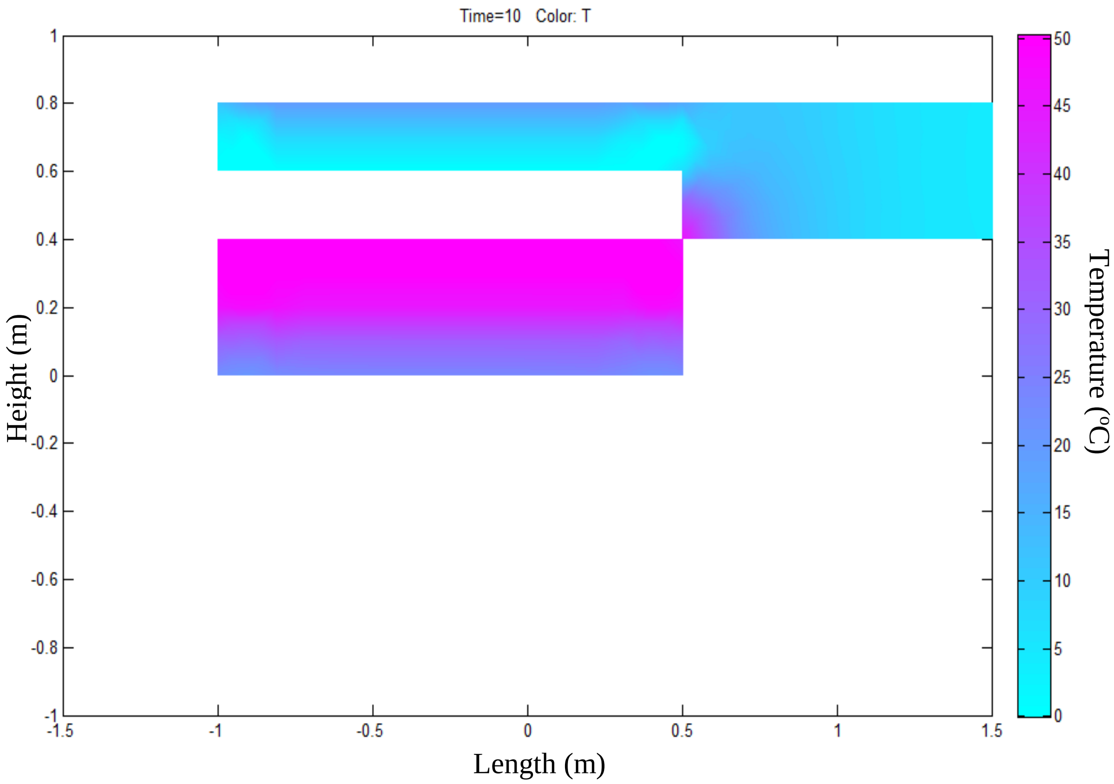

Figure 4.1: Heat map of the solar collector

The values of the parameter included in the modeling process are taken from the literature review:

1. Emissivity of aluminium, ε_a = 0.09
2. Emissivity of glass, ε_g = 0.92
3. Global Solar Radiation = 4.54 kWh/m^2 = 908 W/m^2 (assuming 5 hours exposure)

