DESIGN OF CENTRAL SOLAR TOWER RECEIVER

By

JARED SAMUEL S/O THANGGARAJ

FINAL PROJECT REPORT

Submitted to the Department of Mechanical Engineering
in Partial Fulfillment of the Requirements
for the Degree
Bachelor of Engineering (Hons)
(Mechanical Engineering)

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CERTIFICATION OF APPROVAL

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Approved:

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Dr. Syed Ihtsham Ul Haq Gilani

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK

June 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 or done by unspecified sources or persons.

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Jared Samuel s/o Thanggaraj

ABSTRACT

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Concentrated solar power plants are one of technologies that have been introduced for electricity generation with no usage of fossil fuels and without releasing greenhouse gases to the atmosphere. Concentrated solar plants convert the solar thermal energy from the sun for power production. However, this technology is still new and many advancements and modifications can be done on the concentrated solar tower power plants to make them more efficient and feasible. This project would solely base on designing the central receiver with materials that would have high rate of heat absorptivity and low rate of heat loss to the atmosphere. To achieve the objectives of this research, 3 main steps would be undertaken during this research project. The steps which were taken are mathematical study on the central receiver, simulation on TRNSYS and finally modeling the required design of the receiver. From the research carried out, the results obtained looks promising for this technology to be implemented in Malaysia because of the high amount of solar radiation (600W/m^2), the high surface temperature of the receiver (300°C – 350°C) and the high fluid outlet temperature of 350°C. Based on the findings, it can be said that the central receiver is one of the promising technology for electricity generation in Malaysia in the future.

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CHAPTER 1: INTRODUCTION

1.1 Project Background

Energy is one of the most essential fuel which runs mankind's daily life. Since the discovery of fossil fuels in the 19^{th} century such as coal, petroleum and natural gas, electricity is mainly produced by converting the heat energy from the fossil fuels into mechanical energy and finally into electricity to be used by people all over the world. However, since the depletion of oil reserves around the world many researches are done to harvest alternative energy source such as the solar energy, hydro power energy, biomass energy and tidal energy for electricity generation and concurrently reduce the high dependency on fossil fuels for power generation.

One of the natural sources to harvest the alternative energy is the sun. The solar energy has great potential because it has a maximum solar irradiation of $1000W/m^2$ on the earth's surface. Currently, the sun is used to produce electricity through solar photovoltaic (PV) and concentrated solar power plants. There are many types of concentrated solar power plants such as linear Fresnel collector, parabolic through plants, central receiver and solar tower receiver. In this project, only the solar tower receiver would be studied and designed for optimal heat storage.

The concentrated solar tower plant has many reflectors (heliostats) to reflect the collected sun light to a central receiver located at the center of the plant. The receiver of the plant acts as a heat exchanger to absorb the heat energy from the heliostat field and transfer the heat energy into heat transfer medium such as oil, water or molten salt. Then, this heat in the transfer fluid is exchanged with water in another heat exchanger to produce steam. The steam is then flowed into the steam turbine to create kinetic energy which turns the generator to produce electricity. According to Sandia National Laboratories, the advantages of using the concentrated solar tower plant are high temperatures can be easily achieved and this concept is highly flexible in terms of design. The engineers can select from many types of reflectors, receivers and transfer fluids while designing a concentrated solar tower plant with a central receiver.

For the Final Year Project, a study was carried out on the design of central receivers to develop a central receiver that could harvest the solar thermal energy more efficiently and lower the thermal storage capacity of the plant.

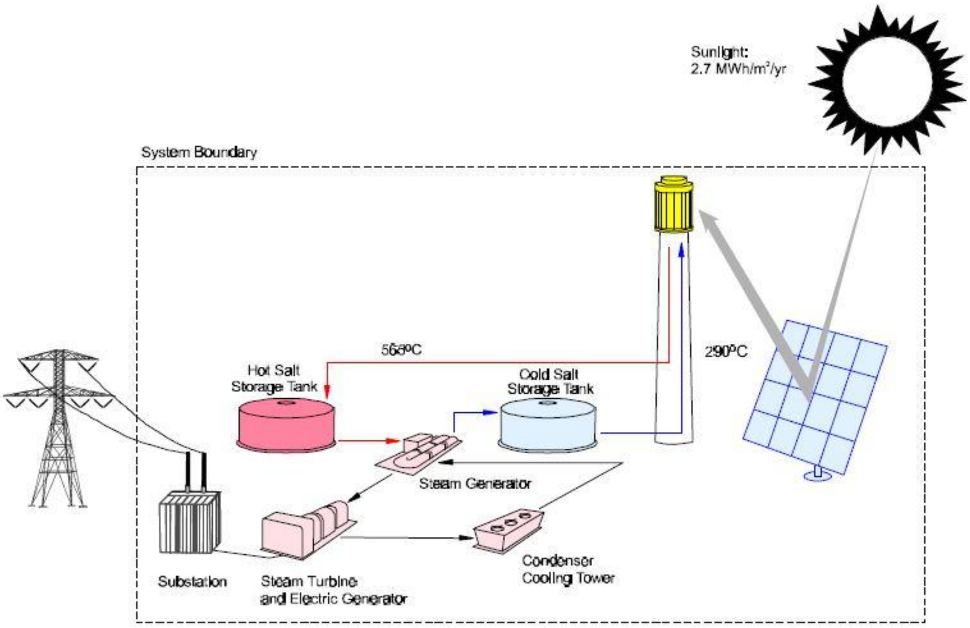


Figure 1.1: Solar TWO Concentrated Power Plant schematic diagram [4].

1.2 Problem Statement

The sun emits heat to the earth by solar radiation. In this research, the heat from the sun is reflected to a focal point; therefore the temperatures might reach a few hundred °C at this particular point. To store this heat we need an equipment with materials that is low heat resistance to absorb the heat from the sun efficiently. Besides that, it should also have a high heat resistance characteristic to avoid heat loss to the atmosphere. To design such a equipment with both the characteristics above would be the challenge in this project.

1.2.1 Problem Identification

In most cases, the solar tower receiver would be subjected to very high heat losses mainly due to heat convection and heat radiation from the receiver to the atmosphere. This loses are big, due to the huge temperature difference between the surface temperature of the receiver and the average temperature of the atmosphere. In addition to that, the heat loses would be even bigger if the receiver is subjected to wind as forced convection takes place. The main design problem that we would be facing here are on how to minimize the heat loses from convection and radiation.

Secondly, the external receiver would be subjected to very high temperatures and this would lead to thermal expansion of the materials especially the receiver pipes. The second problem in this project would be the rate of the thermal expansion of the pipes and the proper design to allow the pipes to expand without damaging the other parts of the receiver.

1.2.2 Significance of Project

In this project, a design of the solar tower receiver would be done in the CAD software. The design would be based on the mathematical study and the weather data in UTP. Then a real time simulation would be carried out in TRNSYS to verify the mathematical study With the data obtained, a prototype tower receiver would be designed with the suitable materials and a good heat transfer fluid.

The result of this study will be an evidence that solar receiver in the concentrated power plant can be used to generate electricity. At the end of this project, the feasibility of having a central solar tower receiver in Malaysia would be obtained from the results of this study.

1.3 Objectives

There are several objectives that need to be achieved when completing this project. The objectives are:

1) To carry out the mathematical study of the heat storage collector for a central collection and storage system
2) To run a real time simulation in TRNSYS with the external solar tower receiver to compare the results at different parameters. .
3) To design a prototype central solar tower receiver on the top of a model solar tower.

1.4 Scope of Study

The scope of work for this project is involves the heat transfer mechanism between the receiver, heat transfer fluid and water. It consist of mathematical study and literature review of radiation and convection heat transfer, properties of surface material, properties heat transfer fluid and water, size of the pipes, size of the field area and finally the receiver area.

Besides that, a study would also be conducted on methods to implement the solar receiver to efficiently generate steam. The main concern of this study would be on how to minimize the losses of the receiver and to efficiently harvest the heat from the focal point of the receiver to the heat transfer fluid.

Finally, the proposed model of the suitable solar tower receiver would be done with the suitable materials and fittings.

1.5 Relevancy and Feasibility of the Project

This project is relevant to the author's field of majoring since concentrated solar energy is one of the focuses in alternative energy. The project is also relevant with the recent technologies where many researches are currently carried out to harvest alternative energy and concurrently reduce the carbon footprint on earth. In this project, the author has applied heat transfer, fluid mechanics and solar energy theory to study the formulation heat transfer between surface of the receiver and the heat transfer fluid.

The project is feasible since it is within the scope and time frame. The author completed the research and literature review at the 7th week of the first semester while preparing the mathematical study and the preliminary design of the receiver after the mid-semester break. For the Final Year Project 2 which commenced in May 2012, the author dedicated the first three weeks of semester to run the real time simulation of the solar tower receiver plant in TRNSYS, the next five weeks for of finalizing the design of the heat exchanger on the solar tower receiver and the final four weeks of designing the structure of the tower receiver for the plant and finalizing the entire design of the tower receiver.

CHAPTER 2: LITERATURE REVIEW AND THEORY

The current trend of the energy demand in the world today largely depends on fossil fuels for power generation. The energy from fossil fuels is unsustainable economically, environmentally and socially [1]. To overcome this problem, many alternative energy researches and development are currently being carried out. One of the high potential alternative sources is the solar thermal energy. Solar thermal energy converts heat from the sun to heat water for domestic use. This technology can be further improved by heating water to steam by concentrating the sun's heat to a single focal point, to produce high pressure and high temperature steam to rotate the steam turbine blades for electricity generation. Many countries have already adapted to the solar thermal technology for domestic water heating. Cyprus has the widest implementation of the solar thermal energy with 92% of households and 53% of houses having solar flat plate collectors for internal water heating while Greece was the earliest country to adopt this solar thermal technology [2]. Nevertheless, there are only a few concentrated power plants around the world for electricity production and other industrial uses such as reverse osmosis for desalination

At the moment, the sun is the largest alternative energy source available and it is estimated to be available for another 4 billion years. The amount the energy that the sun produces is 10000 times more than the world energy demand [3]. So the potential of using the solar energy for power production is very high if the solar technology matures. With the current design and technology, a large concentrated solar power plant can produce up to 250 MW.

According to the Department of Energy United States the costs of producing electricity from small solar plants are quite high. It cost around, 12¢ per kilowatt-hour (kWh) of solar power. Nevertheless, with the increasing demand of this type of energy and building of bigger capacity concentrated solar power plants, the cost can be brought down to 8¢ per kWh. In addition to that, with the development of better central receivers, more efficient steam turbines and higher capacity of thermal storage, the cost of electricity production can be further reduced to 3¢ per kWh which is comparable to the cost of electricity production from a nuclear power plant.

2.1 Working Principles of Solar Tower Receiver

The working principles of a solar tower power plant are the usage of heliostats or reflectors around the field to reflect and concentrate the heat from the sun to the receiver (single focal point) on top of a tower. The reflectors function to direct the large energy from the plant field area and concentrate the large energy to a small space at the receiver and increase the surface temperature and air temperature around the receiver.

The heat from the outer side of the receiver is then transferred into the heat transfer fluid inside the thin walled pipes at the receiver. This is possible because according to the Thermodynamics second law, heat transfers from higher temperature to lower temperature. In the concentrated solar tower central receiver case, the surface temperature of the receiver is higher than the temperature of the heat transfer fluid inside the pipes. So the heat transfer would be from the receiver surface to the heat transfer fluid which enters the central receiver tubes at lower temperatures and exits the central receiver at much higher temperatures.

The heat energy from the heat transfer fluid is then transferred to a different working medium (water) in a heat recovery steam generator and the medium (water) is heated up to produce steam. The steam produced at a certain temperature and pressure is then flowed into the steam turbine to rotate the blades and then power up the plant generator to produce electricity.

The main advantage of the solar tower receiver is converting the solar energy by optical means to one central receiver unit as the energy input for energy production [4]. Besides that, the output from the receiver can also be used in the conventional steam turbine Rankine Cycle or the combined cycle to produce and supply electricity to the households. Thus, this technology can be adaptable to the systems in the conventional coal power plants.

2.2 Heat Transfer Medium

The heat transfer mediums that has been successfully tested and used in the Concentrated Solar tower power plant are water, air and molten salt [5]. The SOLAR ONE plant in United States uses water as the medium, whereas the SOLAR TWO plant uses two molten salt tanks as the heat transfer medium. In Spain, the Plataforma

Solar de Almería (PSA) plant uses atmospheric air has the heat transfer medium. It has the capability to heat up the air from 20 °C up 1000 °C during a clear sunny day.

