Parametric Analysis of Flat Plate Solar Collector

For Performance Evaluation

by

Ahmad Husaini Bin Bahaman

A Dissertation submitted in partial fulfilment of

the requirements for the

Bachelor of Engineering (Hons)

(Mechanical Engineering)

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Universiti Teknologi PETRONAS
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CERTIFICATION OF APPROVAL

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Approved by,

(Dr Aklilu Tesfamichael Baheta)

Project Supervisor

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TRONOH, PERAK

May 2012

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 by unspecified sources of persons.

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AHMAD HUSAINI BIN BAHAMAN

ABSTRACT

Harvesting solar energy is one way to reduce environmental issues on carbon emission. One of the solar energy convertor is solar water heater that use flat plate collector as a medium. The aim of this project is to study the effect of fluid mass flow rate and collector area on the performance of solar water collector. The effects can be studied experimentally or with the help of simulation model. Experimental method is the most practical and accurate method. However, this practice is very costly that requires constructing the prototype, repeating the experiment many times which is expensive and time consuming. The most cost effective and time saving method is by mathematical model with computer simulation. Thus, this project was modelling of a flat plate solar collector and developing its computer simulation model in MATLAB environment. The developed model was used for parametric analysis of flat plate solar collector for performance study. Final results are interpreted in the form of thermal efficiency and fluid outlet temperature. It is predicted to get efficiency around 70% and fluid outlet temperature of 40 – 50 °C.

ACKNOWLEDGEMENT

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NOMENCLATURES

UL   Overall Heat Losses Coefficient (W/m^{2}k)

T_{pm} Absorber Plate Temperature

T_a Ambient Temperature

T_i Inlet Temperature

A_c Collector Area

S   Solar Radiation Absorbed by a Collector per Unit Area of Absorber (W/m^2)

Q_u Useful Energy Gain

F_R Collector Heat Removal Factor

$F^{''}$ Collector Flow Factor

$F^{'}$ Collector Efficiency Factor

g   Gravitational constant (9.81 m/s^2)

G   Irradiance

H   Daily Irradiation

I_b Beam Irradiance (W/m^2)

I_d Diffuse Irradiance (W/m$^{2)}$)

I_g Global Irradiance (W/m^2)

H   Heat Transfer Coefficient, Planck's constant

I_{TC} Hourly Critical Radiation in titled surface

k Thermal Conductivity

l Length, thickness

q Energy per unit time per unit length or area

Q   Energy, energy per unit time

α   Absorbance

γ   Surface azimuth angle

ε   Emissivity

θ   angle between surface normal and incident radiation, angle of incidence

θ_s (The sun's) zenith angle = $90° - \alpha_s$

ω   Hour angle

η   Efficiency

τ   Transmittance

λ   Wavelength

μ   Absolute viscosity

ν   Kinematic viscosity

ρ   Reflectance

δ   Declination, thickness

γ   Surface azimuth angle

γ_S The sun's azimuth angle

β   Slope

σ   Stefan Boltzmann Constant (5.67×10^{-8} W/m^{2}K)

CHAPTER 1

INTRODUCTION

1.1   Background of Study

At the moment as the nation developed, the energy consumption is increasing. As the result, energy conversion is one of the important issues at present. Solar energy is one of the raw energy resources. The solar energy was chosen for research works because it is the most substantial source and will last forever until the end of the world. Other than that, environmental issues have made alternative energies on the rise tremendously. Currently, solar energy is one of the most convincing and potential renewable energy platforms.

Iordanou (2009) points out that "In 2001, Greece held the first place in Europe for solar collector area installed per capita and the 2nd place in the world. Harper (2007) points out the significance of solar energy, technically "all the other renewable energy sources actually come from the sun, even the fossil fuels which we are burning at unsustainable rate at the moment, actually originally came from the sun".

Current technology of solar collector is used to collect the sun radiation. Flat plate solar collector is used to convert solar energy into useful heat gain, usually to heat water and generate steam. The heat produced by solar collector can provided directly to customers or stored. Hot water is used for household usage such as hot shower, laundry and washing dishes. Usually 40°C to 47°C for hot shower is considerably fine. Steam can be used to drive absorption chillers in air conditioning applications and also can be use directly for space heating. In order to meet energy demand, the thermal performance of the collector is described in terms of thermal efficiency and fluid outlet temperature of the collector.

Several criteria may affect the solar collector performance. Foster (2010) recommends "a combination of high transmittance toward the solar radiation of the cover and high absorptivity of the receiver that brings great performance for a well-designed solar collector" (p.74).

Other than that, physical properties of material, fluid flow rate, dimension of solar collector and solar irradiance are also the main aspects that have been considered in performance evaluation. With that, this project forecast the thermal efficiency and fluid temperature outlet of flat plate solar collector based on variation of control parameters.

1.2 Problem Statement

There is energy scarcity as the world population increases. Fossil fuels are not sustainable energy sources due to their decreasing reserves with time and it also harm the environment. Moreover, fossil fuels price is keep rising with time and resource not evenly distributed in the world. Alternative energy sources are required to lessen the problems. Solar energy is one of the renewable energies that can be used for free as long as there is a conversion system. It is the solution for long-term to substitute the conventional energy systems. Common usage of solar water heater will reduce the demand of fossil fuels for heat energy production and Carbon dioxide, CO_2 emission. Thus, the solar energy is the best alternative to start on as mentioned by Harper (2007) "Solar energy is clean, green, free and best of all, isn't going to be going anywhere for about the next five billion years".

Manufacturer of solar system commonly will specify the efficiency of the solar collector based on particular region. The low efficiency of solar collector will results to the low cost efficient and gives small benefits to consumer that pay at high price. Manufacturers are struggling to provide high efficiency solar collector at affordable price. Other alternative is to sell these products only at country which have high solar irradiance like Africa and Saudi Arabia.

However, the public awareness on solar energy has made a high demand on solar collector system. Thus, it is essential for manufacturer make an effort to increase the

collector efficiency depends on the country's location. Then, research and development of solar collector system is important for performance improvement.

Experimental method is one of the choices and it may give accurate and applicable findings in the real environment. However, this method may take countless of time when repeating the experiments to meet the parameters variation. It also leads to excessive budget when experiments conducted need an expensive solar collector system prototype and other supporting equipment for the test. Hence, the most effective way to start is to develop a mathematical model with computer simulation. This model is very convenient to carry out any possible potential improvements.

It is also called as parametric analysis, where the works carried out using computer simulation model. Some parameters can be varied such as size of solar collector, inclination angle, total radiation, position of solar collector, pipe size, material of solar collector and fluid flow rate in the mathematical model. Finally, through computer simulation in MATLAB environment, the efficiency of solar collector and fluid outlet temperature are determined.

Recently, government of Malaysia under Ministry of Energy, Green, Technology and Water (KeTTHA) has shown interest in this technology and offered Renewable Energy (RE) incentive to users. Secretary General of KeTTHA says that "the use of Renewable Energy (RE) and the adoption of Energy Efficiency (EE) for sustainable development by granting increasingly attractive fiscal incentives for the energy users to reduce their cost of doing business and to maintain their competitive edge in the international market"(p.3). Non-stop process of performance evaluation of flat plate solar collector will make the solar company retain competitive.

1.3 Objective and scope of the study

The objective of this project is to study performance of flat plate solar collector using mathematical model with computer simulation.

The scope of study for this project covers only steady-state performance that classified to thermal efficiency and fluid outlet temperature. This project is

conducted in-house using computer software EXCEL and MATLAB. This model is very convenient to carry out any possible potential improvements.

This project may relevance for the study of flat plate solar collector in Malaysia weather and temperature and applicable also for nearest country. The result of this project also based on sample data of solar irradiance obtained from Universiti Teknologi PETRONAS, Tronoh solar field. This project covers the effects of variation of fluid mass flow rate and collector area into solar collector performance. Other parameters values used are considerably relevance based on previous research and sample from references. This project can be a concrete base for further studies that using experimental method to verify all results obtained from the mathematical model.

Duffie & Beckman mentions that flat plate solar collectors are inexpensive, robust, and developed construction and have got wide applications in solar technologies. The special optical characteristic of flat plate collector is its advantage in using both beam and diffuse solar radiation. Temperatures of 40 to 70 °C can easily be attained by flat plate collectors".

The feasibility of the project depends on time taken for the learning processes, where time is allocated to study the computer software programming to develop mathematical model. In-house simulation required less time compared to experimental model thus, twenty four weeks (two semesters) is adequate for project completion.

CHAPTER 2

LITERATURE REVIEW

This section discussed more on theories and paperwork reviews related to flat plate solar collector and performance evaluation.

2.1 Flat Plate Solar Collector

To utilize the abundance of solar irradiance, flat plate solar collector is installed in the most of residential area for domestic space heating and water heating application.
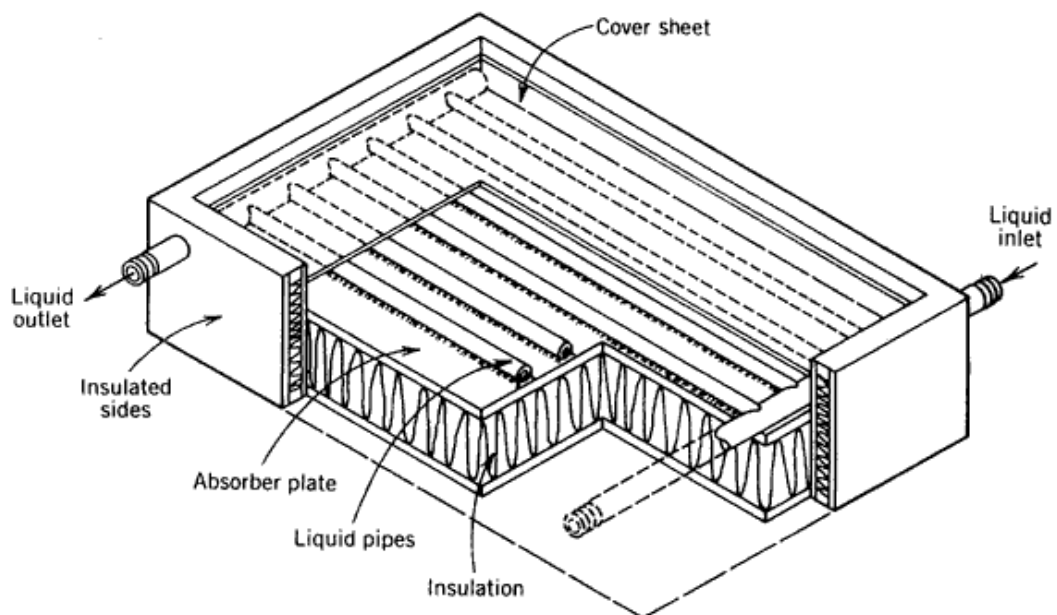
Figure 2.1: A typical liquid Flat Plate Solar Collector (Tiwari, 2002)

A typical flat plate solar collector consists of an absorber, cover sheets, insulation box and pipe. It may connect to storage or water tank for other purposes. The absorber is usually a thin sheet that made of high thermal conductivity material such as copper. Absorbance (α) of absorber is one of the factors for performance evaluation and made the surface painted black or coated to maximise the radiant

energy absorption. The insulation box provides an assembly of sealing to reduce heat losses from back and sides of the collector. Sheet cover also called glazing allow the sunlight to pass through to the absorber and it reduce glare and reflection, and also prevent cool air from enter this space. Low-iron tempered glass is used as cover material because of its high transmittance (τ). Other than that, copper pipe is used to let fluid flow inside pipe and become one of the heat transfer medium between absorber and water.
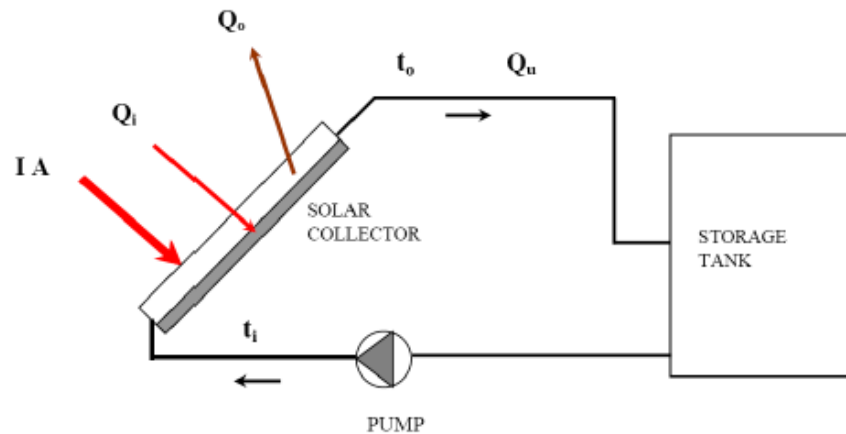
Figure 2.2: Typical solar energy collection system

Figure 2.2 shows the schematic of a typical solar collector system employing a flat plate solar collector and a storage tank. The collector housing is insulated vastly at the bottom and sides, however there are still come heat losses due to temperature difference between the absorber and the ambient air that results convection and radiation losses. Iordanou (2009) says that "the convection losses are caused by the angle of inclination, the spacing between the glass cover and the absorber plate, while the radiation losses are caused by the exchange of heat between the absorber and the environment" (p.13).