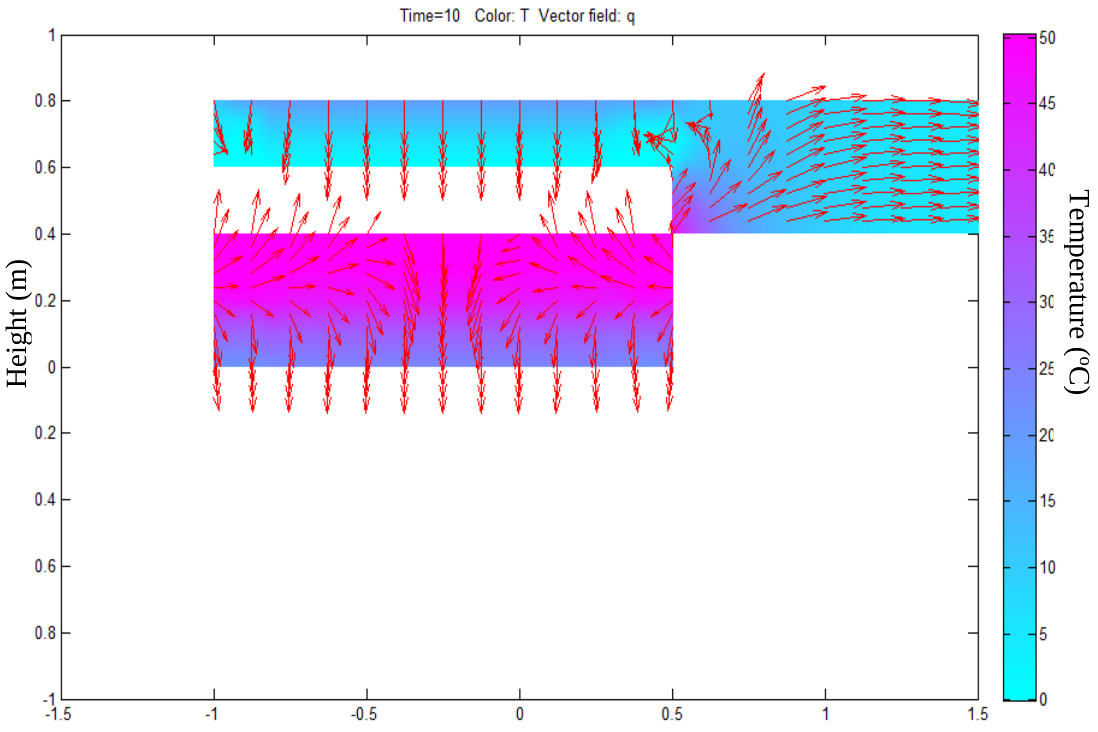

Figure 4.2: Heat direction inside the solar collector

As shown from the Figure 4.1 and 4.2 the heat energy is the highest at the absorber plate region, this is due to its high thermal conductivity and absorptivity. The insulation functions very well reduce the heat loss. The highest temperature for the absorber plate is 50 ^{0}C.

The value of the radiation heat transfer energy from the absorber plate is 28.4. W**.** The result shows that aluminium is a good material for absorber plate as it can absorb a lot of heat during the heat transfer process. The convective heat transfer energy is calculated to be 1.15 kW.

The maximum temperature inside the drying chamber is recorded to be in a range 45.3 ^{0}C which is enough for drying food products such as herbs and fruit which required 30 ^{0}C. It is calculated that the useful heat energy obtained by the collector is 1452.8 W. Using the equation (16), the maximum calculated thermal efficiency of the solar air collector is calculated to be 0.65.