There are many types of heat transfer fluid that are successfully tested and are currently used for concentrated solar power plants such as;

- Air

Air is a very safe heat transfer fluid and it will not freeze or boil and is non-corrosive. Nevertheless, it has a very low heat capacity, and tends to leak out of collectors, ducts, flanges and dampers.

- Water

Water has very high specific heat capacity and low viscosity which makes it easy to pump into the receiver. Besides that, water is also nontoxic and inexpensive. However, water has a relatively low boiling point and a high freezing point. So the heat transfer in water would be many phases and it would be difficult to handle. In addition, it can also be corrosive if the pH (acidity/alkalinity level) is not maintained at a neutral level and water with a high mineral content can cause mineral deposits/fouling to form in collector tubing and system plumbing.

- Hydrocarbon oils

Hydrocarbon oils have a higher viscosity and lower specific heat than water. They require more energy to pump. These oils are relatively inexpensive and have a low freezing point. The basic categories of hydrocarbon oils are synthetic hydrocarbons, paraffin hydrocarbons, and aromatic refined mineral oils. Synthetic hydrocarbons are relatively nontoxic and require little maintenance. Paraffin hydrocarbons have a wider temperature range between freezing and boiling points than water, but they are toxic and require a double-walled, closed-loop heat exchanger. Aromatic oils are the least viscous of the hydrocarbon oils.

- Molten Salt

Molten salt are good heat transfer fluids if the temperature at the receiver is very high and there is a need for a very high thermal storage. Examples of molten salt are the ternary salt consisting of 48% $Ca(NO_3)_2$, 7% $NaNO_3$, and 45% KNO_3 and the binary salt consisting of 60% $NaNO_3$ and 40% KNO_3 [6] . The advantages of using molten salt are it has high specific heat, low viscosity and can retain the heat in it for a long period of time. However, there are certain disadvantages such as high freezing temperature and it is a corrosive fluid on the receiver materials.

The heat transfer fluid in the concentrated solar power plant should attain certain properties to be able the plant to operate safely and or a good heat transfer rate between the receiver surface and the heat transfer fluid. The properties that the heat transfer fluid should have are:

- Stability at High Temperature
- High heat capacity
- Low Viscosity
- Non- Corrosive

Comparison of various heat transfer fluids are shown in Table 2.1 below

Table 2.1: Properties and working temperatures of various heat transfer fluids.[21]

Heat transfer Fluid	T [°C]		Properties
	Low	High	
Synthetic oil	13	395	high application temperature, flammable
Mineral oil	-10	300	inexpensive, flammable
Water	0	>500	high receiver pressure required
Silicon oil	-40	400	odorless, nontoxic, expensive, flammable
Nitrate salt	220	500	high freezing temperature, high thermal stability, corrosive
Ionic liquids	-75	416	good thermal properties, very costly
Air	-183	>500	low energy density

Nevertheless, in this final year project suitable synthetic oil would be proposed as a heat transfer medium which is capable of handling high temperatures at the receiver and does not deteriorate at high temperatures.

2.3 Receiver Material

The receiver material is one of the important considerations in this project. The receiver material should be able to withstand high temperatures impinging it during the peak time of solar radiation. In addition to that the material on the receiver should also have high heat transfer coefficient to transfer the heat to the working fluid inside the receiver tubes. The emissivity and the absorptivity of the material are also an important consideration for this project to avoid excessive heat loss and lower the efficiency of the plant. The material should have low emissivity value and high absorptivity value to enhance the heat transfer rate

Besides that, the choice of the materials would also be based on the design of the receiver. Basically there are two types of design, the first one is called volumetric receiver while the other is called tube receivers. The volumetric receiver is a porous type of receiver which is made of mesh wires and silicone ceramics (SiC)[7]. In the volumetric receiver, ceramic is used as the heat transfer material between air and the working fluid. Ceramic is used in the volumetric receiver because it is subjected to very high temperatures (1200 – 1500 °C) [8] in a concentrated solar tower plant.

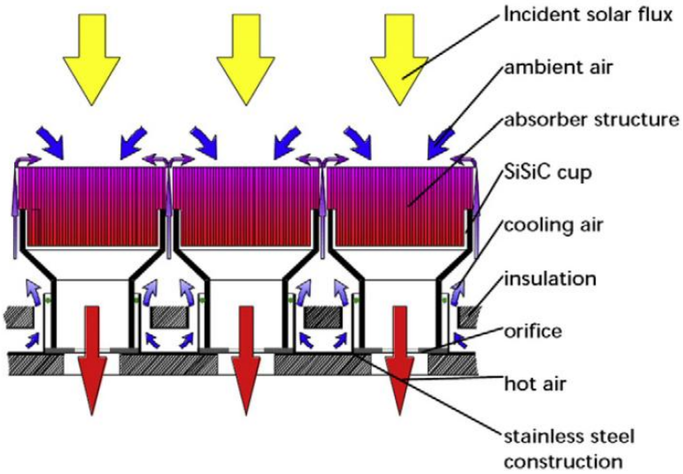


Figure 2.1: Sectional view of the volumetric receiver [11]

However in the tube receivers, metals such as steel alloys, aluminum alloys and coppers are used to transfer the heat to the working fluid. Tube receivers are used when the surface temperatures of the receiver are below 800°C. Nevertheless, research is still on going to find the best material that can be used on the solar receiver tower with lower thermal stress and high reliability. Besides that, another main consideration of the materials is the capability of the material to withstand thermal shock. Thermal shock on the receiver would be high when the solar radiation from the sun is blocked by the clouds in the sky for a short time. When the solar radiation does not reach the heliostats, the temperature at the receiver would drop very quickly and it will not be good for the receiver because of the quick heating and cooling effect.

Comparisons of various materials for the solar tower receiver are listed in table 2.2 below.

Table 2.2: Properties of potential materials for the solar tower central receiver[21]

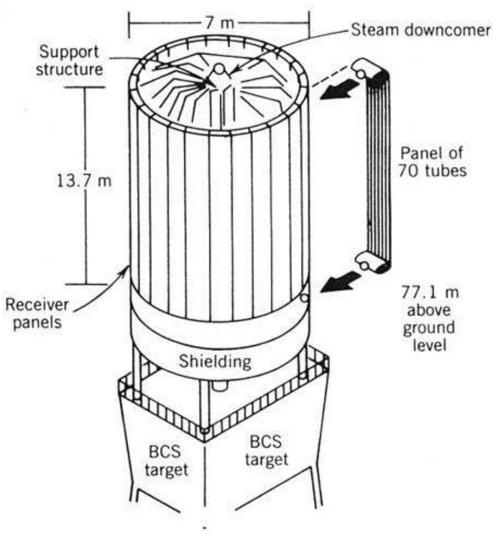
Material	Melting Point [K]	Solar Absorptance	Emittance Value
Aluminium 6061	933	0.37	0.04
Copper-Black oxidized in ebanol C	1358	0.91	0.16
Nickel (Tabor 110 - 30)	1662	0.05	0.85
Stainless Steel – AISI 410	1670	0.15	0.76
Zinc (Tabor 120-20)	693	0.14	0.89
Heated Chromium	1857	0.18	0.78

The choice of the materials for the final year project would be based on the surface temperature of the receiver, the availability of the required shape of the material (tubes, pipes, etc) based on the design, the cost of the materials and the properties (absorptivity, reflectivity and emissivity) of the materials and finally the capability of the material to withstand thermal shock.

2.4 Design of Central Receiver

For the central receiver, its design should be based on maximizing heat transfer from the surface of the receiver to the transfer fluid. So, for a high heat transfer rate the overall surface area of the receiver has to be big [9]. Besides that, the design of the solar receiver should have heat transfer pipes at same interval distance throughout the receiver section and its arrangement should be parallel to the heliostats [10]. The backside of the receiver should also be properly insulated to prevent heat loss to the atmosphere as well as increase the cycle efficiency.

In theory there are two types of solar receivers. The first is the external receiver which was used in the Solar One Power Plant and the second type of receiver is the cavity receiver. Both this receivers are basically heat exchangers to transfer the heat from concentrated heat flux into the working fluid inside the pipes of the receivers. The external receiver consists of many small downcomer panels which run along the receiver. In the panel there are 70 tubes in each panel to increase the surface area of heat transfer and have a higher heat transfer rate to the working fluid inside the tube. The main problem with this design is the excessive heat loss due to convection and reflection to the atmosphere.



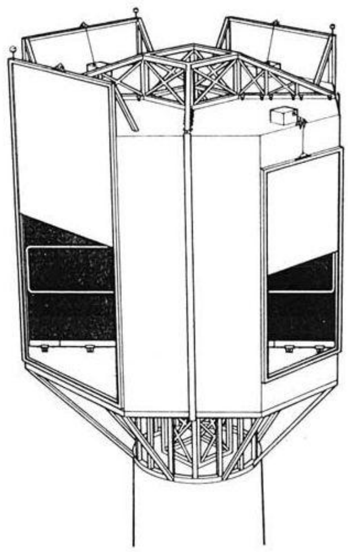


Figure 2.2: External and Cavity Central Receiver [22]

The cavity receiver was designed to counter the excessive heat loss of the external receiver. The design of the solar cavity receiver usually has only aperture or openings around it for the concentrated sunlight from the reflector field to pass across the aperture and project on the surfaces inside the cavity receiver [11]. The surface of the cavity receiver consists of many tubes to with heat transfer fluid to extract heat from the heat flux. The main advantage of the cavity receiver is excessive heat loss is prevented because the tube section of this receiver is inside the aperture and it protected from the direct wind of the atmosphere.

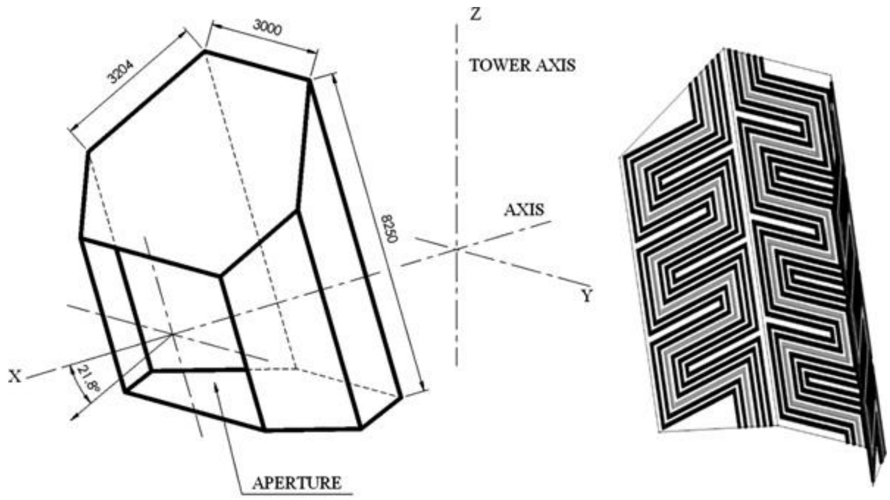


Figure 2.3: Tube layout in a cavity receiver [11]

In these final year project, the preliminary design that would proposed for the central receiver would consist of a flat receiver, with copper tubes running through the receiver, to efficiently harvest the solar thermal energy from the heliostats. In addition to that, the backside of the receiver should also be properly insulated with Aerogel insulation (lower heat conduction coefficient than ceramics) [12] to prevent heat loss to the atmosphere as well as increase the cycle efficiency. In summary, the receiver must be designed to intercept, absorb and transport the highest amount of heat flux to the working fluid inside the tubes with minimum losses.

2.5 Solar coatings

With the increasing of the man operating temperature of the receiver, it is required to have a proper solar coating on the receiver pipes. The solar coatings function to increase the solar absorptance rate of the receiver as well as lower the thermal emittance of the receiver pipes. The absorption efficiency of the receiver depends mainly on the type of coating on the receiver pipe. A receiver tube with Pyromark coating has only around 0.35 of heat absorption efficiency while a receiver with the Co-Cd-BT coating has significant increase of its heat absorption efficiency which is around 0.64.[23] However for this project, a better coating has to be selected for better heat absorption efficiency.