2.2 Product of absorbance and transmittance

Absorber plate which covers most of the collector space is required to execute three functions:

(a) Absorb solar irradiance as much as possible

(b) Transfer the absorbed energy into water inside through a pipe

(c) Reduce heat losses as many as possible
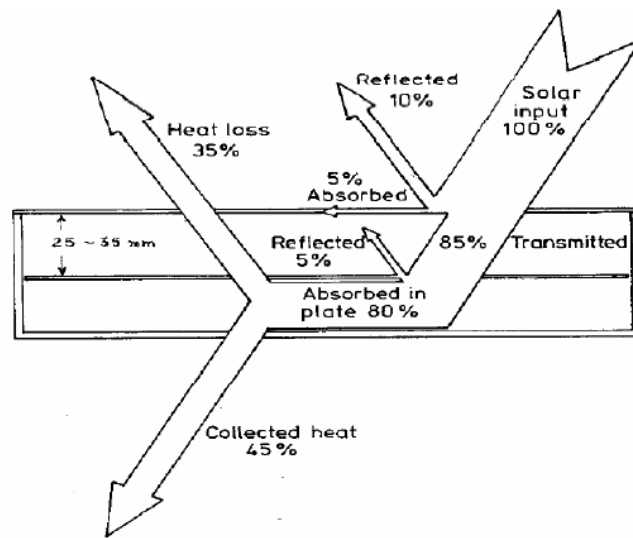
Figure 2.3: Heat flow through a Flat Plate solar collector (Struckman, 2008)

Figure 2.3 shows a part of solar radiation is reflected back to the sky, another component is absorbed by the glazing and the rest is transmitted through the glazing and reaches the absorber plate as short wave radiation.

Tiwari (2002) says that the most commonly used glazing material is glass as it can transmit up to 90 percent of the incident short wate radiations while its transmittance to the long wave heat radiation (5.0 to $50^{-6}m$), emitted by the absorber plate, is negligible.

Iordanou (2009) points out that there are correlation between fluid inlet temperature and flow rate. The use of fluid inlet temperature through pipe makes the application of the performance correlation easier in design studies and it is recommended test flow rate for a liquid collector is 0.02 kg/hr.

2.3 Performance Evaluation

The performance of flat plate solar collector is measured by considering the value of thermal efficiency, fluid outlet temperature and useful heat gain. There are many parameters and factors involved for thermal performance formulation within solar collector system. Formulation of a mathematical model will describe the thermal performance of the collector in a computationally efficient manner.

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2.3.1 Thermal Efficiency

In thermodynamics, the thermal efficiency (η) is a dimensionless measure of a device that uses thermal energy. Relationship of thermal efficiency may be described as useful heat gain divide by a product of solar irradiance and collector area.

$$\eta = \frac{Q_u}{I \times A_c} \tag{2.1}$$

Experiments were conducted by Struckman (2008) to examine the thermal efficiency for a given collector and flow rate using equation 2.1. These parameters designation are attached in nomenclature part at the beginning of report.

The result of efficiency is a linear function of the three parameters defining the operating condition of solar irradiance (I), fluid inlet temperature (T_i) and ambient air temperature (T_a).

The collector efficiency is plotted against (T_i-T_a)/I. The slope of this line (-$F_R U_L$) represents the rate of heat loss from the collector. This is indicates that collectors with cover sheets will have less of a slope than those without cover sheets.
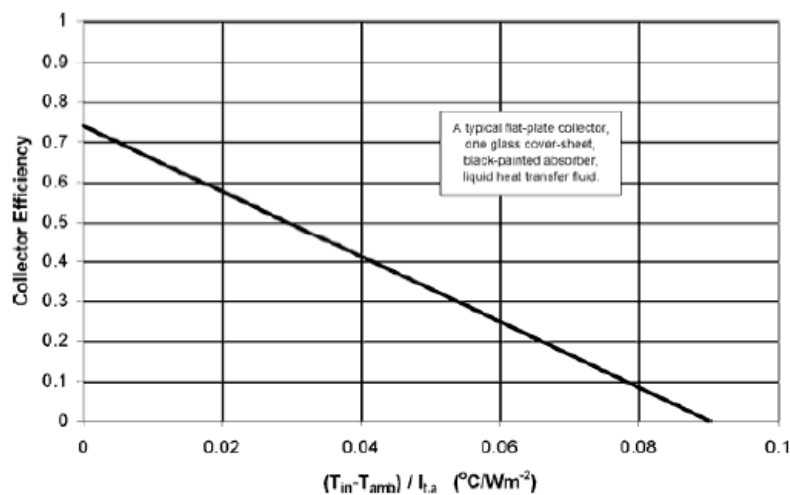
Figure 2.4: Performance of a typical flat-plate thermal collector (ambient temperature 25°C) (Struckman, 2008)

Figure 2.4 shows the maximum efficiency is 75% at zero value of x-axis. It means that, to get highest efficiency, fluid inlet temperature (T_i) must equal to ambient air

temperature (T_a), at the same time considering all of the assumptions stated before. For this condition, the ΔT/I value is zero and the intercept is F_R ($\tau\alpha$).

A way to describe the importance of thermal performance of a Flat Plate Solar Collector by measuring collector efficiency has been shown. For future enhancement or improvement, it is recommended to consider the overall heat loss coefficient (U_L), heat removal factor (F_R), transmission of the cover, and other parameters to get more precise and detailed analysis.

Besides that, table 2.1 shows the result of useful gain and efficiency results from $2m^2$ collector area and 0.03 kg/s fluid mass flow rate while the inlet fluid temperature remains at 40°C made by Duffie & Beckman (1990).

Table 2.1: Results of efficiency and useful gain (John A. Duffie, William A. Beckman, , 1980)

Time	T_a C	I_T MJ/m^2	S MJ/m^2	$U_L(T_i-T_a)$ MJ/m^2	q_u MJ/m^2	η
7–8	−11	0.02	–	–	0	0
8–9	−8	0.43	0.35	1.38	0	0
9–10	−2	0.99	0.82	1.21	0	0
10–11	2	3.92	3.29	1.09	1.76	0.45
11–12	3	3.36	2.84	1.07	1.42	0.42
12–1	6	4.01	3.39	0.98	1.93	0.48
1–2	7	3.84	3.21	0.95	1.81	0.47
2–3	8	1.96	1.63	0.92	0.57	0.29
3–4	9	1.21	0.99	0.89	0.08	0.07
4–5	7	0.05	–	0.95	0	–
Sum		19.79			7.57	

2.3.2 Fluid Outlet Temperature

Fluid outlet temperature of 40-47°C is considerably enough for hot shower in Malaysia. Higher liquid temperature is used for chiller, steam turbine or other equipment. Fluid enters the system either by forced circulation or natural circulation. Kazeminejad (2001) made an experiment that water is used for fluid circulation and fluid inlet temperature approximately the same to ambient temperature. Then

compute the outlet temperature, T_{fo} for the given fluid mass flow rate and inlet temperature once the Q_u is determined from equation 2.2.

$$Q_u = \dot{m} c_p (T_{fo} - T_{fi}) \qquad (2.2)$$

Where Q_u is the useful energy, $\dot{m}$ is the fluid mass flow rate, c_p is the heat capacity for water (4180 J/kg K) and T_{fi} is fluid inlet temperature. Experiments were done at various mass flow rates and tube spacing to determine the fluid outlet temperature. Figure 2.5 shows the result plotted with the fluid outlet temperature as a function on mass flow rate.
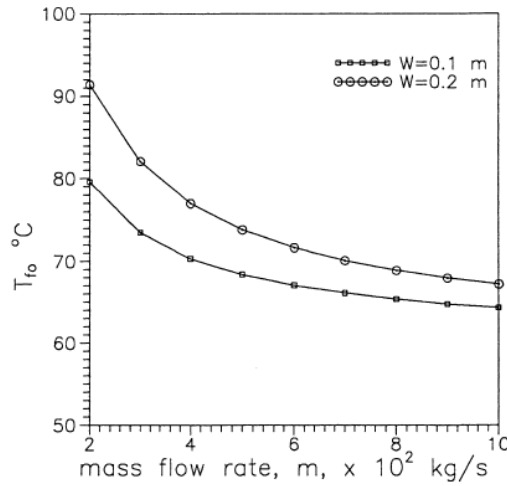
Figure 2.5: Effect of tube spacing, w on fluid outlet temperature, T_{fo} (Kazeminejad, 2001)

2.3.3 Useful Energy Gain

Duffie A. & Beckman W (1980) says that the thermal energy gained represented as product of solar radiation, S multiplied by collector heat removal factor F_R and collector's area A_c. The thermal energy lost from the collector to the surroundings by conduction, convection, and radiation can be represented as the product of a heat transfer coefficient times the difference between temperatures. Useful Energy gains interpreted as described by equation below.

$$Q_u = A_c F_R [S - U_L (T_i - T_a)] \qquad (2.3)$$

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Performance of flat plate solar collector may be estimated by the ratio of useful energy gain over total irradiance absorbs by absorber. This estimation is simple yet only crude value of solar collector performance based on useful energy gain, thus it just an overview before direct to the main performance value.

2.4 Parametric Analysis

The aim in parametric analysis is to forecast suitable parameters over optimum performance. At present, there are two target parameters for evaluation which are mass flow rate and collector area. All simulation conducted must at least give results on thermal efficiency and fluid outlet temperature.

2.4.1 Fluid Mass flow rate

Fluid mass flow rate is dependent on quantity of tube exist in flat plate solar collector. This relationship $\dot{m} = \dot{m}_{f1} \times N$ is used to determine total fluid mass flow rate. Where $\dot{m}_{f1}$ is fluid mass flow rate in each tube and N is quantity of tube Experiments were done at various mass flow rates to determine the efficiency. Figure 2.6 shows the results of efficiency plotted against mass flow rate.
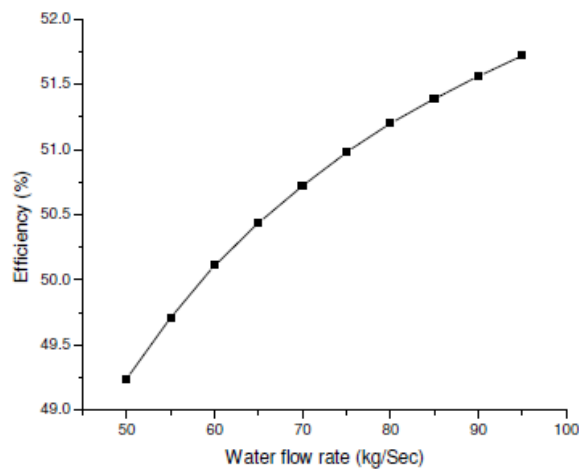
Figure 2.6: Efficiency vs. Water flow rate (Prasad, 2011)

Graph above show the results predicted for the variation of water flow rate with efficiency. Collector efficiency increases with the increase in water flow rate due to absorption of heat energy with high velocity of flow rate and less radiation losses.