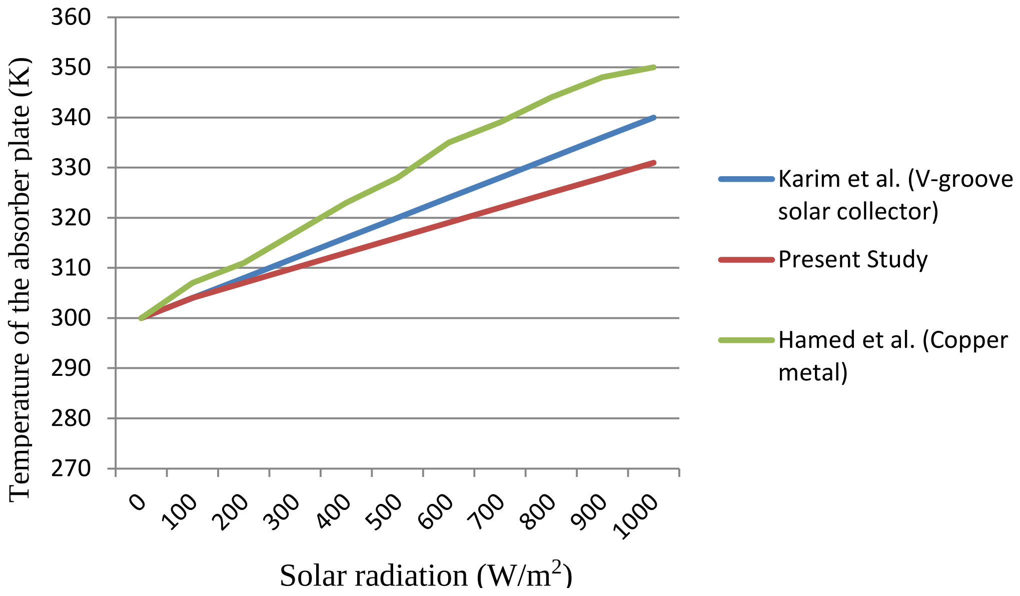

Figure 4.3: Temperature of the absorber plate vs solar radiation

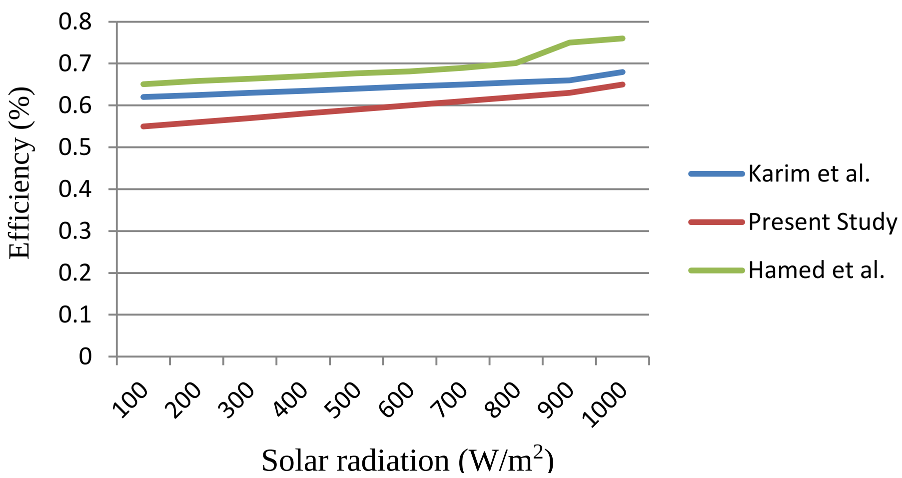

Figure 4.4: Efficiency vs solar radiation

Figure 4.3 and 4.4 compare the study done by Hamed et al.[8] and Karim et al.[12] with this study. The material chosen for the absorber plate also plays a role in depicting the efficiency of the solar collector as the Figure 4.3 shows that the solar collector that is using copper as the absorber plate resulting a higher temperature compare to aluminium. Meanwhile Figure 4.4 shows that design of the solar collector also contributes to the thermal performance of the solar collector as the solar collector with the V-groove design absorber plate shows the highest efficiency compare to flat plate absorber design. From this comparison, the type of metal chosen for the absorber plate and the design of the absorber plate plays a significant role in thermal performance of the solar collector

CHAPTER 5

CONCLUSION & RECOMMENDATION

Conclusion

There are a lot of factors that affect the solar collector system efficiency. These factors are the design parameters of the solar collector and its environmental factors. A partial differential equation model has been developed in order to visualize the heat transfer process inside a solar collector of a solar dryer using MATLAB software. From the model, two factors were identified to be playing significant role in the thermal performance of the solar collector there are the thermal conductivity and the specific heat capacity of the absorber plate. Hence, for a high efficient solar collector, a high thermal conductivity and low specific heat capacity is required.

The model also proves that aluminium can be used as the material for an absorber plate due to its sufficient thermal properties. Materials such as copper and steel are common options for the absorber plate, but aluminium is preferred due to its lightweight, cost and rustproof. It is important for us to accurately study these factors so that one can determine which factor that can be manipulated to ensure a very high efficient solar collector. The major factors that might affect the efficiency of the solar collector are the design factor, the effective incident radiation and the glazing material.

Recommendation

A further study on other metal such as steel, copper, alloy and etc needs to be done for the purpose of comparing the performance efficiency with aluminium hence the best material for the absorber plate can be affirmed. Furthermore, experimentation of this model is required for critical affirmation of the modelled result.