By installing a coated pipe the overall efficiency of the plant will also increase due to the higher heat absorption rate and the lower heat loss rate due to radiation and convection. There are many types of coating which are available in the market, for this final year project the author would suggest to use the black-chrome deposition with high absorptance (α=0,93) and quite-low emissivity (ε=0,17)

2.6 Mass Flow Rate

The mass flow rate of the heat transfer fluid inside the receiver to transfer the the heat from the surface of the receiver is controlled by the pump the receiver. The function of the pump is to control the speed of the fluid flow inside the receiver at a certain point of time to efficiently harvest the heat from the surface of the receiver. The higher the speed of the fluid flow inside the pipe, the higher the heat absorption rate of the receiver. However, the wall temperature drops linearly with the increase of the fluid flow speed. [24].

To calculate the mass flow rate of the heat transfer fluid the energy balance equation is used.

$$Q = m.Cp.(T_s - T_f)$$ where:

Q = Rate of thermal energy emission, W

m = mass flow rate

Cp = Constant Specific of Fluid

T_s = Fluid Outlet Temperature, K

T_f = Fluid Inlet Temperature, K

2.7 Pumps

Pumps are equipments which are used to transfers fluids from one point to another by using mechanical power which is either driven by electric motor or coupling system. In this final year project a pump is need to circulate the heat transfer fluid around the receiver tubes at different flow rates. The circulation of the fluid is used to heat up the heat transfer fluid to a required temperature and generate steam later on. There are many pumps which are available in the market. Below is the comparison of the pumps available.

Table 2.3: Pump types for the solar tower central receiver [25]

Pump Type	**Applications**	**Recommended fluid**
End Suction Pump	Any transfer or circulation of liquid. Handles clean or dirty liquids and liquids with low viscosity.	Water and relatively low viscosity liquids
Axial low Pump	Flood dewatering, power plant circulating water pump, evaporator services, and irrigation.	Water and relatively low viscosity liquids
Gear Pump	Common pump for clean oils and other viscous liquids.	Oils and viscous fluid
Booster Pump	Potable water distribution, irrigation booster, cooling water booster, process booster service	Water and relatively low viscosity liquids
Screw Pump	Fuel transfer, elevators, and other applications requiring relatively high flow rates of viscous liquids.	Oils and viscous fluid
Diaphragm Pumps	Many applications in general plant service where the liquid being pumped has high solids content or high viscosity	Oils and viscous fluid. Fluid with a mixture of solid particles

Based on the pumps above, for this project the most suitable pump would be the screw pump because the pump has to pump high flow rates of synthetic oil.

2.8 Design Calculation and Heat Loss

The total energy flow and losses of the solar tower receiver is estimated by using the Stefan Boltzmann law and Newton Cooling Law. [13]

General Assumptions:

1) Calculations are done estimating the receiver's surface is completely flat.
2) The properties of Copper-Black oxidized in ebanol C is used in the calculations
3) Reflector is assumed to have a size of 2m x 1m.
4) Total reflectors used are 60 units.
5) Reflector Field Efficiency is fixed at 70 %

The temperature of the receiver surface is estimated using the equation obtained from the radiation simulation and thermal control experiment done by NASA. The equation obtained relates emissivity and absorptivity of the material to estimate the surface temperature of a material.[14] This calculation is done to estimate the surface temperature of the receiver walls.

The equation obtained is:

$$A_r\, s\, \alpha = A\, \sigma\, \varepsilon\, (T_s^4 - T_a^4)$$

where Ar = Receiver Area

s = Solar Radiation Constant

α = Absorpvity value of the material

A = Total Area Emitting Radiation

σ = Stefan Boltzmann constant

ε = Emissivity Value of the material

T_s = Surface Temperature

T_a = Ambient Temperature

2.8.1 Analysis of plant field and receiver

The arrangements of the heliostats in the field are put apart from each other to avoid the shadow of the heliostats from blocking the reflection of the heat flux to the receiver on the tower.[15] So only a fraction of ground area (φ) is covered on the field.

To calculate the fraction ground area φ

$$\varphi = \frac{NAm}{Ag}$$

where

N = Number of heliostats

Am = Area of each mirror (m^2)

Ag = Total ground area used around the tower (m^2)

The ground area around the tower is obtained from the following equation

$$Ag = \frac{4H^2}{tan^2} \times \frac{1}{\theta_r}$$

where

H = height of the tower (m)

θ_r = rim half angle between receiver and heliostat field

The total energy reflected by the heliostat field to the receiver is estimated by;

$$Qa = I \times Ag \times \varphi \times \rho \times \eta \times \alpha$$

Where

Qa = Total energy reflected

I = Solar Incident Radiation

Ag = Total Field ground area

φ = Fraction of ground area

ρ = Mirror utilization factor

η = fraction of solar reflection received by the receiver

α = Absorptance value of receiver

2.8.2 Heat Losses from Solar Tower Central Receiver

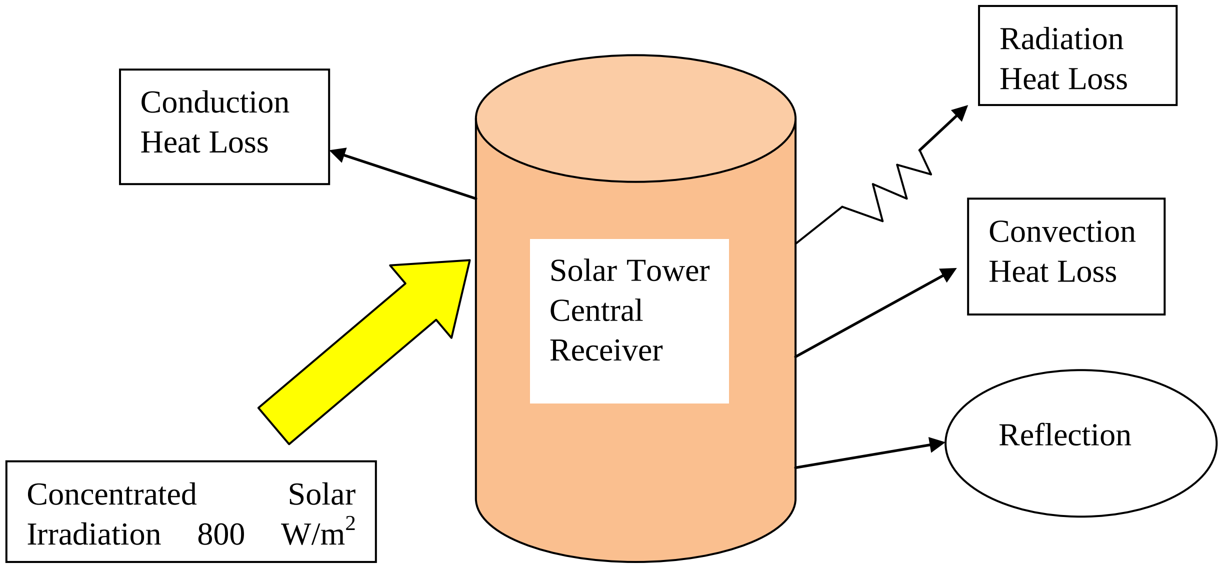


Figure 2.4: Energy flow in a Solar Tower Central Receiver

In this project, the heat loss from the receiver is analyzed because it directly affects the efficiency the receiver to transfer the concentrated heat from the solar irradiation to the working fluid. The types of heat losses which are subjected to the receiver are conduction heat loss, natural convection and forced convection heat loss, radiation heat loss and reflection heat loss. However, for simplification purpose the calculations for conduction heat losses are neglected due to very minimal heat losses compared to the other types of heat losses. Convection heat loss, radiation heat loss and reflection heat loss are taken into consideration.

2.8.2.1 Convection Heat Loss

The convection heat losses on the solar tower central receiver are divided to two main losses which are natural convection losses and forced convection losses. Natural convection on the receiver is very difficult to estimate due to the difference of many factors such as wind speed, wind density, geometry shape of the receiver and wind temperature around the receiver. [16]

The heat loss through convection is calculated using the equation below

$$Q_{con} = h_{combined} .A. (T_s - T_a)$$

Where

Q_{con} = Rate of thermal energy loss by convection, W

$h_{combined}$ = Combined heat transfer coefficient

A = Surface area, m^2

T_s = Surface Temperature, K

T_a = Ambient Temperature, K

2.8.2.2. Radiation Heat Loss

The radiation heat loss from the receiver is estimated by using the Stefan Boltzmann law. There would be radiation heat loss from the receiver due to the difference in temperature of the receiver and unlike conduction and convection, radiation heat transfer does not require a medium for transmission as energy transfer occurs due to the propagation of electromagnetic waves.

In this project the heat loss by radiation is estimated by using the equation below

$$Q_{rad} = h_r . A . (T_s - T_{sky})$$

where

Q_{rad} = Rate of thermal energy emission, W

h_r = Radiation coefficient $W/m^2.K$

ε = Emissivity of the surface

σ = Stefan-Boltzmann's constant, 5.669 X 10^{-8} $W/m^2.K^4$

A = Surface area, m^2

T_s = Surface Temperature, K

T_{sky} = Sky Temperature, K

T_a = Ambient Temperature, K

$$h_r = \frac{\sigma\varepsilon\ (Ts+Tsky)(Ts^2 - Tsky^2)(Ts - Tsky)}{(Ts - Ta)}$$

$$T_{sky} = 0.0553(T_a)^{1.5}$$

Useful Energy to the receiver is obtained by:

$$Q_{useful} = Q_a - Q_{radiation} - Q_{convection}$$

CHAPTER 3: METHODOLOGY

3.1 Research Methodology

The methodologies implemented to incorporate the solar tower receiver into the concentrated solar tower power plant (CSP) are:

1. Obtain weather data from previous experiments in Ipoh.
2. Maximum Power Calculation of the solar field.
3. Calculate Energy to the Central Tower from the reflectors.
4. Research and Selection of Suitable Materials.
5. Research on the required Design of the Central Receiver.
6. Design to solve the thermal stress and thermal expansion problems.
7. Research on the Structural design of the central receiver tower.

3.2 Project Flow Chart

The project execution flow chart has been drafted to show the procedures and steps to be taken throughout the project research period. This flow chart however only covers the current objectives of the research.

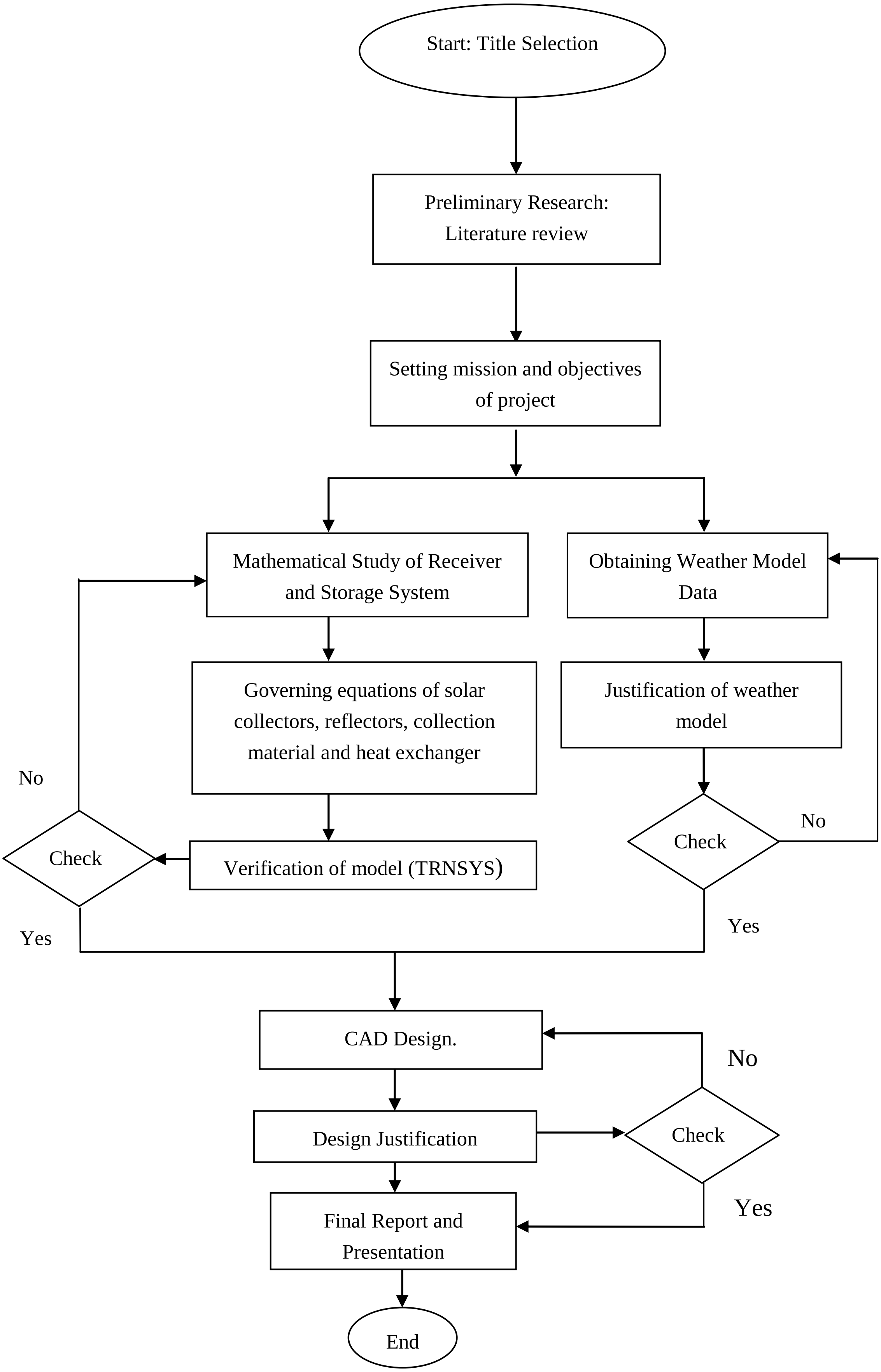


Figure 3.1: Project Flow Chart and Research Methodology

3.3 Project Activity

The concentrated solar central tower plant has a central receiver which would be designed and analyzed in this final year project There are 3 stages planned to be conducted which are:

- **Stage 1:** Preliminary Study and research on heat loss based on Weather data in Ipoh
- **Stage 2 :** Simulation on TRNSYS to obtain data and validation of data from stage 1
- **Stage 3:** Design of prototype solar tower receiver.