2.4.2 Material of cover and absorber

Particular material use for absorber and cover will affect solar absorption radiation from the value of its absorbance (α) and transmittance (τ) respectively. Currently absorber made of copper with α=0.88 and cover made of low-iron tempered glass with τ=0.88. These values had been used for simulation model.

$$S = I_b\left(\frac{\cos\theta}{\cos\theta_z}\right)(\tau\alpha)_b + I_d(\tau\alpha)_d\left(\frac{1+\cos\beta}{2}\right) + \rho_g(I_b + I_d)(\tau\alpha)_g\left(\frac{1-\cos\beta}{2}\right)$$

$$(2.4)$$

2.4.3 Collector Surface Area

Collector surface area, A_c is the product of collector length, L_1 and collector width, L_2. Since thermal efficiency is a function of A_c, thus graph of efficiency versus collector area illustrated on figure below.
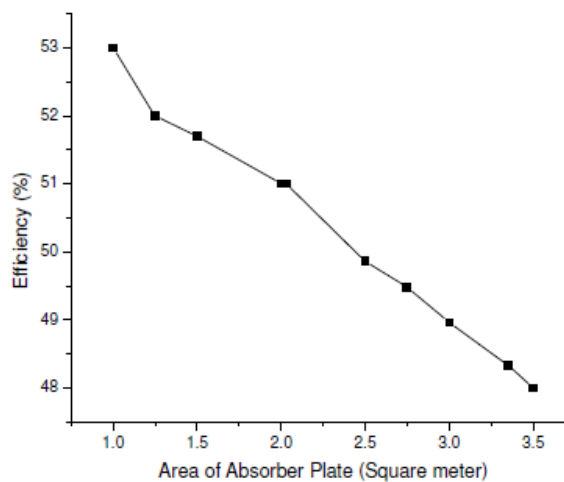
Figure 2.7: Efficiency vs. Area of Absorber Plate (Prasad, 2011)

Figure 2.7 shows when the area of plate increase the efficiency decreases due to more heat losses occurred. Heat loss occurred when the area of absorber plate

increased. This effect is shown by the Figure 2.7 varying area of absorber plate with efficiency.

2.5 Solar Irradiance

India is on the country that abundance of solar irradiance. Solar irradiance is dependent on particular weather and gives smaller value when it is cloudy and raining. Other than that, solar irradiance also depends on field location, time and date of experiment conducted. Table below show the performance of flat plate collector from 8.00am until 5.00pm, experiment conducted at Chickballapur, India at latitude and longitude of [13°24'9" N, 77° 43'49"E] respectively. Table 2.2 shows that the solar irradiances vary from 8.00am to 5.00pm and the peak value of global irradiance, I_g is at 12.00 Noon (1572 W/m^2).

Table 2.2: Performance of a fixed flat plate collector over a whole day at Chickballapur location

Location: Chickballapur (13°24'9", 77°43'49"); Clear day on May 15th.										
IST Hours Parameter	**8.00 Am**	**9.00 Am**	**10.00 Am**	**11.00 Am**	**12.00 Noon**	**1.00 Pm**	**2.00 Pm**	**3.00 Pm**	**4.00 Pm**	**5.00 Pm**
I_b W/m^2	879	1098	1273	1391	1444	1429	1345	1200	1004	769
I_d W/m^2	119	123	126	127	128	127	127	125	122	117
I_g W/m^2	998	1221	1399	1518	1572	1556	1472	1325	1126	886
I_T W/m^2	882	1129	1319	1446	1503	1486	1397	1241	1025	752
S W/m^2	487	722	878	976	1019	1006	938	816	627	350
T_{pm} °K	342	348	352	354	355	355	350	350	346	339
U_t W/m^{2}°K	3.04	3.31	3.47	3.57	3.61	3.60	3.4	3.4	3.2	2.87
q_u Watts	651	1055	1323	1489	1561	1541	1273	1216	893	414
T_{fo} °C	68	73	76	78	79	79	74	74	71	65
η %	36	46	49	51	51	51	49	48	43	27

2.6 Collector Overall Heat Losses Coefficient

Modelling of flat plate collector includes both optical and thermal modelling. The solar energy absorbed by the absorber plate is distributed to useful heat and thermal losses. Thermal losses occur at the top, side bottom and edges of the collector system.

Infrared radiation is the highest heat loss of flat plate solar collector. The exchange is between the cover and the sky, the cover and the ground, and the absorber and the sky. For convective heat loss is due to bottom, side and edges of the collector system.

For conduction heat losses, heat loss by conduction in the collector is due to bottom, side and edges of the collector system.

$$U_L = U_t + U_b + U_e$$

<div align="right">(2.5)</div>

If it is assumed that all losses occur to a common sink temperature T_a, equation 2.5 shows the collector overall loss coefficient U_L is the sum of the top, bottom and edge loss coefficients.

2.7 Energy Efficiency Solution

Study focus on the energy solution by improving the current solar technologies in order to optimize the energy consumption. By putting into practise the utilization of solar energy for water heating that would decrease the dependence on fossil energy consumption and limitation of Greenhouse gas emission. Ramlow & Nusz (2006) says that **three general principles** on saving from consumption of energy by **reducing total heat loss, increasing efficiency of collector** and **reducing energy consumption**.

Ramlow & Nusz (2006) also says that energy consumption is based on individual needs, awareness towards conserving energy make a person consume energy based on actual needs such as take a shower instead of baths, install a flow restrictor that will reduce the number of gallons per minute that it uses. To reduce heat losses, examine the heating system and look for places where heat might leak out. Heat losses in the system end up wasting the energy that actually used for heat the water. Finally, improve the efficiency of every appliance that uses hot water, washing machine and the dishwasher by upgrade these machines to better energy efficient model.

CHAPTER 3

METHODOLOGY

3.1 Research Methodology


```
                        ┌─────────┐
                        │  START  │
                        └─────────┘
                             │
                             ▼
        ┌──────────────────────────────────────────────┐
        │ Initial research work and study from literatures │
        └──────────────────────────────────────────────┘
                             │
                             ▼
        ┌──────────────────────────────────────────────┐
        │ Collect information on local geographical position, │
        │ weather data and other constant for Flat Plate Solar │
        │ Collector                                        │
        └──────────────────────────────────────────────┘
                             │
                             ▼
        ┌──────────────────────────────────────────────┐
        │ Develop mathematical model                     │
        └──────────────────────────────────────────────┘
                             │
                             ▼
        ┌──────────────────────────────────────────────┐
        │ Set a constant and control parameters          │◄──────┐
        └──────────────────────────────────────────────┘       │
                             │                                   │
                             ▼                                   │
        ┌──────────────────────────────────────────────┐       │
        │ Simulation results and discussion              │   No  │
        └──────────────────────────────────────────────┘       │
                             │                                   │
                             ▼                                   │
                          ◇ Reliable ◇──────────────────────────┘
                             │
                            Yes
                             ▼
        ┌──────────────────────────────────────────────┐
        │ Documentation                                  │
        └──────────────────────────────────────────────┘
                             │
                             ▼
                        ┌─────────┐
                        │   End   │
                        └─────────┘
```

Figure 3.1: Flow chart of the project

15

```
┌─────────────────────────────────────────────────────────────────────────┐
│                             ( Start )                                     │
│                                 │                                         │
│           ┌─────────────────────▼──────────────────────┐                 │
│           │ Collect data on solar irradiance,          │                 │
│           │ geographical location, and number of days  │                 │
│           └─────────────────────┬──────────────────────┘                 │
└─────────────────────────────────┴─────────────────────────────────────────┘
```

Start

Collect data on solar irradiance, geographical location, and number of davs

Calculate absorbed solar radiation

$$S = \tau \times \alpha \times I$$

$$I_T = I_b R_b + I_d \left(\frac{1 + \cos\beta}{2} \right) + I_g \rho_g \left(\frac{1 - \cos\beta}{2} \right)$$

Calculate Heat losses

$$U_L = U_t + U_b + U_e$$

Top Loss

$$U_t = \left(\frac{1}{h_{c,p-c} + h_{r,p-c}} + \frac{1}{h_w + h_{r,c-a}} \right)^{-1}$$

Bottom Losses

$$U_b = \frac{k_{ins}}{L}$$

Edge Losses

$$U_e = \left[\frac{(\frac{K_{ins}}{L_{edge}}) \times (2L_{thickness} \times width \times length)}{width \times length} \right]$$