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MATLAB codes

```
function pdemodel
[pde_fig,ax]=pdeinit;
pdetool('appl_cb',9);
set(ax,'DataAspectRatio',[1 1 1]);
set(ax,'PlotBoxAspectRatio',[1.5 1 1]);
set(ax,'XLim',[-1.5 1.5]);
set(ax,'YLim',[-1 1]);
set(ax,'XTickMode','auto');
set(ax,'YTick',[ -1,...
 -0.94999999999999996,...
 -0.90000000000000002,...
 -0.84999999999999998,...
 -0.80000000000000004,...
 -0.75,...
 -0.69999999999999996,...
 -0.64999999999999991,...
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 -0.55000000000000004,...
 -0.5,...
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 -0.19999999999999996,...
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 -0.049999999999999933,...
 0,...
 0.049999999999999933,...
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 0.69999999999999996,...
 0.75,...
 0.80000000000000004,...
 0.84999999999999998,...
 0.90000000000000002,...
 0.94999999999999996,...
 1,...
]);

% Geometry description:
pderect([-1 0.5 0.80000000000000004 0.69999999999999996],'R1');
pderect([0.5 1 0.80000000000000004 0.5],'R2');
pderect([0.5 -1 0.5 0.44999999999999996],'R3');
pderect([0.5 -1 0.44999999999999996 0.34999999999999998],'R4');
```

```
set(findobj(get(pde_fig,'Children'),'Tag','PDEEval'),'String','R1+R2
+R3+R4')

% Boundary conditions:
pdetool('changemode',0)
pdesetbd(14,...
'neu',...
1,...
'5',...
'500')
pdesetbd(13,...
'neu',...
1,...
'0.5',...
'500')
pdesetbd(12,...
'dir',...
1,...
'0',...
'0')
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'dir',...
1,...
'1',...
'0')
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'500')
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'0')