The project activities flow is shown in Table 3 below.

Table 3.1 Research Methodology and project activities for the research project

Activities	Description
Research and Review Literatures	- Building the research base - Extract relevant parameters and design - Research on receiver materials and Heat transfer fluid
Ipoh weather data	- Obtained from the Ipoh Meteorological Weather Department, Ipoh, Perak through the author's supervisor - Analyze weather data.
Mathematical Study	- Calculations done to estimate the reflected energy to the receiver from the Heliostats. - Heat losses from the receiver are calculated based on certain simplifications - Estimation for net energy absorbed by the receiver
Simulation on TRNSYS	- Simulation done with heliostats, central receiver, thermal storage system to obtain transient response of the system - Simulation done to verify the data obtained from the mathematical study
Preliminary Design	- Preliminary Design done to verify and obtain the optimum shape of the receiver
Design Finalization	- Materials and geometry of the receiver are finalized based on the accessibility and shape of the raw materials in the market
Report Writing	- Compilation of all works into a final report

3.4 Tools and Software

For the completion of this research project there are many software that should be utilized to assist the author. Below are the Software required.

Software

- Autodesk Inventor
- TRNSYS
- Microsoft Office Word
- Microsoft Office Excel

3.5 Gantt chart for Final Year Project 1

No	Detail / Week	1	2	3	4	5	6	7	Mid Semester Break	8	9	10	11	12	13	14
1	Selection of Project Topic															
2	Preliminary research work															
3	Submission of Extended Proposal															
4	Proposal Defense															
5	Mathematical Study on Heat Losses and Energy balance															
6	Preliminary Design															
7	Submission of Interim Draft Report															
8	Submission of Interim Report															

Processes

Milestone

Figure 3.2: Gantt chart for the first semester project implementation

3.6 Gantt chart for Final Year Project 2

No	**Detail / Week**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**Mid Semester Break**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
1	Preliminary Research on TRNSYS	■	■													
2	TRNSYS Simulation with the KL weather		■	■	■	■										
3	Preliminary Design Work						■	■		■						
4	Submission of Progress Report									■	★					
5	Simulation Finalization											■	■	■		
6	Design Finalization											■	■	■		
7	Poster Presentation														■	
8	Submission of Final Report/Viva															★

■ Processes

★ Milestone

Figure 3.3: Gantt chart for the second semester project implementation

CHAPTER 4: RESULT AND DISCUSSION

4.1 Results

Results obtained from mathematical study which are stated in Chapter 2 are based on the weather data from the Ipoh Meteorological Department. From the weather data, the important parameters which are used for the calculations are solar irradiation values and wind speed and the time. From the weather data the surface temperature of the receiver is obtained based on assumptions and certain constants.

The assumptions which were made are for the calculations are:

- Calculations are done estimating the receiver's surface is completely flat and having a surface area of 1.2 m^2
- The properties of Copper-Black oxidized in ebanol C are used in the calculations.
- Reflector is assumed to have a size of 2m x 1m.
- Total reflectors used are 60 units.
- Reflector Field Efficiency is fixed at 70 %
- Heat losses from the receiver is only through convection, radiation and reflection
- Conduction heat losses are neglected

Once the surface temperature of the receiver is estimated, the materials for the receiver are determined based on the maximum temperature obtained from the calculations. Based on the calculation, the maximum temperature at the receiver is around 300 ° C. Thus, for the preliminary design the materials that are used are Aluminium alloy, Steel pipes and Copper pipes. The materials chosen are based on the melting temperature of the metals and the heat capacity of the designated materials.

After obtaining the maximum surface temperature of the receiver, the energy that is reflected to the receiver from the heliostat field is calculated. The energy that is reflected to the receiver is obtained by the total field area of the reflector field, the total number of reflectors, the area of 1 reflector and the field efficiency of the plant

The Newton Cooling Law is applied to estimate the convection heat loss of the central receiver. For the convection heat loss, the Rayleigh number and Nusslet number are obtained based on the properties of air at 500K because the average air temperature around receiver is estimated to be around 500K. For radiation heat loss from the receiver, the Stefan Boltzmann Law is applied to estimate the radiation heat loss at various different solar radiation values.

Finally, by applying the energy balance equation where the useful energy which would be calculated after subtracting the convection and radiation heat loss from the total energy reflected to the receiver from the heliostat field.

4.2 Spreadsheet Calculations

The graphs that are obtained below are based on the steps discussed in the result section and in Chapter 2: Literature Review and Theory.

Solar Radiation vs Time graph

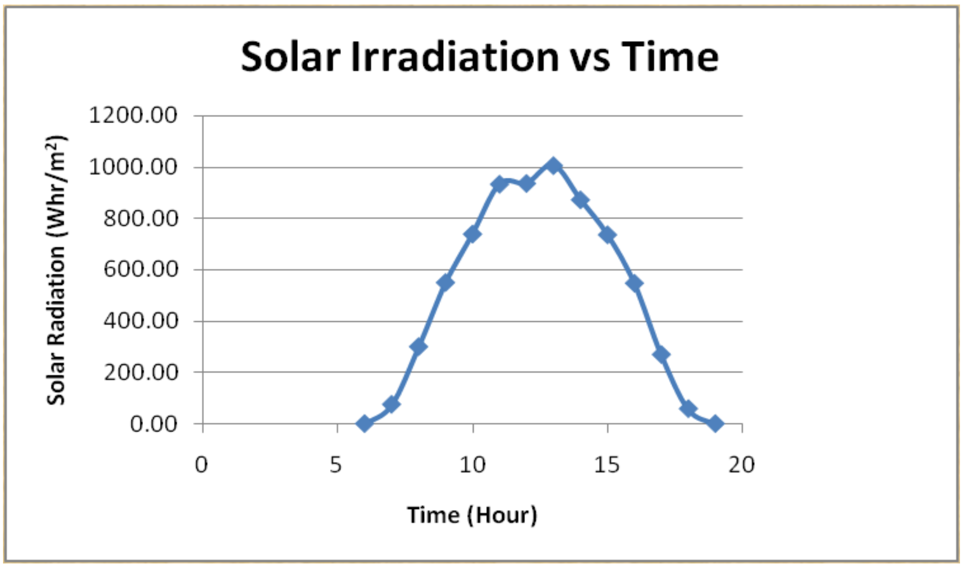


Figure 4.1 Solar Radiation vs Time on a bright sunny day

The graph above is based on the solar radiation data versus time. The graph above is analyzed and based on the analysis; the highest solar radiation value is 1010W/m^2 which happens during the afternoon (around 1pm). The pattern of the graph is like a bell curve where the solar radiation from the sun gradually increases from the morning (7am) to the afternoon (1pm) before decreasing again to the zero in the evening (around 8pm). The graph above shows the radiation value for a good sunny day without much cloud formations in the sky to block the sunlight to the earth's surface

Surface Temperature vs Solar Radiation

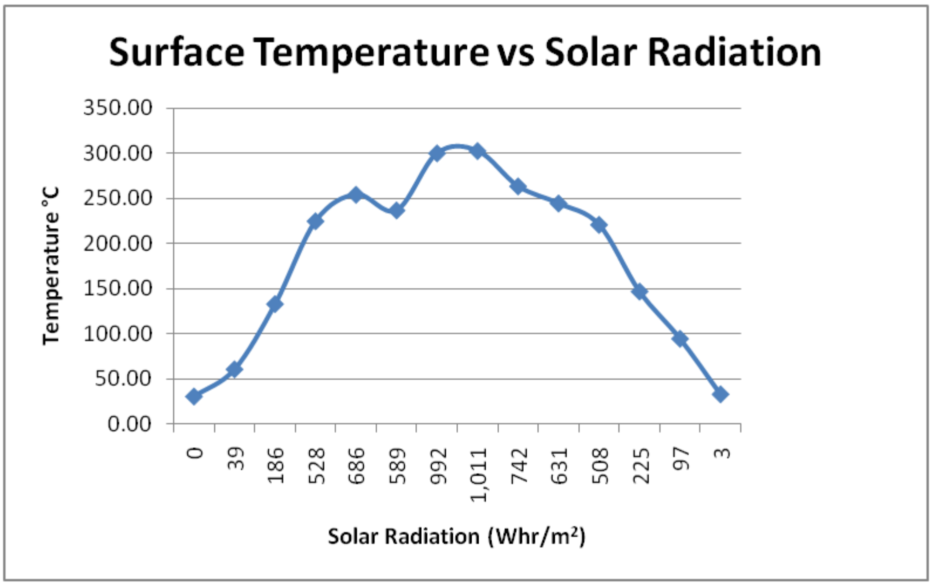


Figure 4.2: Surface temperature vs Solar Radiation of the receiver on a bright sunny day

The 2nd graph is based on the surface temperature of the central receiver versus the solar radiation readings. From the graph, it can be seen that the higher the solar radiation readings, the higher the surface temperature of the central receiver. The highest point in the graph is during the afternoon where the solar radiation is around 1011 W/m^2 and the temperature obtained is around 300 °C at the surface of the central receiver. Besides that, it can also be discussed that the best possible time for the concentrated power plant to operate is during the day time when the solar radiations on the heliostat field are high. The central receiver can only operate during the nighttime if there is a heat storage system in the power plant to run the steam turbines.