Set fluid mass flow rate as control parameter

Variation of control parameter values

Calculate Useful Energy Gain

$$Q_u = A_c \times F_R \times \left(S - U_L \left(T_{fi} - T_a \right) \right)$$

Set collector area as control parameter

Calculate and plot Performance of Flat plate solar collector

Calculate fluid outlet temperature

$$Q_u = \overset{\bullet}{m} \times C_p \times \left(T_{fo} - T_{fi} \right)$$

Calculate Thermal Efficiency

$$\eta = \frac{Q_u}{I_{g,t} \times A_c}$$

At least 2 control parameters
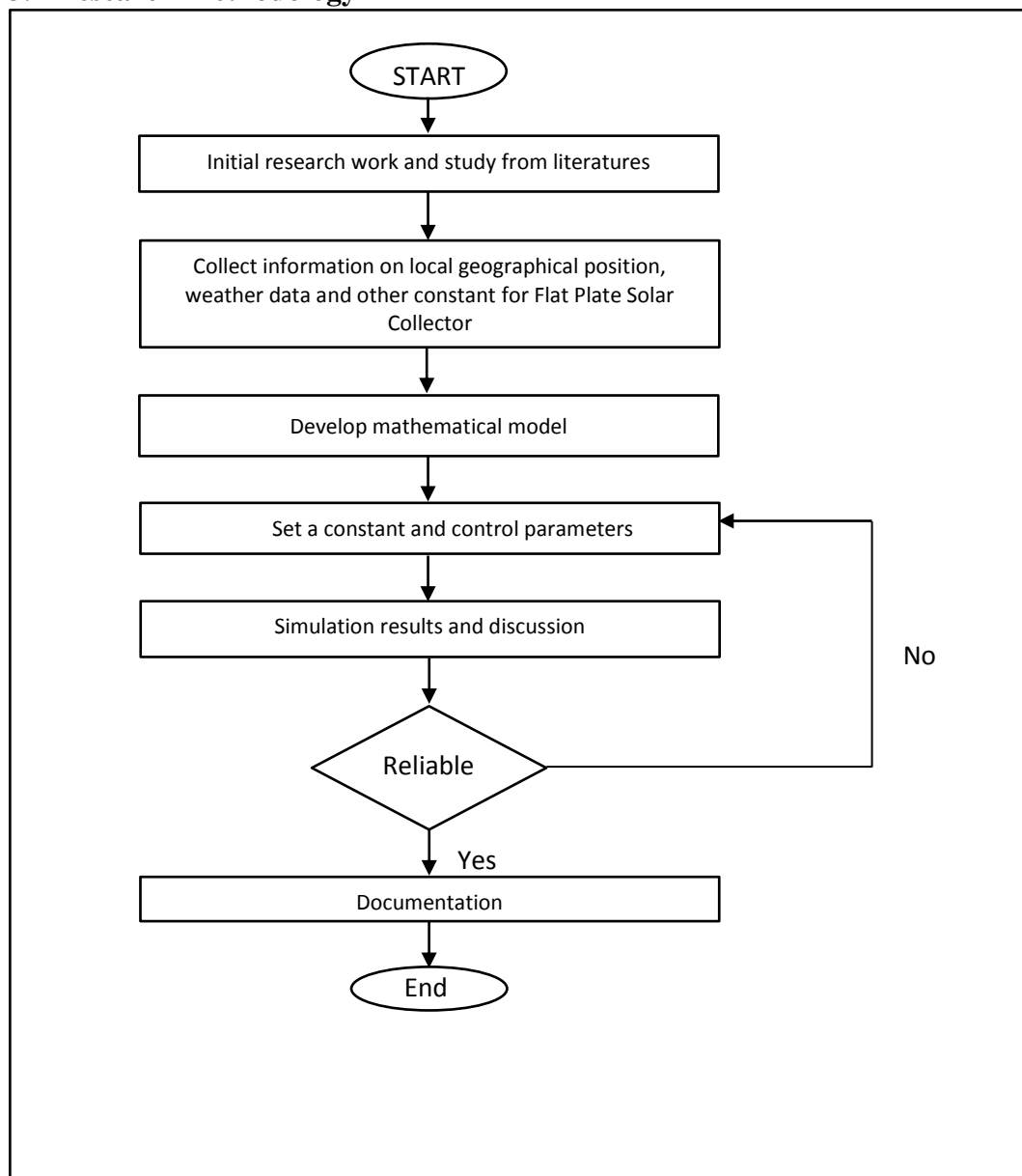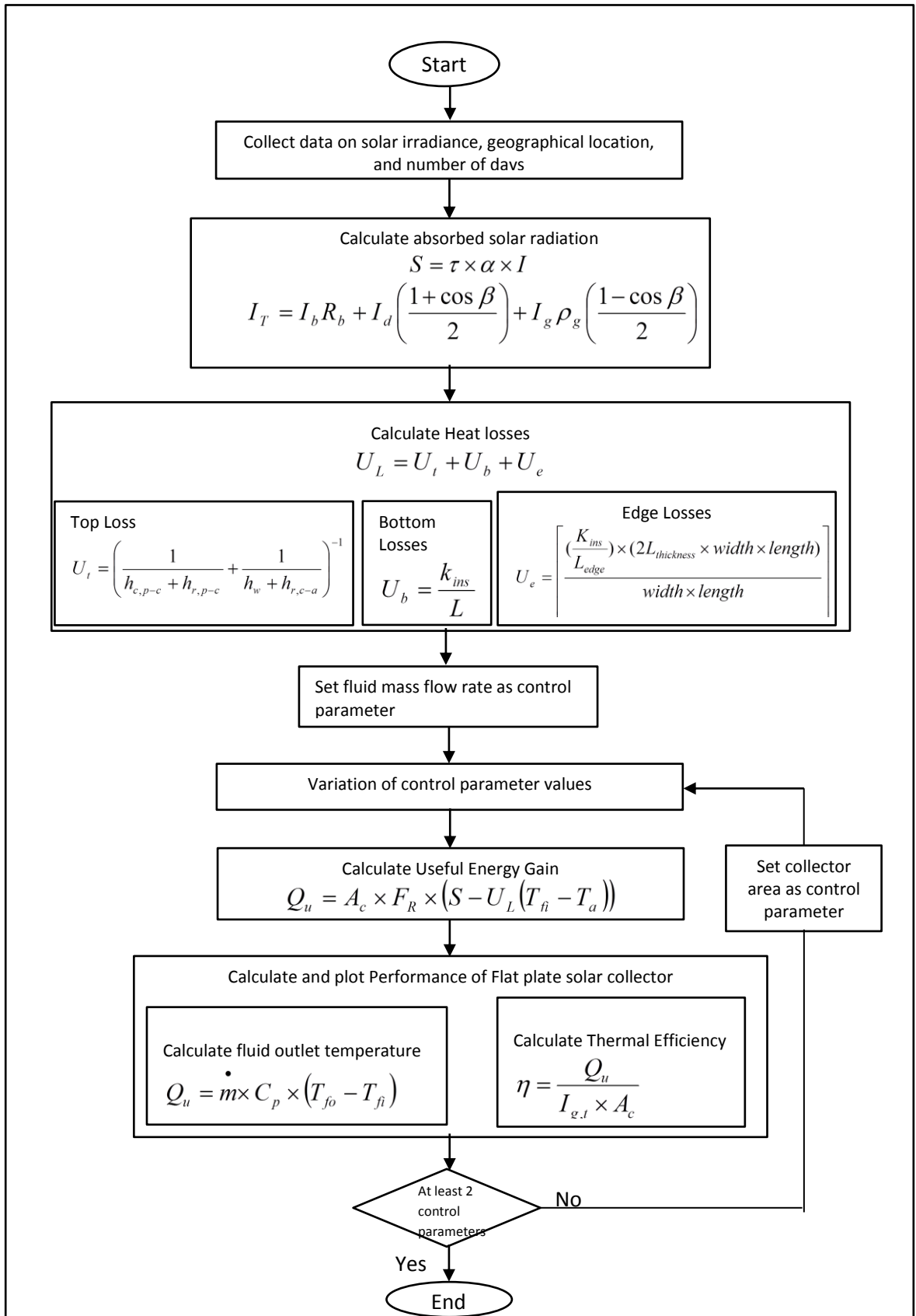
No

Yes

End

Figure 3.2: Flowchart of mathematical model for simulation

Figure 3.1 shows the research methodology of this project was planned to apportion several stages where the activities are distributed accordingly respective to time provided. First stage started with initial research stage to validate the project by concrete findings. Then, second stage is data gathering where all required data for simulation is recorded and carry forward to the third stage which is project development that builds the mathematical model in computer software. Figure 3.2 shows the major formulas and calculation involved in mathematical model step-by-step.

3.2 Initial Research stage

The research starts with problem identification and familiarization. Research was done thoroughly on available books and journals relevant to the project. Information needed was highlighted and recorded for reference while completing this project. The objective is to get better understanding on parameters that affect the flat plate solar collector performance that incorporated to project objective. Prior to meet the objective, one of the most important things in research stage is discussion and consultation with supervisor. From the consistent meeting with supervisor, decision was made on the best and most reliable parameters that highly affect the solar collector performance.

3.2.2 Data Gathering

Project works continues with data gathering of all constant values required for simulation. After all the mathematical formulas involved are confirmed, the required constant parameters are determined either by literature or field works.

3.2.2.1 Weather Data

Data of solar irradiance was collected from Universiti Teknologi PETRONAS solar field by using pyranometer. Data consists of beam irradiance, diffuse irradiance and

global irradiance collected with respect to local standard time. The location of the region is also recorded as one of the parameters involve in mathematical model.

Figure 3.3: Malaysia map with latitude and longitude. (www.mapsofworld.com)

Local standard time (LST) used in Malaysia is based on standard coordinate latitude and longitude of 5°N, 105° given in figure 3.3. For local actual time (LAT) of particular place may refer to its own coordinate as given in table 3.1.

Table 3.1: Latitude and longitude of particular place of interest

Locations	Latitude	Longitude
Ipoh	04°35'N	101°05'E
Kuala Lumpur	03°09'N	101°41'E
Miri, Sarawak	04°23'N	113°59'E
Kota Kinabalu	06°00'N	116°04'E

The solar irradiance availability recorded from 8.00 a.m. (0800) to 5.00 p.m. (1700) taken on 24 December. The equivalent value for 24 December is 354 as summarised in table 3.2. The collector was placed facing the south and tilted similar to latitude angle.

Table 3.2: Number of days, n for the respective date

Geographical	Value	unit
Date	24	December
n	354	day

18

The solar energy reached in the earth's surface is a combination of beam and diffuse components. The diffuse component is the result of atmospheric scattering and ground reflections. The total radiation, I_T on the inclined surface is the sum of beam and the diffuse (also known as global radiation) as summarised in table 3.3. While table 3.4 shows the recorded ambient temperature with time. **The variation of slope and solar azimuth angle (γ) affect the amount of total energy collected** in the flat plate solar collector during monthly, seasonally or annually. Proper optimization of these variables is important in the demand of hot water for household or industrial purpose. To achieve maximum annual absorbed solar energy, a collector tilt angle is equals to the latitude (John A. Duffie, William A. Beckman, , 1980)

Table 3.3: Solar irradiance on 24 December 2012

Date/Time	BEAM	DIFFUSED	GLOBAL
24/12/2010 8:00	18.30	88.19	106.49
24/12/2010 9:00	60.76	95.81	156.57
24/12/2010 10:00	129.43	240.48	369.91
24/12/2010 11:00	746.63	115.25	861.88
24/12/2010 12:00	859.20	176.52	1035.72
24/12/2010 13:00	620.43	237.84	858.27
24/12/2010 14:00	340.78	371.10	711.88
24/12/2010 15:00	316.59	365.06	681.65
24/12/2010 16:00	86.11	360.59	446.70
24/12/2010 17:00	0.31	100.94	101.25

Table 3.4: Ambient temperature on respective date

Local Standard time (hour)	Ambient temperature (K)
8	295.03
9	296.66
10	301.73
11	304.8
12	306.44
13	307.56
14	309.11
15	308.14
16	307.44
17	306.42

3.2.2.2 Design Modelling

The simulation used in this study mainly involved in parametric analysis that examines the relationship between different parameters, such as length, angle and etcetera. In accordance to that, symbolic model is used, while EXCEL and MATLAB are useful tools to simulate the relationship between solar ray distribution, water temperature and the design of solar collector for performance evaluation. Flat plate solar collector dimensions, control and constant parameters are demonstrated as below. A typical solar collector cross-section is shown in figure 3.4 and figure 3.5 shows the side view arrangement of the collector.
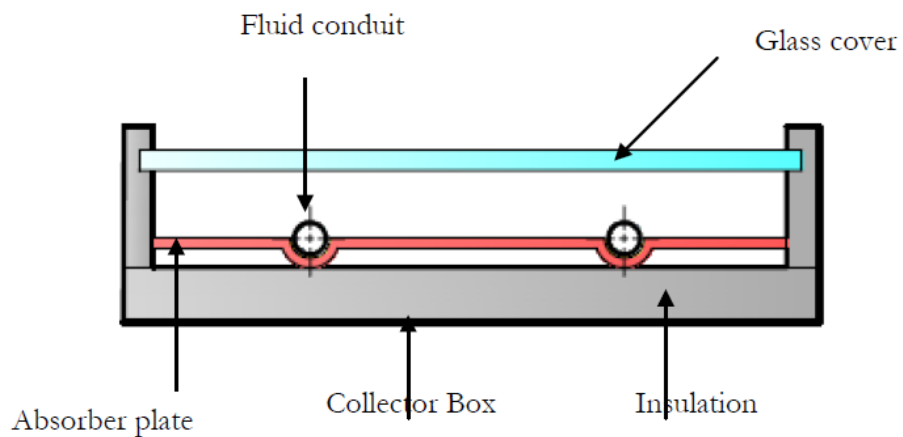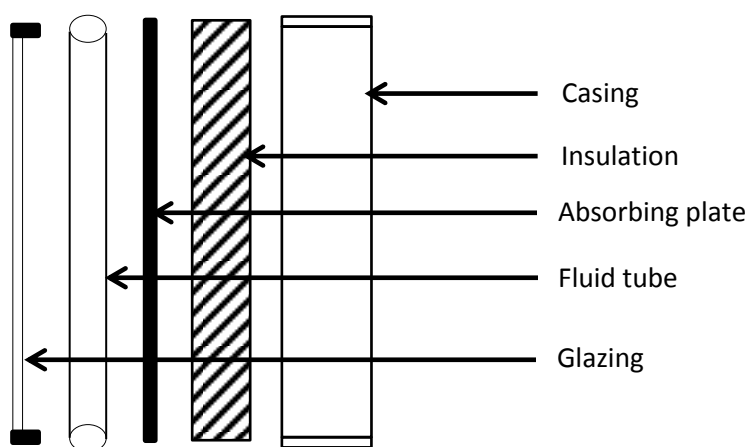

Figure 3.4: Diagram of Solar Collector

Figure 3.5: Exposed cross section through single-glazed flat plate solar collector

For this study, the geometric dimensions of the collector and other fixed parameters involved considered are listed in table 3.5.