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1,...
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'0')
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'25')
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'25')
pdesetbd(3,...
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1,...
'0',...
'0')
pdesetbd(2,...
```
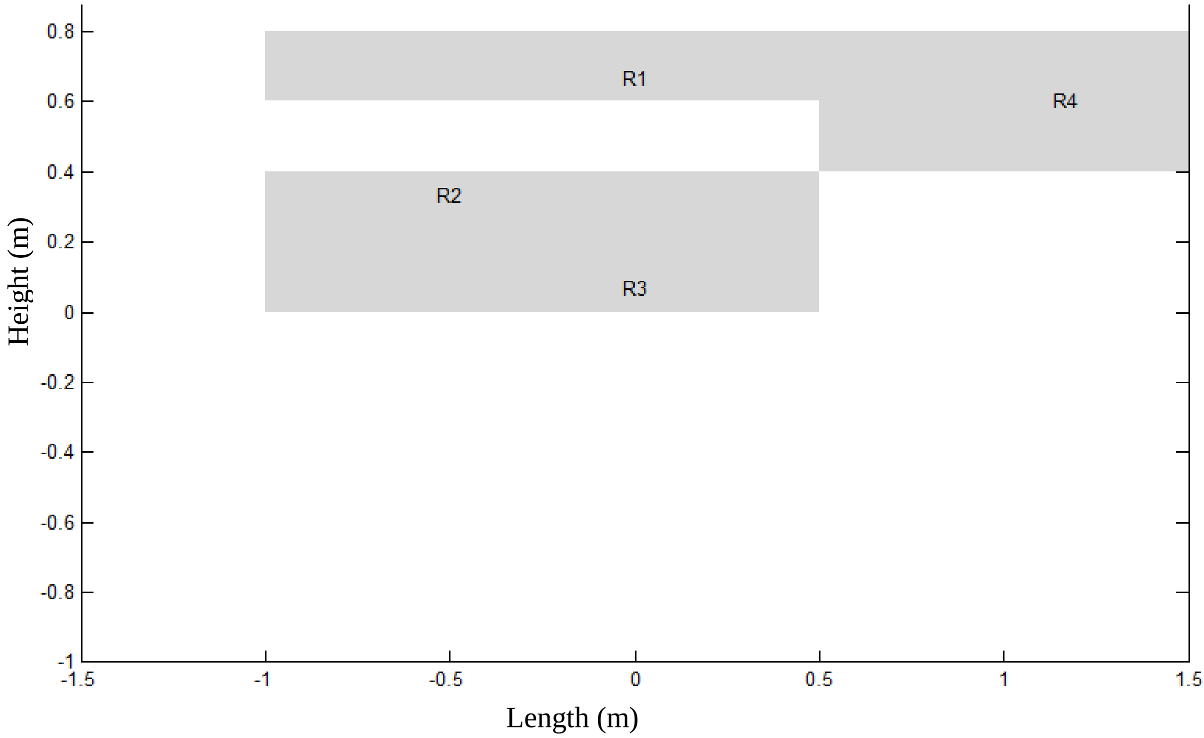
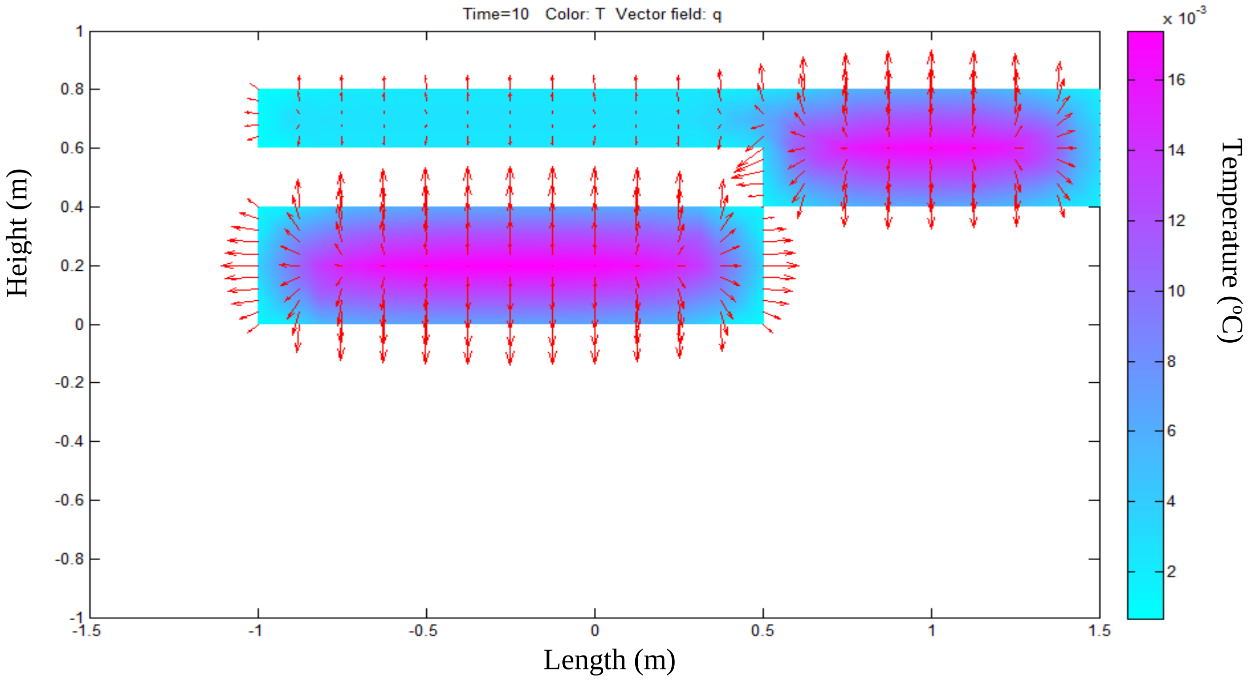

```
'dir',...
1,...
'0',...
'0')
pdesetbd(1,...
'neu',...
1,...
'0',...
'0')

% Mesh generation:
setappdata(pde_fig,'Hgrad',1.3);
setappdata(pde_fig,'refinemethod','regular');
setappdata(pde_fig,'jiggle',char('on','mean',''));
pdetool('initmesh')

% PDE coefficients:
pdeseteq(2,...
'1.05!0.0257!204!0.04',...
'0!0!0!0',...
'(0)+(0).*(25)!(0)+(0).*(25)!(0)+(0).*(25)!(0)+(0).*(0)',...
'(2400).*(840)!(1.29).*(1.012)!(2707).*(0.996)!(48).*(0.67)',...
'0:10',...
'0.0',...
'0.0',...
'[0 100]')
setappdata(pde_fig,'currparam',...
['2400!1.29!2707!48   ';...
'840!1.012!0.996!0.67';...
'1.05!0.0257!204!0.04';...
'0!0!0!0             ';...
'0!0!0!0             ';...
'25!25!25!0          '])

% Solve parameters:
setappdata(pde_fig,'solveparam',...
str2mat('0','1000','10','pdeadworst',...
'0.5','longest','0','1E-4','','fixed','Inf'))

% Plotflags and user data strings:
setappdata(pde_fig,'plotflags',[1 1 2 1 2 2 1 1 0 0 0 11 1 0 0 1 0
1]);
setappdata(pde_fig,'colstring','');
setappdata(pde_fig,'arrowstring','');
setappdata(pde_fig,'deformstring','');
setappdata(pde_fig,'heightstring','');

% Solve PDE:
pdetool('solve')
```



2D model of a solar collector for solar dryer



Heat map and heat direction with default value of boundaries and partial differential equation