Convection Heat Loss vs Solar Radiation graph

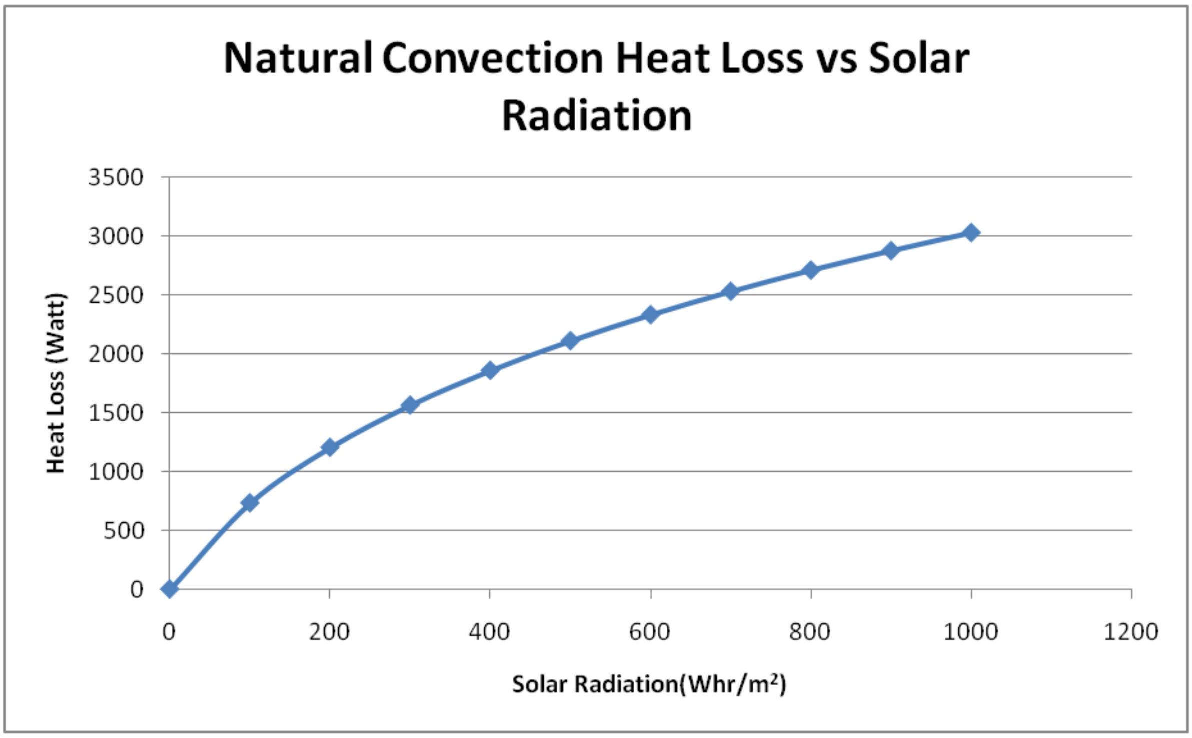


Figure 4.3 Convection heat losses vs solar radiation from the receiver to the atmosphere

Figure 4.3 shows the relationship between the natural convective heat losses and the solar radiation. From the graph line we can clearly observe that the natural convective heat loss from the receiver is higher when the solar radiation from the sun is higher. The graph line also gives a linear relationship between the convective heat loss and solar radiation values from the 1500W and 300 W/m^2 point. Besides that, by comparing the graph above and the graph from Figure 4.2 it can be explained that the convective heat loss on the receiver is usually higher during the afternoon and lower during the morning and evening. The convective heat loss is higher during the afternoon because of the bigger difference in temperature between the receiver and atmosphere compared to the temperature difference during the morning and evening.

Combined Convection Heat Loss vs Wind Speed graph

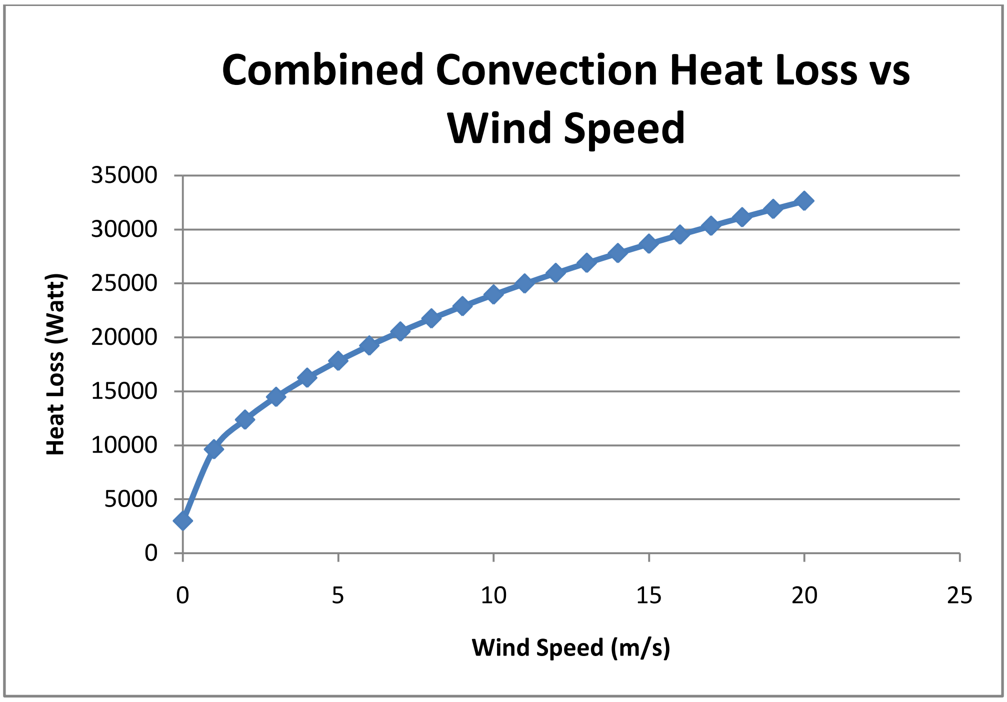


Figure 4.4 Combined convection heat loss of the receiver with respect to the wind speed.

The graph above shows the relationship between the combined convection heat loss and the wind speed around the receiver. Based on the graph line, it can be discussed that the convection losses are greater when the receiver is subjected to high velocity wind speed. To solve this problem from design view, the receiver should be designed to protect the receiver from high wind speeds to avoid excessive heat loss due to forced convection. However, in the Malaysian weather context, the forced convection losses are not so important because of lower wind speeds in Malaysia. The average wind speed in Malaysia is around 4 – 6 ms^{-1}

Useful Energy vs Solar Radiation graph

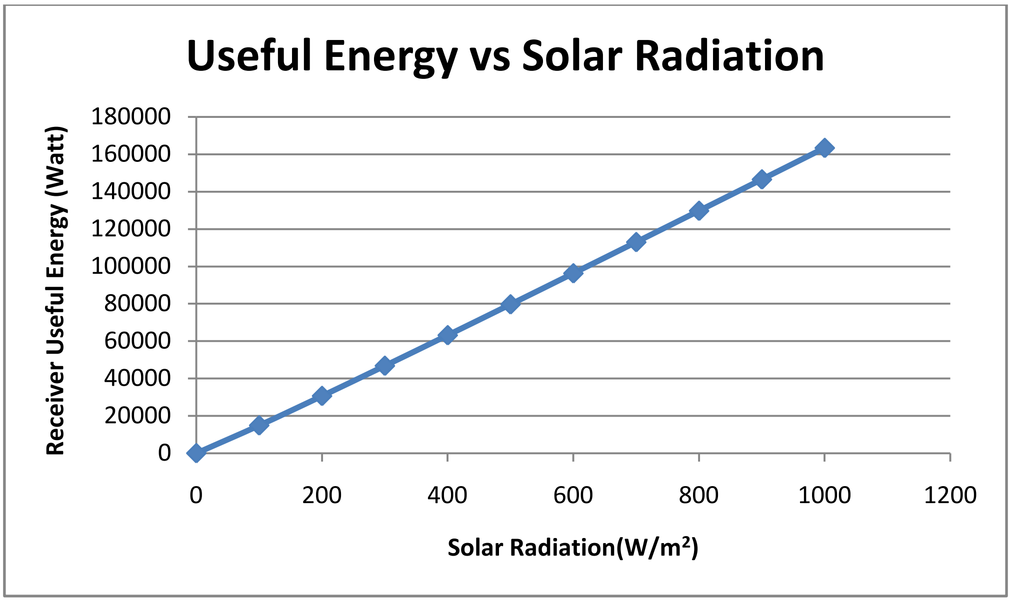


Figure 4.5: Useful energy (net energy) to the receiver from the reflectors vs solar radiation

The graph above is based on the useful energy to the central receiver versus the solar radiation readings. The useful energy to the receiver is the total energy that the heat transfer fluid can absorb from the receiver. It is the net energy on the receiver after accounting the energy losses from the receiver. From the graph we can clearly observe that the useful energy on the receiver is higher when the solar radiation from the sun is higher. Besides that, the useful energy on receiver has a linear relationship with the solar radiation values. The highest value of the useful energy for the receiver would be around 162000 Watt. This energy would be used to heat up the synthetic oil inside the downcomer tubes of the receiver before used for the steam generation process to rotate the steam turbine blades.

Mass Flow Rate Graph

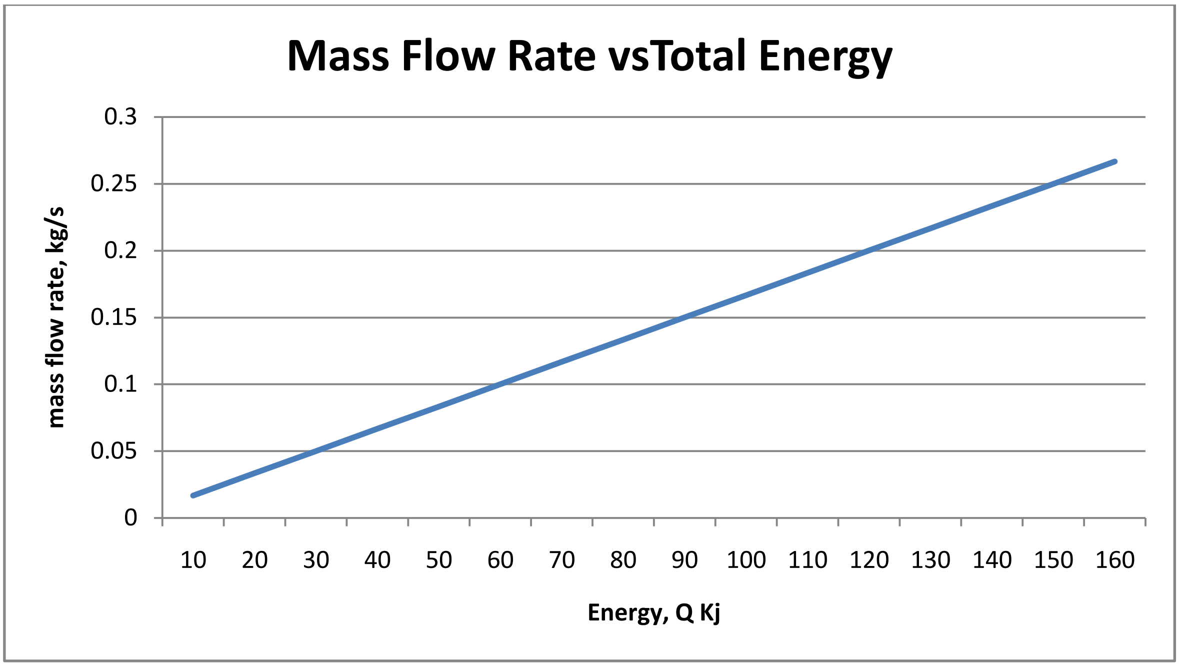


Figure 4.6 Mass Flow rate of HTF with respect to Total Energy reflected.

The graph above show a linear relationship between the mass flow rate of the heat transfer fluid to the total irradiation energy that is reflected by the heliostat field. The total energy that is reflected on the receiver depends on the Direct Normal Irradiation of the solar energy. So the higher the Direct Normal Irradiation, the higher the mass flow rate of the heat transfer fluid. Besides that, the calculations for the graph above are based on certain constants. The constants that are fixed are the surface temperature of the receiver pipes are 350°C and the fluid inlet temperature are 50°C. In addition, synthetic oil is used as the heat transfer fluid.

Further analysis would be done in TRNSYS and the results would be discussed thoroughly for the mass flow rate heat transfer fluid.