Table 3.5: Parameters set to constant

Constant for simulation	Value
Transmittance of the plate	0.88
Absorption of the plate	0.88
Back insulation thickness (m)	0.05
Collector Overall thickness (m)	0.08
Collector edge insulation thickness (m)	0.025
Insulation thermal conductivity (W/m.K)	0.045
Absorber plate thickness (m)	0.0005
Specific heat of water (J/kg.K)	4180
Tube spacing (m)	0.15
Tube inside diameter (m)	0.01
Gap between the cover and the plate (m)	0.025
Absorber thermal conductivity of copper (W/m^{2}K)	385
Water heat transfer coefficient (W/m^{2}K)	300
Wind speed (m/s)	3
Initial cover temperature (K)	345
Thermal conductivity of air (W/m.K)	0.029

3.3 Mathematical Model with Computer Simulation

Execution stage for project development is where the computer simulation takes place in this project. After generation of governing equation, it is possible to evaluate and compare series of possible results without actually build a prototype of solar collector. Computer simulation using MATLAB software is the efficient way to save time and cost. Dieter & Schmidt (2009) says that "MATLAB is one program that includes a Simulation module, which will use the data collected by the System Identification Toolkit to create the model of an object in the simulated system".

Finally, simulation model executed results and certain variables that affecting the result the most will be determined.

3.3.1 Direction of Beam Radiation

The solar energy reached in to the earth's surface is a combination of beam and diffuse components. The total radiation I_g that lies on collector surface is the sum of

beam and the diffuse. The variation of slope and solar azimuth angle (γ) affect the amount of total energy collected in the flat plate collector during monthly, seasonally or annually. Figure 3.6 shows the angle and slope involved clearly and table 3.6 identify the meanings of each angle.
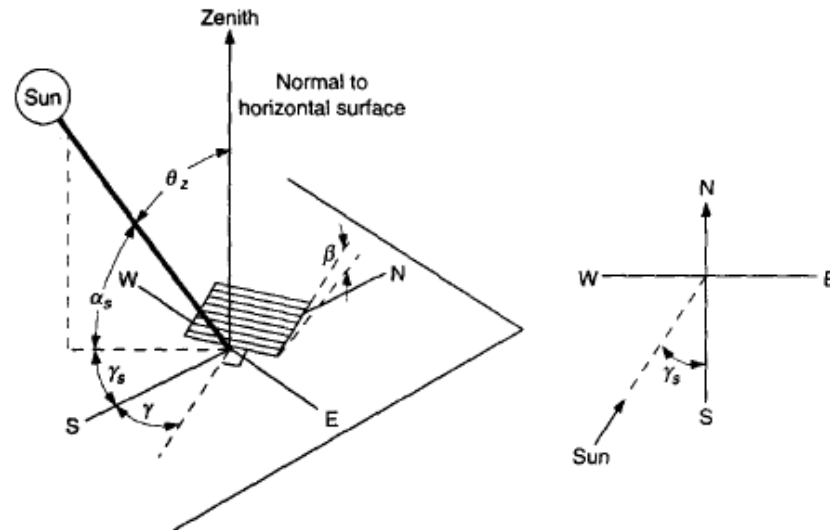

Figure 3.6: (a) Left: Zenith angle, slope, surface azimuth angle, and solar azimuth angle for a tilted surface. (b) Right: Plan view showing solar azimuth angle. (John A. Duffie, William A. Beckman, , 1980)

Proper selection of these variables is important in the demand of hot water for household. For maximum annual energy availability, a collector tilt angle, β equal to the latitude is considered. The declination δ can be found from the equation 6.

Table 3.6: Description of symbols of the angles

symbol	Meaning and Description
ϕ	**Latitude,** the angular location north or south of the equator, north positive; $-90^o \leq \phi \leq 90^o$.
δ	**Declination**, the angular position of the sun at solar noon (i.e., when the sun is on the local meridian) with respect to the plane of the equator, north positive; $-23.45° \leq \delta \leq 23.45°$.
β	**Slope,** the angle between the plane of the surface in question and the horizontal; $0 \leq \beta \leq 180°$. ($\beta > 90°$ means that the surface has a downward facing component.)
γ	**Surface azimuth angle,** the deviation of the projection on a horizontal plane of the normal to the surface from the local meridian, with zero due

	south, east negative, and west positive; $-180° \leq \beta \leq 180°$.
ω	**Hour angle,** the angular displacement of the sun east or west of the local meridian due to rotation of the earth on its axis at 15° per hour, morning negative, afternoon positive.
θ	**Angle of incidence,** the angle between the beam radiation on a surface and the normal to that surface.
θ_z	**Zenith angle,** the angle between the vertical and the line to the sun, i.e., the angle of incidence of beam radiation on a horizontal surface.
α_s	**Solar altitude angle,** the angle between the horizontal and the line to the sun, i.e., the complement of the zenith angle.
γ_s	**Solar azimuth angle,** the angular displacement from south of the projection of beam radiation on the horizontal plane. Displacements east of south are negative and west of south are positive.

$$\delta = 23.45 \sin(360 \frac{284 + n}{365})$$

(3.1)

There is a set of useful relationship among these angles, equation 3.3 and figure 3.4 shows the relation of angle of incidence of beam radiation on a surface, θ to the other angles in simplified form.

3.3.2 Angle of Incident

Angle of incident is largely influence by the position of collector facing sun. Figure 3.7 shows condition and location of an angles and the angle of incident is determined from equation 3.2.
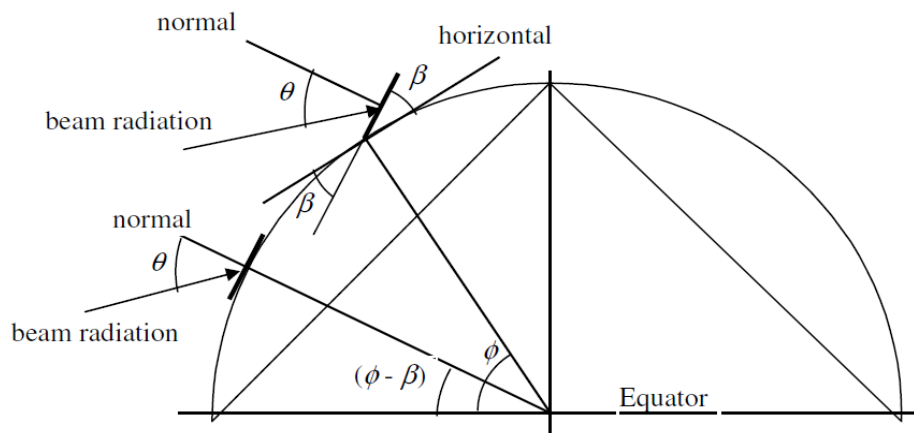

Figure 3.7: Condition of angles

$$\cos \theta = \sin \delta \sin \phi \cos \beta - \sin \delta \cos \phi \sin \beta \cos \gamma + \cos \delta \cos \phi \cos \beta \cos \omega$$
$$+ \cos \delta \sin \phi \sin \beta \cos \gamma \cos \omega + \cos \delta \sin \beta \sin \gamma \sin \omega \quad (3.2)$$

Malaysia is located 4° north from equator, thus solar collector is facing south. R_B is defined as geometric factor.

$$\cos \theta_z = \sin \delta \sin \phi + \cos \delta \cos \phi \cos \omega \quad (3.3)$$

$$\cos \theta = \cos(\phi - \theta_z) \cos \omega \quad (3.4)$$

$$R_b = \frac{\cos \theta}{\cos \theta_z} \quad (3.5)$$

3.3.3 Local Apparent Time (LAT)

LAT is stand for apparent solar time or sundial time, is the actual time for a particular place only, only a small degree of latitude or longitude will change the LAT. Thus every point of interest have its own LAT. LST stands for Local Standard Time, it used as standard time of different geographical region inside a country. It was a great advance for society to have similar reference of time within a country.

$$LAT = LST - 4(L_s - L_i) + E \quad (3.6)$$

Where $E = 9.87 \sin(2B) - 7.53 \cos(B) - 1.5 \sin(B)$

And $B = \dfrac{360 \times (n - 81)}{365.25}$

$\omega = 15 \times (LAT - 12)$

3.3.4 Absorbed Solar Radiation.

The evaluation of solar collector efficiency requires information on the solar energy absorbed by the collector absorber. Absorbed solar radiation is depends on total solar irradiance.

For a tilted surface, Total Solar Irradiance expresses as

$$I_T = I_b R_b + I_d \left(\frac{1 + \cos \beta}{2} \right) + I_g \rho_g \left(\frac{1 - \cos \beta}{2} \right) \quad (3.7)$$

$$I_g = I_b + I_d \tag{3.8}$$

$\left(\dfrac{1+\cos\beta}{2}\right)$ and $\left(\dfrac{1-\cos\beta}{2}\right)$ are the view factors from the collector to the sky and from the collector to the ground respectively. The subscripts b, d, and g represent beam, diffuse and ground respectively. The solar absorbed on a tilted collector is a product of transmittance, absorbance and total solar irradiance.

$$S = \tau \times \alpha \times I \tag{3.9}$$

3.3.5 Total Heat Losses

Modelling of flat plate collector includes both optical and thermal modelling. The solar energy absorbed by the absorber plate is distributed to useful heat and thermal loss. Thermal loss can be through the top, bottom and edges of the collector system. Figure 3.8 shows the principle of possible thermal losses of a typical flat plate collector. The common methods of heat losses are infrared radiation exchanges, convection heat loss and conduction through the insulations.

Infrared radiation exchange is the main heat loss of flat plate solar collectors, the exchange occurs between:

a. The cover and the sky

b. The cover and the ground

c. The absorber and the sky

Convective heat losses are due to the air in the cover, absorber gap and the ambient air. While conduction heat losses occur in the collector due to bottom, side and edges of the collector system. Above thermal losses can be represented as the product of heat transfer coefficient U_L times the difference between the mean absorber
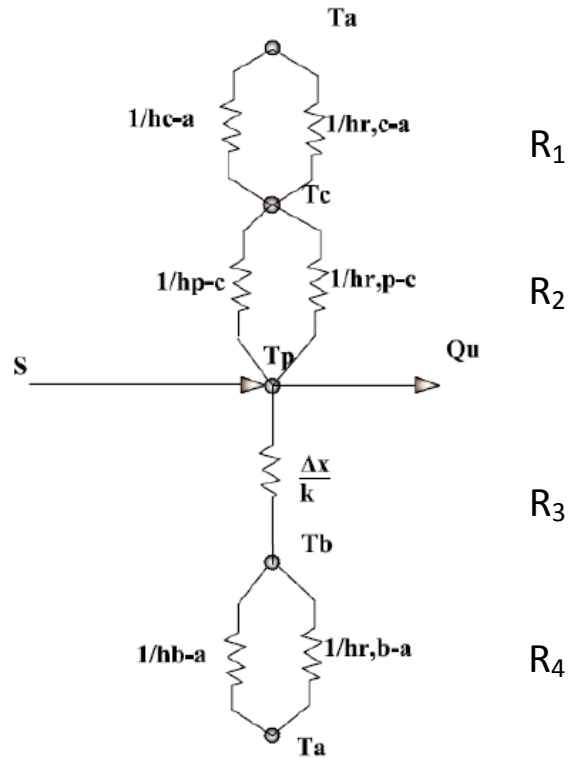
Figure 3.8: Thermal Network for a two cover flat plate collector: (a) in terms of conduction, convection and radiation resistances; b) in terms of resistances between plates (John A. Duffie, William A. Beckman, , 1980)

Figure 3.6 shows the location of heat losses. There are three major places of Heat

Loss occurs which at top, bottom and edge

1) Top Losses

$$U_t = \left(\frac{1}{h_{c,p-c} + h_{r,p-c}} + \frac{1}{h_w + h_{r,c-a}} \right)^{-1}$$

(3.10)

Heat coefficient between absorber plate and cover (radiation and convection)

$$h_{r,p-c} = \frac{\sigma(T_p + T_c)(T_p^2 + T_s^2)}{\dfrac{1}{\varepsilon_p} + \dfrac{1}{\varepsilon_c} - 1}$$

(3.11)

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To find $h_{r,p-c}$, the following steps has to be done

$$Ra = \frac{g\beta' \Delta T L^3}{v\alpha}$$

(3.12)

Parameters in equation 3.12 can be explained by:

v is kinematic viscosity equals to 1.88×10^{-5} m^2/s

α is thermal diffusivity equals to 2.69×10^{-5} m^2/s

$$\Delta T = T_{pm} - T_c \quad \text{and} \quad \beta = \frac{1}{T_{pm} + T_c - 273}$$

$$Nu = 1 + 1.44 \left[1 - \frac{1708(\sin 1.8\beta)^{1.6}}{Ra \cos \beta} \right] \left[1 - \frac{1708}{Ra \cos \beta} \right] + \left[(\frac{Ra \cos \beta}{5830})^{1/3} - 1 \right]$$

(3.13)

$$h_{c,p-c} = Nu \frac{k}{L}$$

(3.14)

Heat coefficient between cover and environment (radiation and wind convection)

$$h_{r,c-a} = \varepsilon_c \sigma (T_c - T_s)(T_c^2 + T_s^2)$$

(3.15)

Wind heat transfer coefficient can be explained by

$$h_w = 2.8 + (3 \times Windvelocity)$$

For the next reading, cover glass temperature are calculated using below equation

$$T_c = T_p - \frac{U_t(T_p - T_a)}{h_{c,p-c} + h_{r,p-c}}$$

(3.16)

2) Bottom Losses

The energy loss through the bottom of the collector is represented by two series resistor, R_3 and R_4 in figure 3.7. Where R_3 represents the resistance to heat flow

through the insulation and R$_4$ represent the convection and radiation resistance to the environment.

$$U_b = \frac{k_{ins}}{L}$$

(3.17)

Where k and L are the insulation thermal conductivity and thickness respectively.

3) Edge losses

Edge losses are estimated around the perimeter of collector system.

$$U_e = \left[\frac{(\frac{K_{ins}}{L_{edge}}) \times (2L_{thickness} \times width \times length)}{width \times length} \right]$$

(3.18)

Therefore, collector overall loss coefficient, U$_L$ is the total of the top, bottom and edge loss coefficients.

$$U_L = U_t + U_b + U_e$$

(3.19)

3.3.6 Collector Heat Removal Factor

Collector heat removal factor is determined as the actual useful energy gain of a collector to the useful gain if the whole collector surface were at the fluid inlet temperature. In equation form it is expressed as

$$F_R = F' \times F''$$

(3.20)

Collector efficiency factor, F'can be expressed as

$$F' = \frac{1/U_L}{W\left[\frac{1}{U_L[D+(W-D)F]} + \frac{1}{C_b} + \frac{1}{\pi D_i h_{fi}}\right]}$$

(3.21)

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Bond conductance, $C_b = 30 \text{ W/mC}$

The Function F is the standard fin efficiency for straight fins with rectangular profile

$$F = \frac{\tanh[m(W-D)/2]}{m(W-D)/2}$$

(3.22)

Collector flow factor, F''can be expressed as

$$F'' = \left[\frac{\dot{m}C_p}{A_c U_L F'}\left(1 - \exp(\frac{A_c U_L F'}{\dot{m}C_p})\right)\right]$$

(3.23)

3.3.7 Useful Energy Gain

Useful energy gain is an realistic energy gain value after considering possible loss occurs in the fluid entrance represents by the collector heat removal factor, F_R. The maximum possible useful energy gain in a solar collector occurs when the whole collector temperature is similar to the inlet fluid temperature, thus results heat losses to the surrounding became minimum. The collector heat removal factor times maximum possible energy gain is equal to the actual useful energy gain, Q_u.

$$Q_u = A_c \times F_R \times \left(S - U_L\left(T_{fi} - T_a\right)\right)$$

(3.24)

3.3.8 Fluid Outlet Temperature

Results for fluid outlet temperature is determined from energy balance equation as below

$$Q_u = \dot{m} \times C_p \times \left(T_{fo} - T_{fi}\right)$$

(3.25)

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3.3.9 Collector Efficiency

The efficiency of the flat plate solar collector can be calculated at an instantaneous time, thus all parameters are using value at instantaneous time. Thus, simulation program handle it with no time. The equation is expressed as

$$\eta = \frac{Q_u}{I_T \times A_c}$$

(3.26)

Where;

Q_u = Useful Heat Gain

I_T = Total solar radiation

A_c = Collector Area

3.4 Documentation of Results

The thesis was produced after all activities and simulation works are completed, the results are combined together and was documented in an orderly fashioned. The references and appendices at the back of thesis may help further understanding in this report.

3.5 Software used

Software	Functions/purposes
Microsoft Excel 2010	Used to plot a graph of efficiency and outlet temperature with time.
MATLAB	MATLAB is a programming environment for algorithm development, data analysis, visualization, and numerical computation. Used to develop solar system mathematical model and simulate mathematical mode with different parameter's values. To determine the effect of particular parameters on efficiency and outlet fluid temperature.

3.6 Project Milestones

Table 3.7: Timeline for FYP 1

No.	Details	Weeks							Mid-semester break							
		1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	Selection of Project Topic	▉	▉													
2	Preliminary Research Work		▉	▉	▉	▉										
3	Meeting and discussion with supervisor		▉	▉	▉	▉	▉	▉		▉	▉	▉	▉	▉	▉	▉
4	Preparation of Extended Proposal				▨	▉	▉									
5	Submission of Extended Proposal						▉									
6	Preparation of Proposal Defence						▉	▉		▉						
7	Proposal Defence									▨	▉					
8	Project Work Continues											▉	▉	▉		
9	Analysis on finalize journals												▉	▉		
10	Preparation for interim report												▨	▉	▉	
11	Submission of Interim Draft Report														▉	
12	Submission of Interim Report														▨	▨

▨ Scheduled task

▉ Completed task

Table 3.8: Timeline for FYP 2

No.	Details	Weeks							Mid-semester break							
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Project Work Continues	■	■	■	■	■	■	■								
2	Submission of Progress Report								▨	■						
3	Project Work Continues								■	■	■	■	■			
4	Pre-EDX											■				
5	Submission of Draft Report												■			
6	Submission of Dissertation (soft bound)													■		
7	Submission of Technical Paper													■		
8	Oral presentation														▨	
9	Submission of Project Dissertation (Hard bound)															▨

▨ Scheduled task

■ Completed task

CHAPTER 4

RESULTS & DISCUSSIONS

This chapter discuss the result of the mathematical model with computer simulation conducted using MATLAB from the Perak solar irradiance readings. Results are deduced in table and graph in orderly form. This chapter also provide explanation on the parameters change for evaluating its efficiency and fluid outlet temperature.

4.1 Simulation Results

The present parametric study is based on meteorological data for Ipoh, Perak [4°35', 101°05'] during the month of December 2010. Hourly solar radiation at particular date and constants parameters from figure 4.1 was considered in simulation. Table 4.1 shows the parameters that fixed and control in the simulation. Thermal efficiency and outlet temperature of liquid in flat plate solar collector are calculated and its value dependent on mass flow rate and collector area.
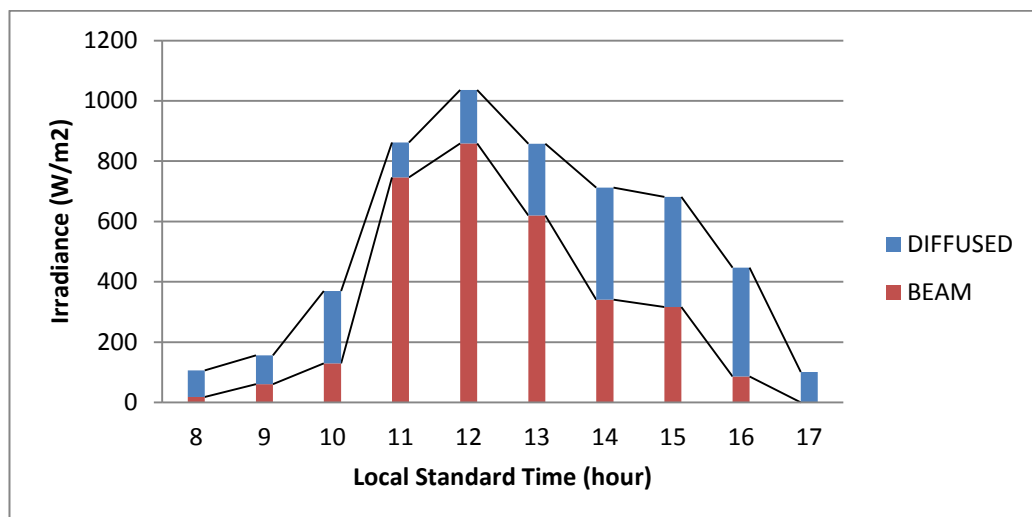

Figure 4.1: Hourly Solar Irradiance versus Local Standard time

Table 4.1: Parameters set to control for simulation 1

Parameters	Simulation 1			
Width (m)	1.5	1.5	1.5	1.5
Length (m)	2	2	2	2
Number of tube	10	10	10	10
Area of cover (m2)	3	3	3	3
Fluid mass flow rate in tube (kg/s)	0.015	0.03	0.045	0.06
Fluid total mass flow rate in tube (kg/s)	0.15	0.3	0.45	0.6

4.1.1 Parametric Analysis on mass flow rate

First simulation conducted using different value of mass flow rate (fluid flow rate; m_1 ,m_2 ,m_3,m_4) with constant collector area (A_c of $3.0m^2$) as shown in table 4.2, table 4.3, table 4.4 and table 4.5. Different flow rate affect the value of collector efficiency and fluid outlet temperature. However some of parameters keep unchanged and not affected due to the change of mass flow rate. Results of the simulation tabulated in table below.