4.3 TRNSYS Simulation

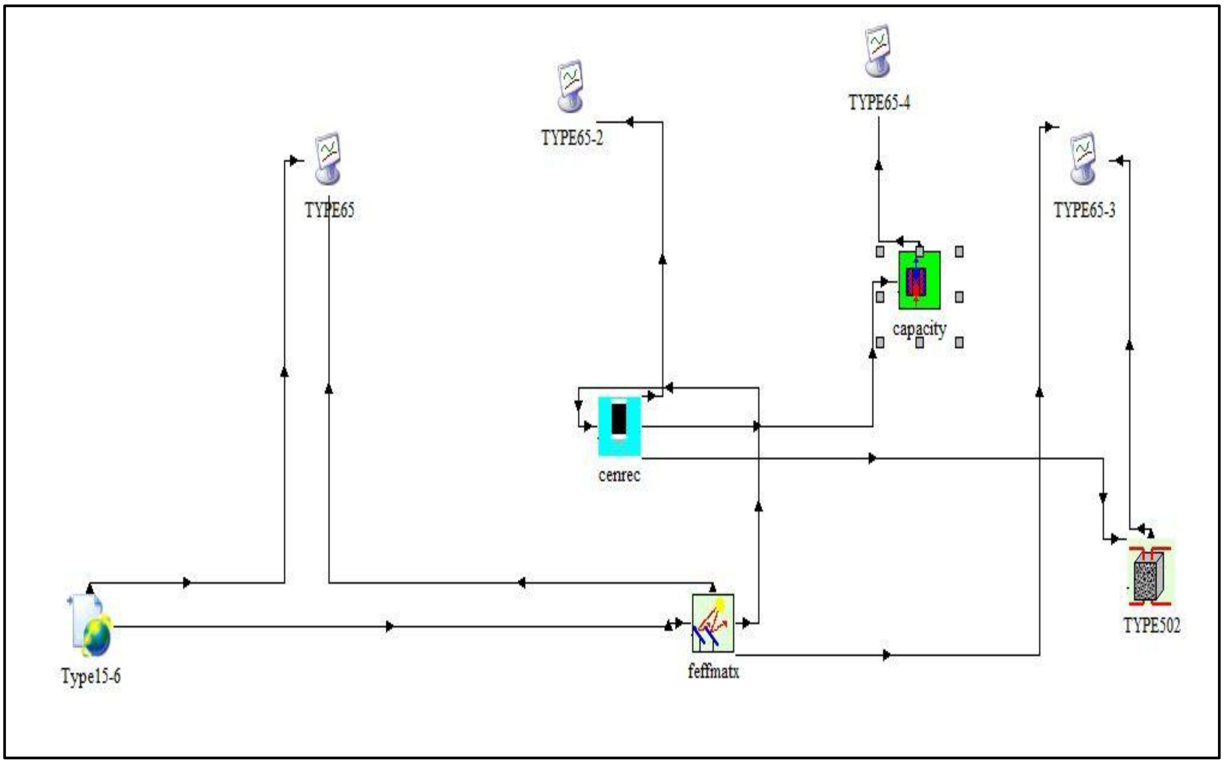


Figure 4.7: Main Simulation Diagram

The figure above shows the main components of the simulation for the design of external. The main components which are involved in this simulation are the weather data generator (Type 15-6), the heliostat field, external receiver, heat storage device and the online plotter (Type 65).

The simulation on TRNSYS for this final year project is run based on the KL weather data and the simulation in run for a total of 240 hours. The main purpose of this simulation is to obtain the fluid outlet temperature of the external receiver and compare the results between the simulation data and the calculation data for the design of the solar tower receiver.

For the simulation results below, the constants are:

Mirror surface area – 4 m^2

Number of reflectors – 60 units

Temperature set point – 350 °C

4.3.1 Direct Normal Irradiance and field efficiency

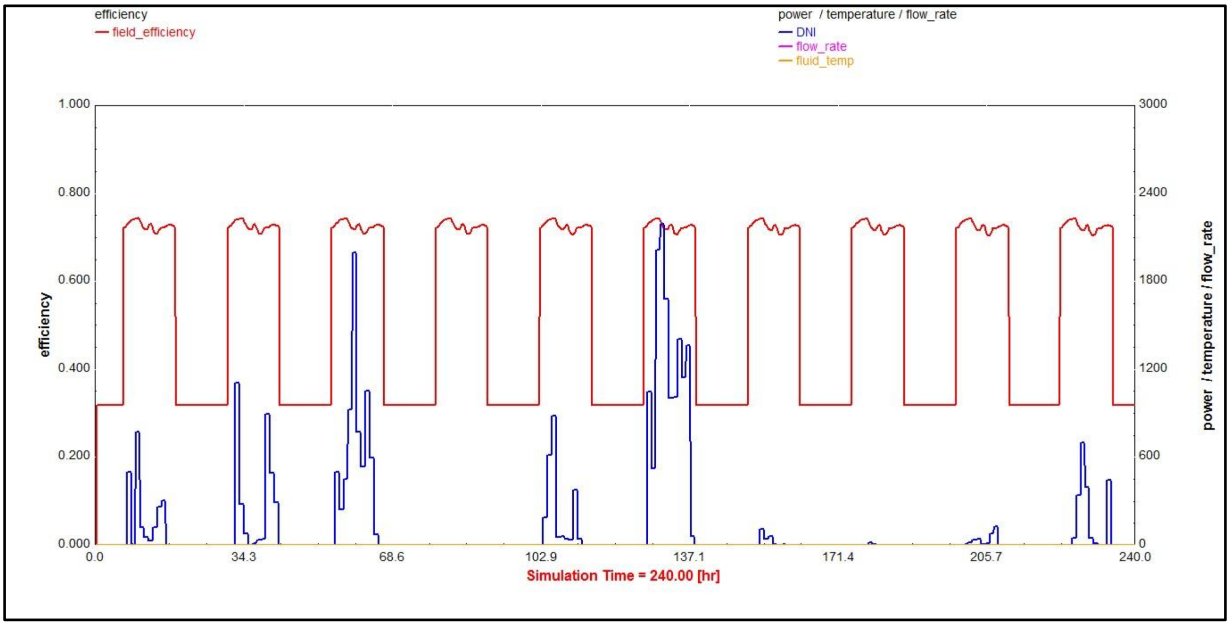


Figure 4.8: Direct Normal Irradiance (DNI) and the field efficiency

The figure above describes the Direct Normal Irradiance of the sunlight of the Kuala Lumpur Weather for 10 days. From the graph above, the blue line represents the Direct Normal Irradiance while the red line represents the efficiency of the field to reflect the sunlight to the central receiver.

The maximum Direct Normal Irradiance is around 2300 kJ/hr.m^2 which occurs at the 6th day from while the minimum Direct Normal Irradiance value is around 100 kJ/hr.m^2 which occurs during the 7th day. During the 4th day there are no Direct Normal Irradiance detected, this is due to the overcast skies during the daytime which blocks the sunlight from reaching the ground.

The efficiency of the heliostat field is around 75% - 80%. The heliostat field reaches its maximum efficiency from 30% when there is no irradiation. As the Direct Normal Irradiance increases, the efficiency of the field also increases. The efficiency of the reflector field is maximum during the afternoon. After that, as the direct normal irradiance decreases the efficiency of the field also decreases. Towards the evening, when there is not direct normal irradiance the efficiency of the field will reach 30%. The efficiency of the field always reaches 30% during the late evenings because this efficiency value is fixed for this simulation. This cycle continues for the next 10 days of the simulation.

4.3.2 Total Power to the Central receiver

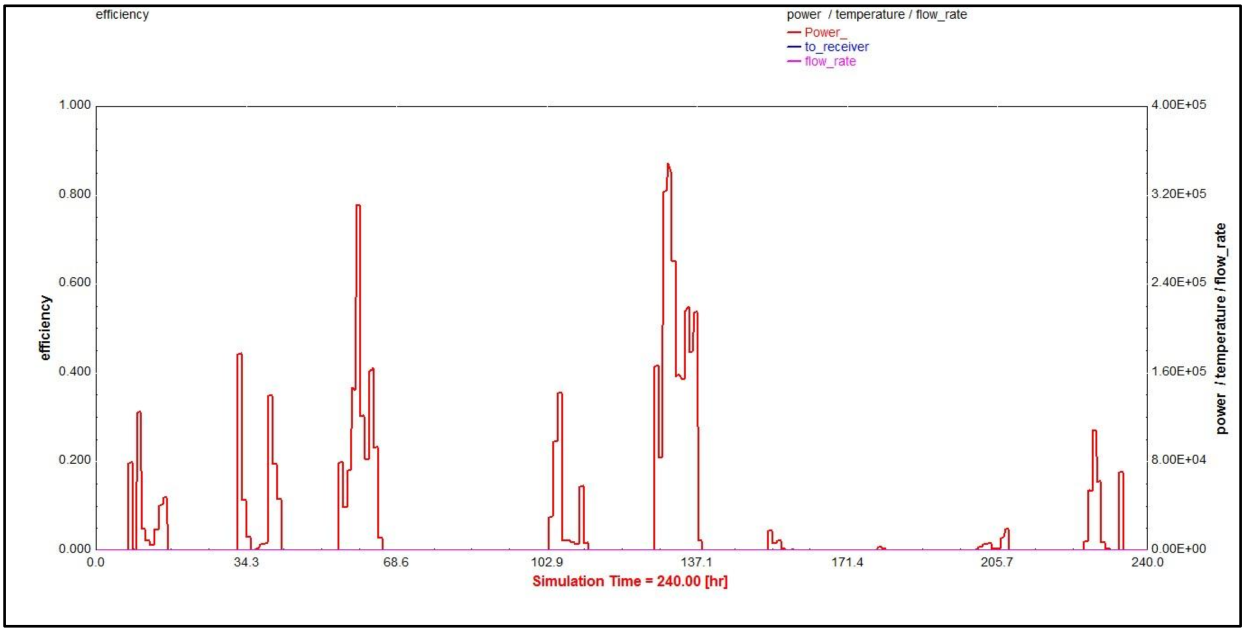


Figure 4.9: Total Power to the central receiver

The graph above shows the total power that is reflected from the heliostat flied to the central receiver. The Total power from the heliostat field correlates with the Direct Normal Irradiance data graph. The higher the Direct Normal Irradiance radiating in the reflectors, the higher the total power that is received by the central receiver. The maximum total power to the receiver is during the 6th day which is around 350000 kJ/hr. Besides that there is also a strong relationship between the number of reflectors and the total power to the central receiver. The higher the number of reflectors, the higher the total power to the receiver. In addition, the bigger the surface area of each of the reflectors, the higher the total power to the reflectors. Thus from the graph above and the parameters, it can seen that the total power to the receiver correlates with the Direct Normal Irradiance(DNI), Number of reflectors and the surface area of each reflectors.

4.3.3 Fluid Outlet Temperature and Mass flow rate demand

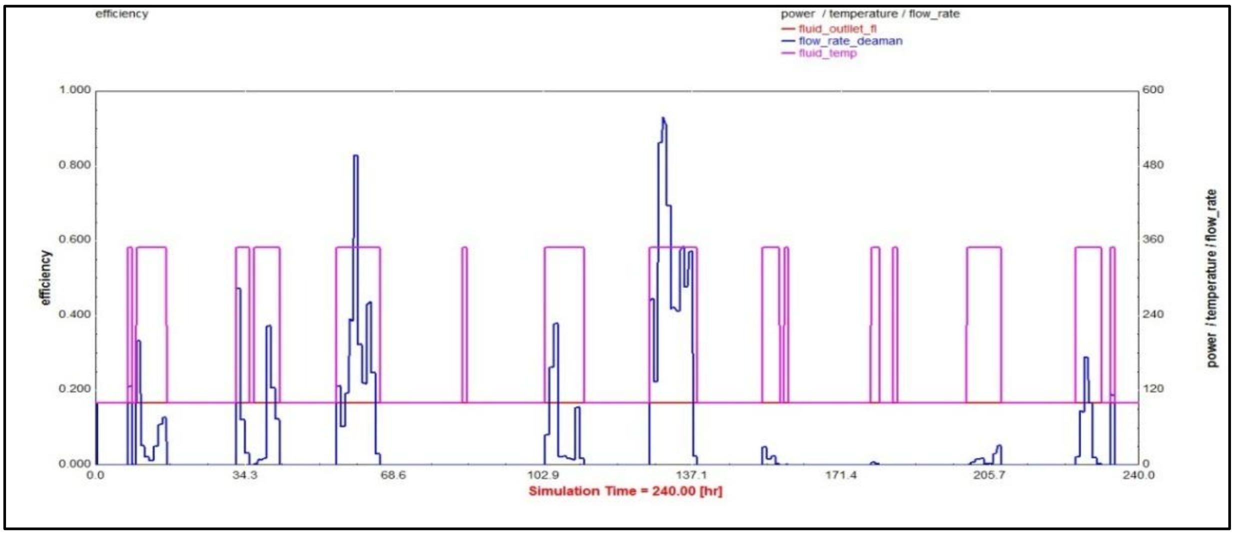


Figure 4.10: Fluid Temperature and mass flow rate readings(without losses)