Table 4.2: Standard results for initial efficiency and fluid outlet temperature of mass flow rate at 0.15 kg/s and collector area 3.0 m^2

CHANGE TOTAL MASS FLOW RATE, AREA CONSTANT 3m2			
M=0.015x10=0.15 kg/s			
AREA=1.5mx2m=3.0		N=10	
Local standard Time	efficiency	Tin	Tout
8	0.361	295	295.3
9	0.719	295.3	295.9
10	0.7487	295.9	297.3
11	0.71	297.3	300.8
12	0.6973	300.8	304.9
13	0.6876	304.9	308.1
14	0.6772	308.1	310.7
15	0.6575	310.7	313.1
16	0.6158	313.1	314.5
17	0.2811	314.5	314.6

Table 4.3: Results for efficiency and fluid outlet temperature of mass flow rate at 0.30 kg/s

CHANGE TOTAL MASS FLOW RATE, AREA CONSTANT 3m2			
M=0.03x10=0.3 kg/s			
AREA=1.5mx2m=3.0		N=10	
Local standard Time	efficiency	Tin	Tout
8	0.6084	295	295.2
9	0.7275	295.2	295.5
10	0.7587	295.5	296.2
11	0.7209	296.2	298
12	0.7133	298	300
13	0.7163	300	301.7
14	0.7238	301.7	303.1
15	0.7114	303.1	304.4
16	0.7115	304.4	305.2
17	0.6901	305.2	305.4

Table 4.4: Results for efficiency and fluid outlet temperature of mass flow rate at 0.45 kg/s

CHANGE TOTAL MASS FLOW RATE, AREA CONSTANT 3m2			
M=0.045x10=0.45 kg/s			
AREA=1.5mx2m=3.0		N=10	
Local standard Time	efficiency	Tin	Tout
8	0.6107	295	295.1
9	0.7303	295.1	295.3
10	0.762	295.3	295.8
11	0.7242	295.8	297
12	0.7187	297	298.4
13	0.7262	298.4	299.5
14	0.7399	299.5	300.4
15	0.7303	300.4	301.3
16	0.7452	301.3	301.9
17	0.142	301.9	302

Table 4.5: Results for efficiency and fluid outlet temperature of mass flow rate at 0.60 kg/s

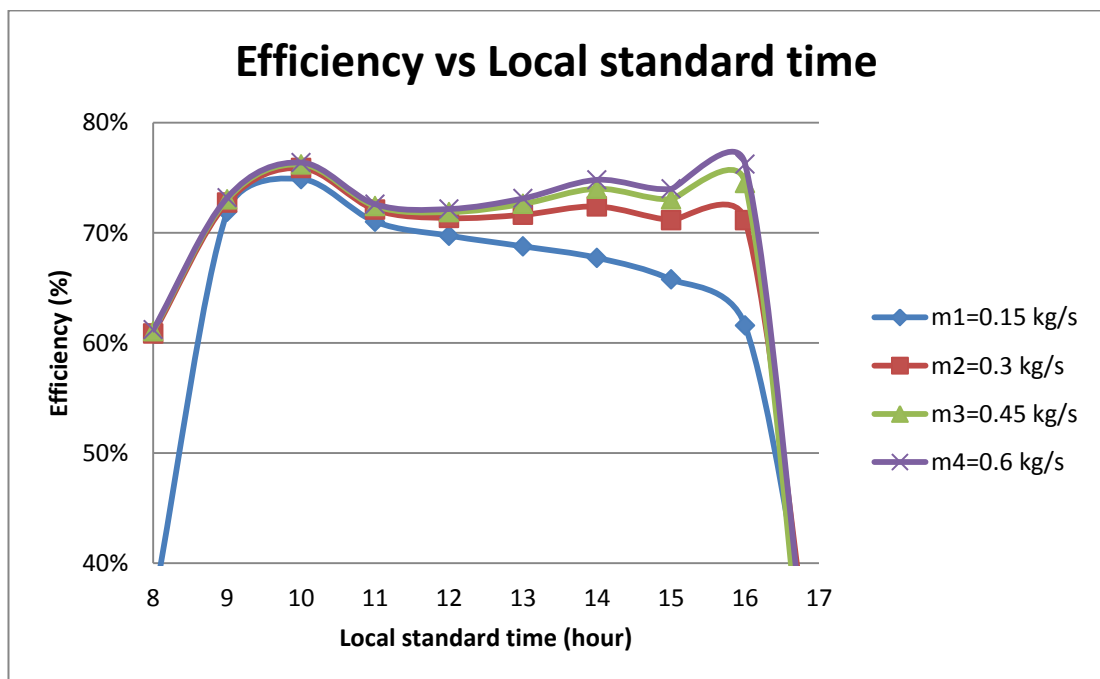| CHANGE TOTAL MASS FLOW RATE, AREA CONSTANT 3m2			
M=0.06x10=0.6 kg/s			
AREA=1.5mx2m=3.0		N=10	
Local standard Time	efficiency	Tin	Tout
8	0.6119	295	295.1
9	0.7318	295.1	295.2
10	0.7637	295.2	295.6
11	0.7259	295.6	296.5
12	0.7215	296.5	297.5
13	0.7311	297.5	298.4
14	0.748	298.4	299.1
15	0.7398	299.1	299.8
16	0.7624	299.8	300.2
17	0.1996	300.2	300.3

Figure 4.2: Efficiency versus local standard time of different mass flow rate

Figure 4.2 shows the result for the variation of water flow rate with efficiency. Collector efficiency increases with increasing in water flow rate due to absorption of heat energy with high velocity of flow rate and less radiation losses. Efficiency for

most of the fluid is above 70% from 9 a.m. until 4.00 p.m. It is seen that efficiency increases with increasing fluid mass flow rates. Fluid with highest mass flow rate of 0.6 kg/s experiences the highest efficiency along the time. This may be explained by the fact that the increase in fluid mass flow rate is followed by an increase in the convection heat transfer coefficient to the fluid, thus fluid useful heat gain increases and give better efficiency to collector While, fluid with lowest mass flow rate of 0.15 kg/s have lowest efficiency compared to the others.
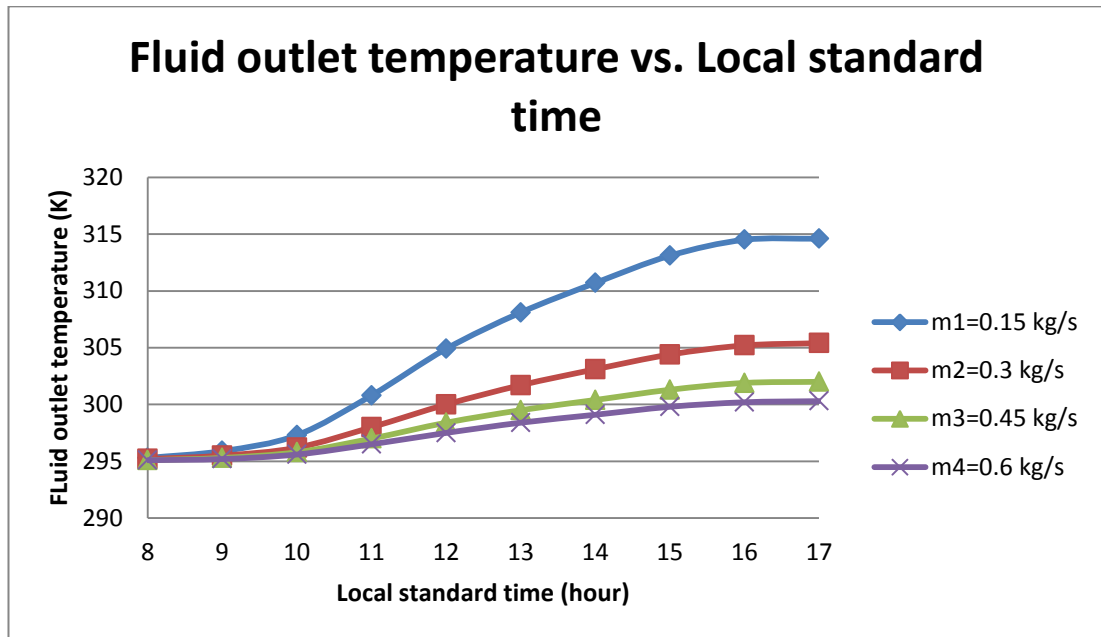

Figure 4.3: Fluid outlet temperature versus Local standard time of different mass flow rate

Figure 4.3 demonstrates the increment of fluid outlet temperature pattern over the time for different mass flow rates. It shows the fluid outlet temperature increases with time and increases with decreasing mass flow rate. This indicates that the low mass flow rate exhibits high fluid outlet temperature over time because mass flow rate is indirectly proportional to fluid outlet temperature. It gives more time for water to be heated up (uniform heat transfer) during slow movement of liquid through tube.

As the fluid mass flow rate through the collector increases, the temperature rise through the collector decreases. This wills results lower losses since the average collector temperature is lowered and there is corresponding increase in the useful energy gain.

4.1.2 Parametric Analysis on collector area

Second simulation conducted using different value of collector area (collector area; A_1, A_2, A_3, A_4) with constant collector area (M of 0.15 kg/s). Tabl3 4.7, 4.8 and 4.9 shows different collector area used in simulation and its affect the value of thermal efficiency and fluid outlet temperature. Variation of tube number may change to keep the value of mass flow rate constant. Table 4.6 shows 6 parameters that were set to control or fixed in simulation.

Table 4.6: Parameters set to control for simulation 2

Parameters	Simulation 2			
Width (m)	1.5	1.8	2.1	2.4
Length (m)	2	2	2	2
Number of tube	10	12	14	16
Area of cover (m2)	3	3.6	4.2	4.8
Fluid mass flow rate in tube (kg/s)	0.015	0.0125	0.01071	0.009375
Fluid total mass flow rate in tube (kg/s)	0.15	0.15	0.15	0.15

Table 4.7: Results for Efficiency and fluid outlet temperature of collector area of 3.6 m^2

CHANGE OF COVER AREA, MASS FLOW RATE CONSTANT 0.15 kg/s			
M=0.0125x12=0.15 kg/s			
AREA=1.8mx2m=3.6		N=12	
Local standard Time	efficiency	Tin	Tout
8	0.377	295	295.6
9	0.7106	295.6	296.3
10	0.7426	296.3	298
11	0.7065	298	302.1
12	0.6905	302.1	307
13	0.6757	307	310.8
14	0.6614	310.8	313.8
15	0.636	313.8	316.6
16	0.5781	316.6	318.1
17	0.1002	318.1	318.2

Table 4.8: Results for Efficiency and fluid outlet temperature of collector area of 4.2 m^2

CHANGE OF COVER AREA, MASS FLOW RATE CONSTANT 0.15 kg/s			
M=0.01071x12=0.15 kg/s			
AREA=2.1mx2m=4.2		N=14	
Local standard Time	efficiency	Tin	Tout
8	0.345	295	295.6
9	0.7106	295.6	296.3
10	0.7402	296.3	298.3
11	0.7033	298.3	303.1
12	0.6849	303.1	308.7
13	0.6653	308.7	313.1
14	0.6451	313.1	316.5
15	0.6167	316.5	319.7
16	0.5444	319.7	321.4
17	0.1023	321.4	321.3

Table 4.9: Results for Efficiency and fluid outlet temperature of collector area of 4.8 m^2

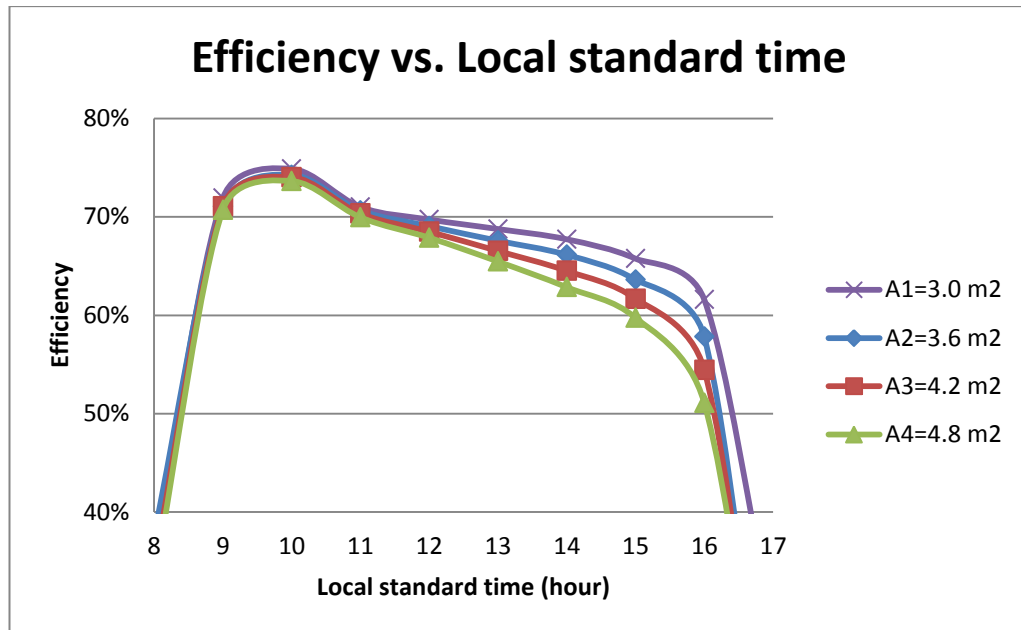| CHANGE OF COVER AREA, MASS FLOW RATE CONSTANT 0.15 kg/s			
M=0.009375x12=0.15 kg/s			
AREA=2.4mx2m=4.8		N=16	
Local standard Time	efficiency	Tin	Tout
8	0.331	295	295.6
9	0.7071	295.6	296.5
10	0.7363	296.5	298.8
11	0.6995	298.8	304.3
12	0.6788	304.3	310.6
13	0.6546	310.6	315.5
14	0.6285	315.5	319.3
15	0.5974	319.3	322.8
16	0.5108	322.8	324.6
17	0.1022	324.6	324.5