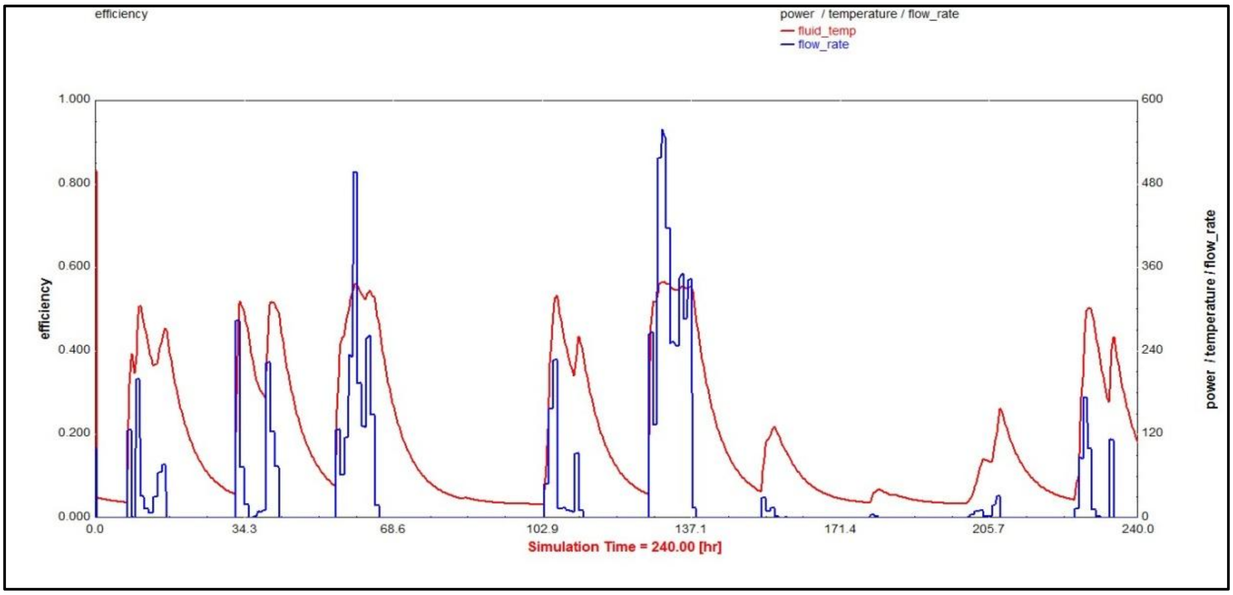


Figure 4.11: Fluid Temperature and mass flow rate readings(with losses)

Figure 4.11 above is obtained to analyze the mass flow rate demand of the fluid and the fluid temperature. The blue line represents the mass flow rate while the red line represents the fluid temperature. Besides that, the graph above shows the true readings of the mass flow rate and the fluid temperature because the heat losses are taken into account for this simulation.

The mass flow rate and the fluid temperature also a correlates with direct normal irradiance. The higher the direct normal irradiance, the higher the mass flow rate and the temperature of the heat transfer fluid.

The temperature of the heat transfer fluid is controlled by the varying the mass flow rate of the heat transfer fluid. The highest temperature of the heat transfer fluid is around 350 ° C on a clear sunny day. The highest mass flow rate demand is around 500 kg/hr on a good day. However, if direct normal irradiance is lower, the mass flow rate of the heat transfer fluid would be reduced to a lower value to for the heat transfer fluid to reach the required temperature of 350°C.

The temperature of the heat transfer fluid can be controlled by varying the mass flow rate because the internal convection of the heat from the receiver tubes to the heat transfer can be controlled by changing the speed of the heat transfer fluid which is pumped into the receiver tubes. The higher the speed of the heat transfer fluid the better the heat is transferred through convection into the heat transfer fluid. However, there should be a controlled internal convection of heat inside the pipe. This is to make sure that the surface temperature of the receiver is controlled and the heat transfer fluid is heated to the required value to generate steam.

4.3.4 Comparison of various parameters in TRNSYS Simulation

The simulation in TRNSYS simplifies the work of the author to compare between different parameters that are involved in the design of the central solar receiver tower. The parameters which are compared are the number of heliostats, surface area of each heliostat, heat transfer fluid and temperature set point. By differentiating each of the parameter, the maximum total power from the heliostat field, the maximum fluid outlet temperature and the mass flow rate demand of the fluid is obtained and compared.

Besides that, by differentiating between the different parameters it will be helpful in the designing processes because the author would know the important parameters that need to be considered. For an example, the most important parameter would the fluid outlet temperature because it would be used to estimate the surface temperature of the receiver for material selection. Besides that, the fluid outlet temperature is also important for the steam generation process after the receiver. In addition, the mass flow rate demand of the heat transfer fluid is also an important parameter because the circulation of the heat transfer fluid inside the receiver prevents the receiver from overheating and it is also one of the safety feature in the receiver.

Basically, there are 6 results which are taken to do the comparison. The graphs are all shown in the next pages.

<u>1st Comparison Simulation Results</u>

No. of reflectors - 40 units

Surface Area - $4m^2$

Heat transfer fluid – Synthetic Oil

Temperature Set Point – 350 °C

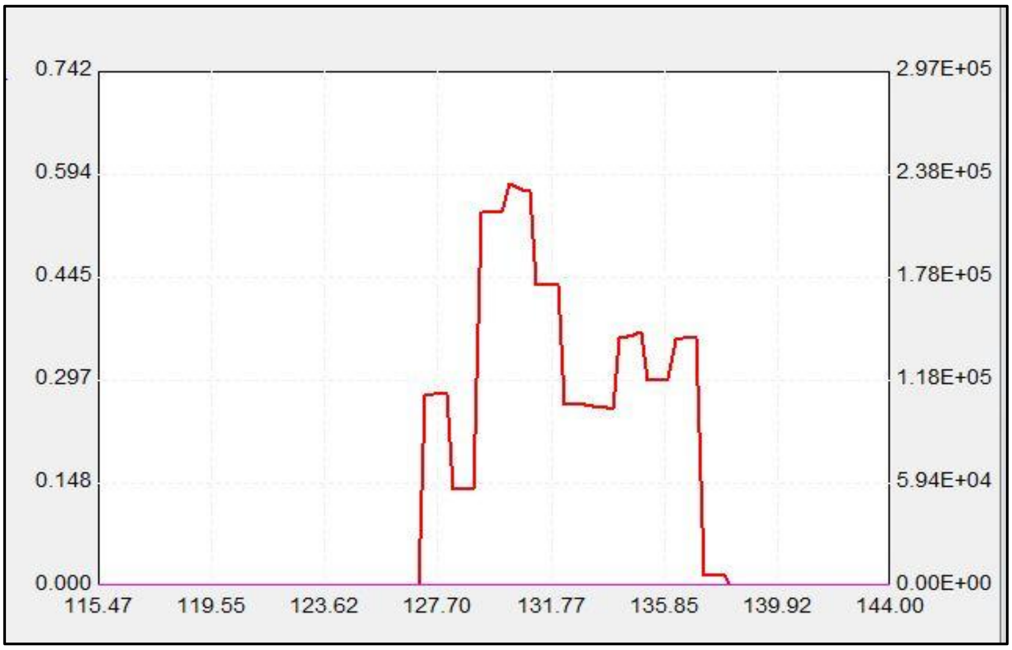


Figure 4.12: Total Power to the central receiver (Result 1)

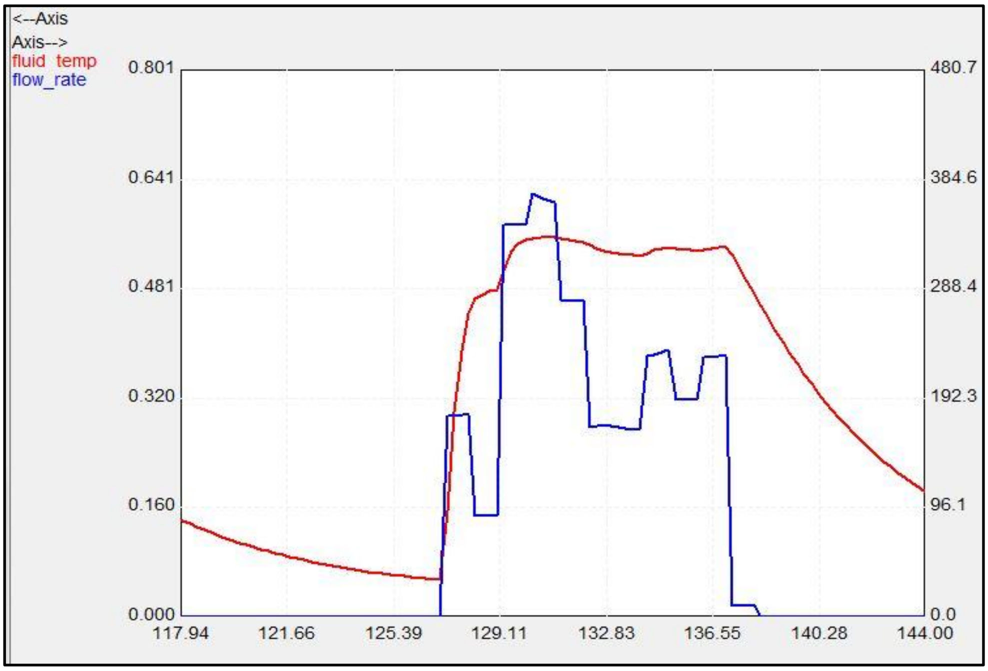


Figure 4.13: Mass flow rate demand and Fluid outlet temperature (Result 1)

2nd Comparison Simulation Results

No. of reflectors - 60 units

Surface Area - $4m^2$

Heat transfer fluid – Synthetic Oil

Temperature Set Point – 350 °C

Figure 4.14: Total Power to the central receiver (Result 2)

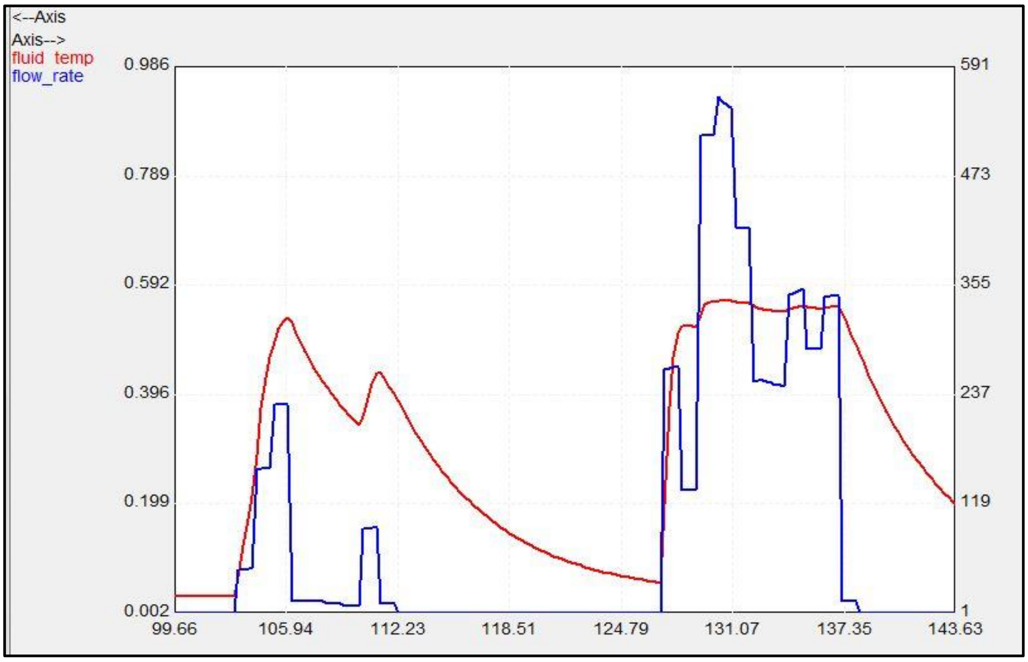


Figure 4.15: Mass flow rate demand and Fluid outlet temperature (Result 2)