Figure 4.4: Variation of Efficiency versus local standard time of different collector area

Four different values of collector area may results from the increment of collector width. However, this condition also may affect number of tube, n where $n = \dfrac{collector\,width}{tube\,spacing}$. To make the fluid mass flow rate remain constant at 0.15 kg/s, the fluid mass flow rate per tube is control accordingly from table 4.5 until table 4.7. Fluid mass flow rate equals to the product of fluid mass flow rate on each tube and number of tubes. Figure 4.4 shows the efficiency increase with decreasing collector area. Fluid with smaller collector area (3.0 m^2) experiences the highest efficiency along the time. This may be explained by the fact that the ability of heat transfer in small area is greater than large area.
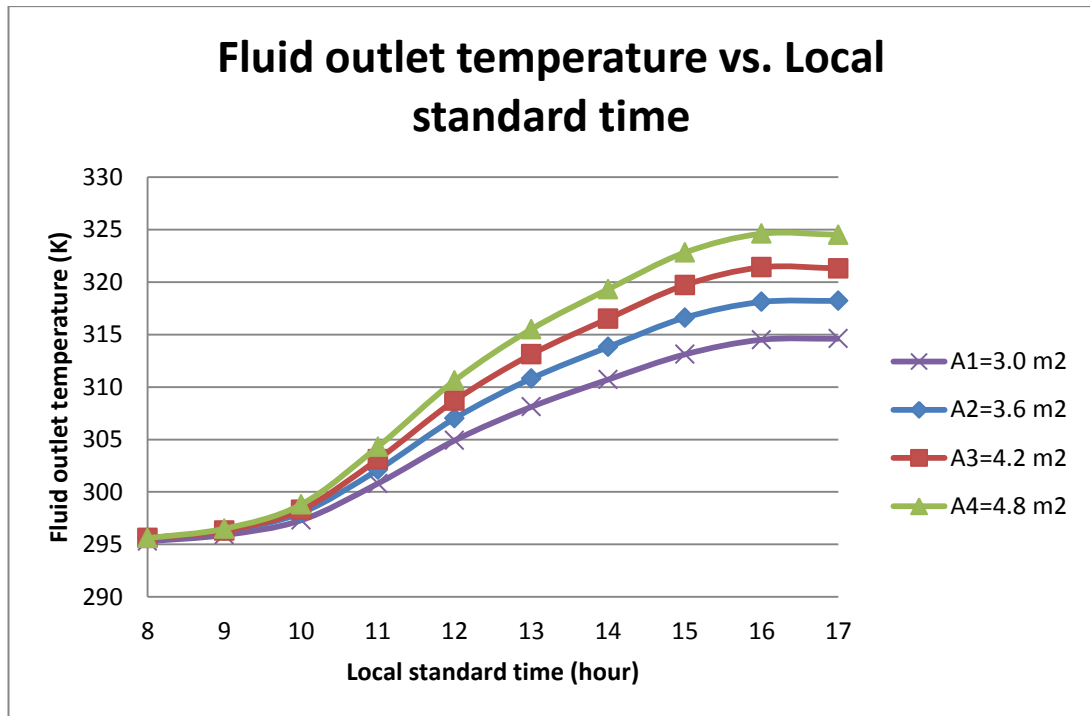
Figure 4.5: Variation of Fluid outlet temperature versus local standard time of different collector area

Figure 4.5 demonstrate the increment of fluid outlet temperature pattern over the time for different collector areas. It indicates that the fluid outlet temperature increase with time and increases with increasing collector area. The increment of fluid outlet temperature with collector area is because collector area is directly proportional to fluid outlet temperature. Water gets heated quickly in large collector area, where there is abundance of heat transfer available on the heat transfer process.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

A way to describe the thermal performance of flat plate solar collector has been distinguished via mathematical model with computer simulation developed in MATLAB environment. As expected, the efficiency of solar collector increases with increased fluid mass flow rate and decreases with increased in collector area. Fluid outlet temperature is the other way round where it increases with decreased fluid mass flow rate and increases with increased collector area. Increasing the fluid mass flow rate increases the efficiency, while increasing the collector area increases the fluid outlet temperature. Figure 5.1 and figure 5.2 interpreted the results for efficiency in better view.

Thus, the objectives to investigate effect of mass flow rate and collector area on efficiency and fluid outlet temperature are achieved. To have better efficiency, go for high mass flow rate and small collector area. While to have better fluid outlet temperature, low mass flow rate and large collector area are preferred.

5.2 Recommendations

Author's belief this simulation can be conducted with reliable source of data from the irradiance data from another date where no interruption from cloud and rain. A more precise and detailed analysis should include the fact, that the overall heat loss coefficient, U_L and other factors are not constant values. It is recommended for manufacturer to set a clear objective to get the system optimum at high efficiency or high temperature fluid outlet. To get high efficiency, it is recommended to design flat plate solar collector with large liquid mass flow rate or small collector area. While high liquid outlet temperature needs small liquid mass flow rate or large collector area. If the performance evaluation is conducted in future, design and dimension of solar collector should be included in control parameter as well. Other parameters like

cover and absorber material, ambient temperature, slope and weather are likely influence the solar collector performance. Since the suitable value for collector area and mass flow rate was determined, continuous simulation on other parameters is relevance to find the parameters value for top performance.

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APPENDICES

Sample calculations for collector Efficiency and fluid outlet temperature at conditions of 0.15 kg/s fluid mass flow rate and 3.0 m^2 collector area. Solar irradiance taken at 24/12/2010 15:00

$$\delta = 23.45\sin(360\frac{354+135}{365}) = 19.52°$$

$$B = \frac{360 \times (135-81)}{365.25} = 269$$

$$E = 9.87\sin(2 \times 269) - 7.53\cos(269) - 1.5\sin(269) = 1.976$$

Calculate value of LAT at 3.00pm

$$LAT = \frac{11(60) - 4(102\ -101\ ) + 1.976}{60} = 10.966$$

Hour angle, $\omega = 15 \times (10.966 - 12) = -15.5°$

Latitude= 4°35' = 4.58= ϕ

To get optimum result $\beta = \phi = 4.58$

$$\theta = \cos^{-1}[\cos(4.58-0)\cos(-15.5)] = 16.15°$$

$$\cos\theta_z = \sin 19.52° \sin 4.58 + \cos 19.52° \cos 4.58\cos(-15.5°) = 0.932$$

$$R_b = \frac{\cos\theta}{\cos\theta_z} = \frac{0.9605}{0.932} = 1.0306$$

Next, Useful heat gain was determined with given:

I_b=316.59 W/m^2 I_d=365.06 W/m^2 I_g=I_b+I_d=681.65W/m^2

$$Rd = \left(\frac{1+\cos 4°35'}{2}\right) = 0.9984$$

$$Rg = \left(\frac{1-\cos 4°35'}{2}\right) = 0.0016$$

$$I_T = 316.59 \times 1.0306 + 365.06 \times 0.9984 + 681.65 \times 0.0016 = 692\,\text{W/m}^2$$

$$S = 692 \times 0.88 \times 0.88 = 536 \text{ W/m}^2$$

$$U_L = U_t + U_b + U_e = 5.7072$$

$$F_R = F' \times F'' = 0.8755$$

$$Q_u = 3.0 \times 0.8755 \times (536 - 5.7072(297.3 - 295)) = 1373W$$

Exit water temperature was determined by using equation $Q_u = \dot{m} \times C_p \times (T_{fo} - T_{fi})$

$$1373 = 0.15 \times 4180 \times (T_{fo} - 297.3)$$
$$T_{fo} = 299.5K = 26.5°C$$

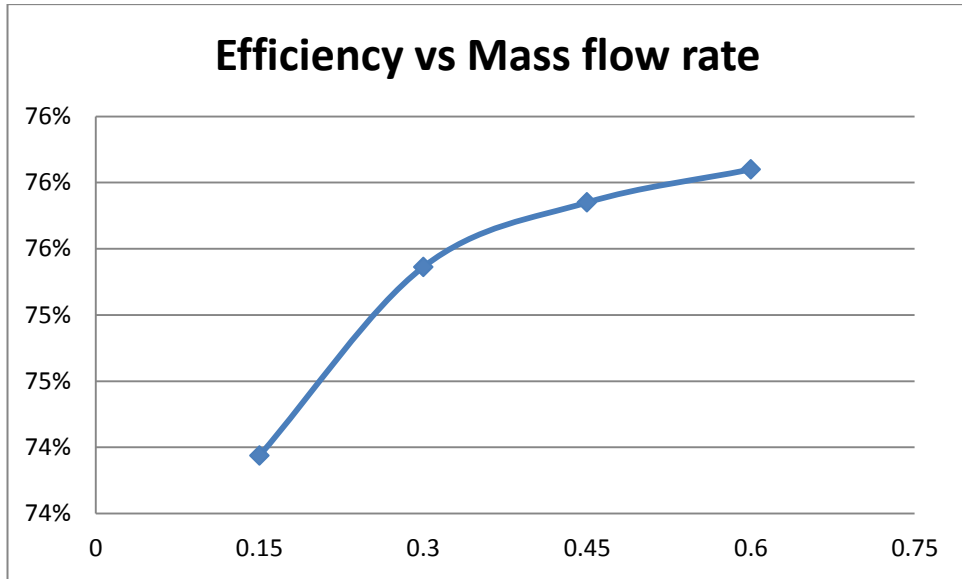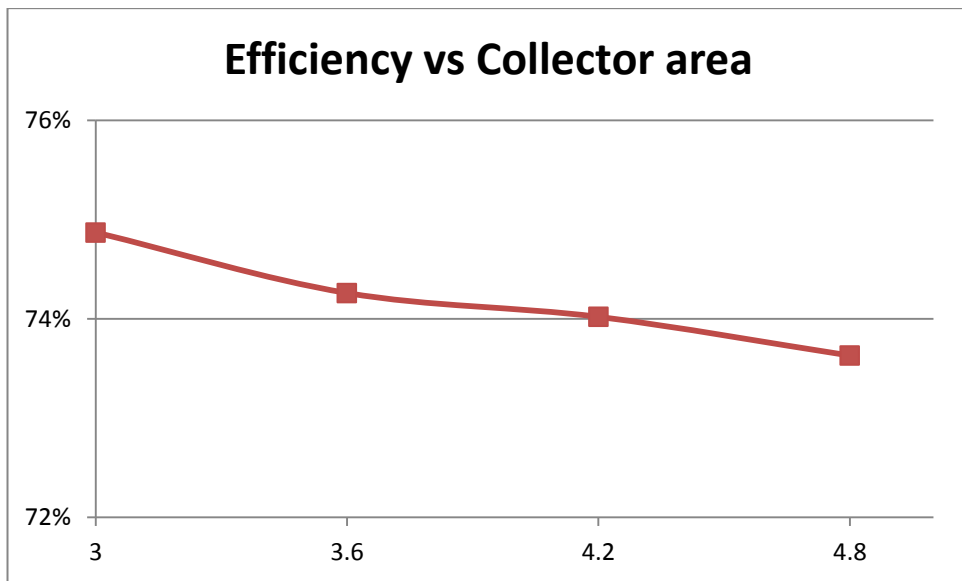$$\eta = \frac{1373}{692 \times 3.0} \times 100\% = 66.2\%$$

Figure 5.1: Efficiency against mass flow rate

Figure 5.2: Efficiency against collector area