<u>3rd Comparison Simulation Results</u>

No. of reflectors - 60 units

Surface Area –2 m^2

Heat transfer fluid – Synthetic Oil

Temperature Set Point – 350 °C

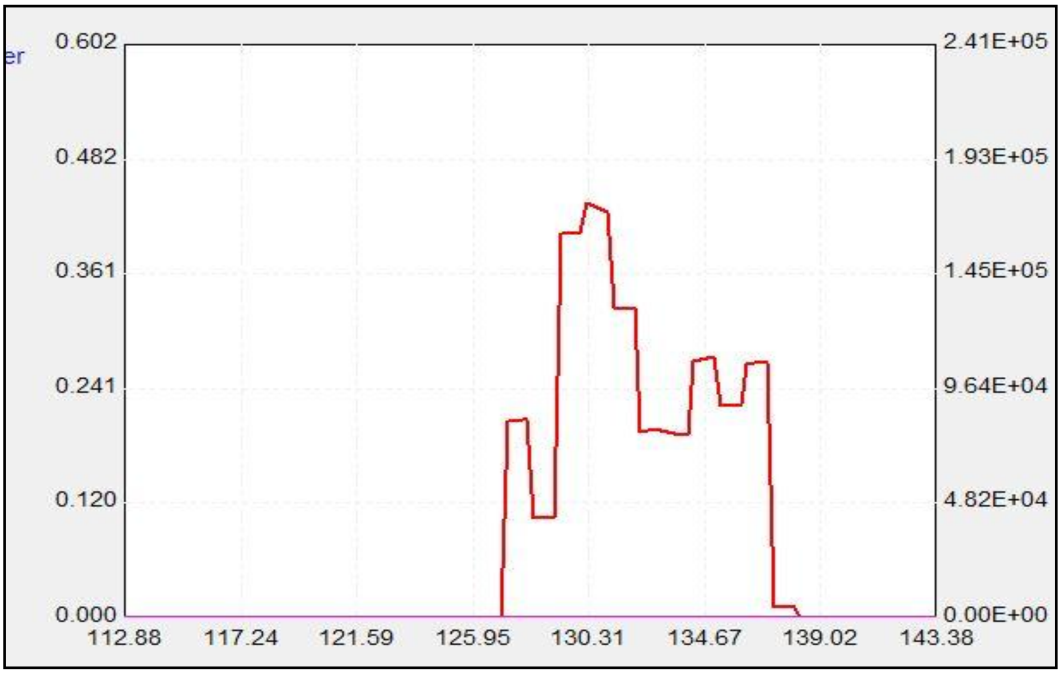


Figure 4.16: Total Power to the central receiver (Result 3)

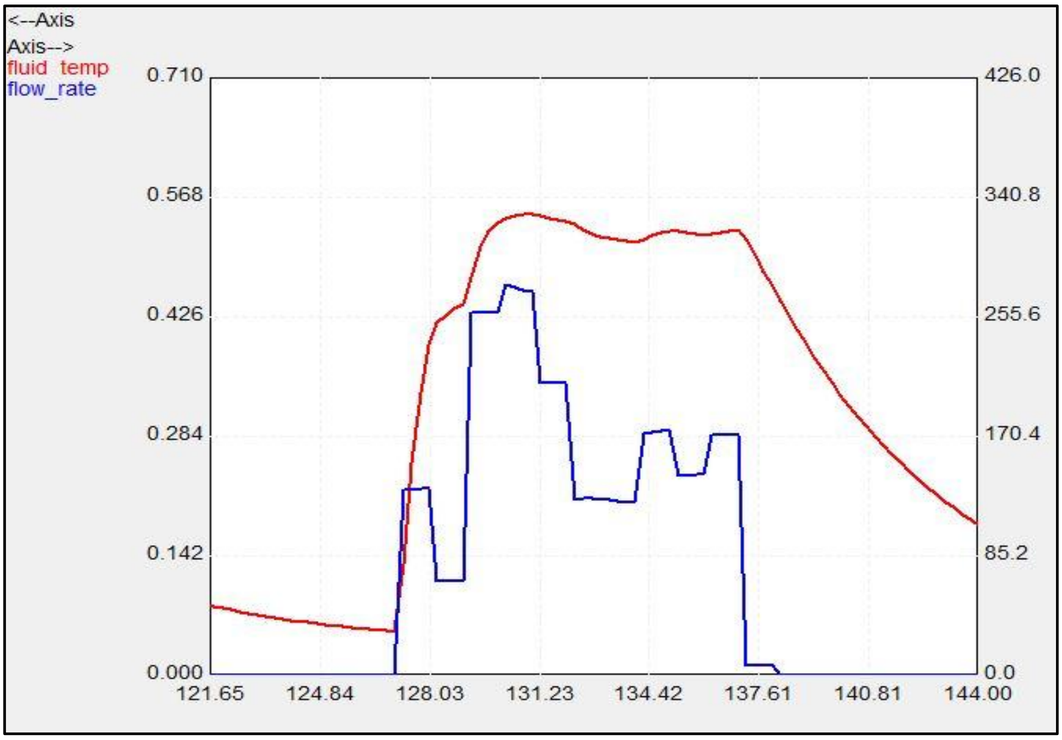


Figure 4.17: Mass flow rate demand and Fluid outlet temperature (Result 3)

4th Comparison Simulation Results

No. of reflectors - 60 units

Surface Area –1 m^2

Heat transfer fluid – Synthetic Oil

Temperature Set Point – 350 °C

Figure 4.18: Total Power to the central receiver (Result 4)

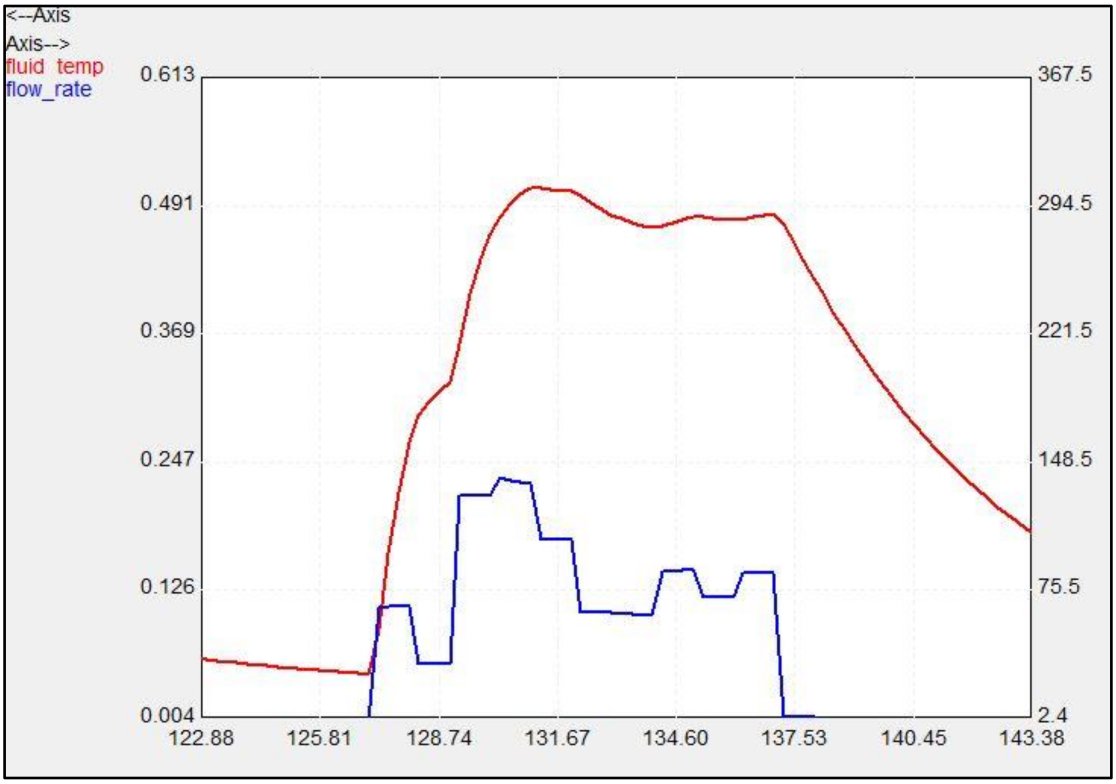


Figure 4.19: Mass flow rate demand and Fluid outlet temperature (Result 4)

5th Comparison Simulation Results

No. of reflectors - 60 units

Surface Area - 4m^2

Heat transfer fluid – Water

Temperature Set Point – 350 °C

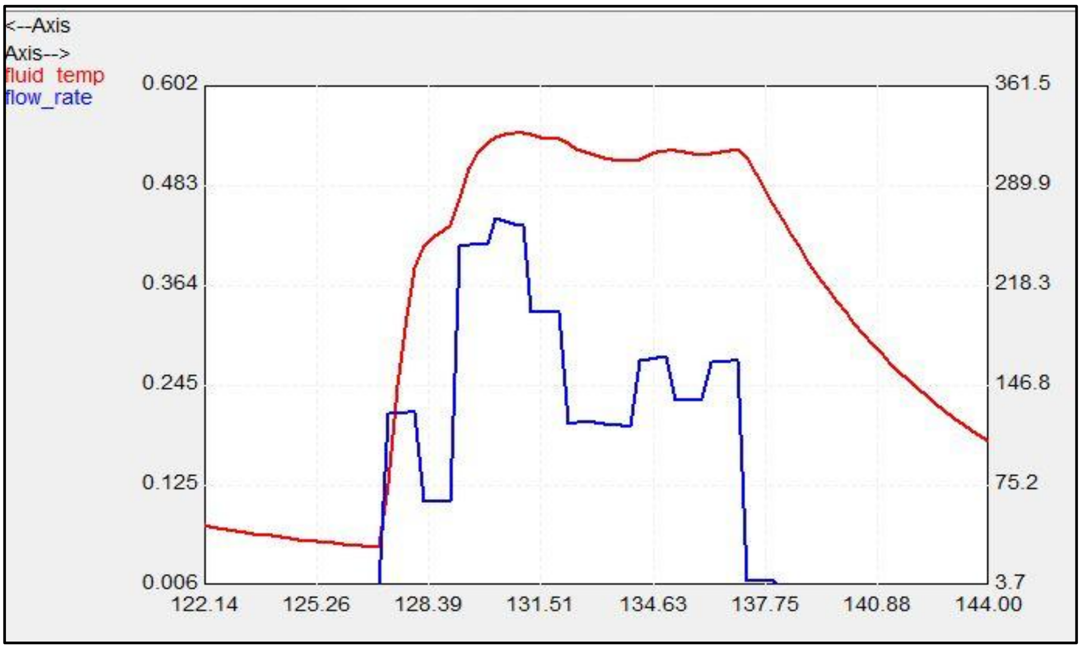


Figure 4.20: Mass flow rate demand and Fluid outlet temperature (Result 5)

6th Comparison Simulation Results

No. of reflectors - 60 units

Surface Area - 4m^2

Heat transfer fluid – Synthethic Oil

Temperature Set Point – 300 °C

Figure 4.21: Mass flow rate demand and Fluid outlet temperature (Result 6)

Table 4.1: Comparison between various parameters from the simulation results

Parameter	**Results 1**	**Results 2**	**Results 3**	**Results 4**	**Results 5**
No of Concentrators	**60 units**	**60 units**	**40 units**	**60units**	**60 units**
Temperature Set point °C	350	350	350	350	300
Highest DNI (W/m^2)	666.67	666.67	666.67	666.67	666.67
Surface Area	**4**	**1**	**4**	**4**	**4**
Heat Transfer Fluid	**Synthetic Oil**	**Synthetic Oil**	**Synthetic Oil**	**Water**	**Synthetic oil**
Maximum Total Power (W)	**97222.22**	**23611.1**	**66666.67**	**97222.22**	**97222.22**
Fluid Outlet Temperature °C	**350**	**300**	**350**	**340**	**300**
Maximum Mass Flow Rate Demand (kg/hr)	**580**	**150**	**380**	**250**	**700**

From the table above, various parameters are compared such as the number of reflectors, surface area and many more. By comparing the values above we can see that the number of reflectors in the field plays and the surface area of each reflector plays an important part to direct the energy from the sun to the receiver. The simulation results (Result 1, 4 and 5) which has 60 mirrors and the surface area of 4m^2 for each of the reflectors has the highest amount of total power which is around 97222.22 W while simulation with only 40 mirrors and the same value of surface area (Result 3) has the total power of 66666.67 W. Besides that, the simulation results with 60 reflectors and the surface area of 1m^2 (Result 2) for each of its reflectors has the lowest total power to the central receiver with value of only 23611.1 W. Based on the results obtained we can see that one of the main consideration of this project would be the surface are of each of the reflectors followed by the number of reflectors.

Differentiating the types of heat transfer fluid inside the receiver, we can see that if oil is used as the heat transfer fluid the mass flow rate demand of the oil is higher (580kg/hr) compared to the mass flow rate demand of water (250kg/hr), This can be explained by the heating capacity of the oil and water. Synthetic oil has lower heating capacity which is around 2 KJ/kg.K while water has a higher heating capacity which is 4.18 KJ/kg.K. Hence the mass flow rate demand of water is slower because it needs more energy to be heated up to the required temperature, while for oil the mass flow rate demand is faster because it needs lesser energy to be heated up to the required temperature.

The total energy reflected from the heliostat field is important because the outlet fluid temperature of the heat transfer fluid totally depends on the total power from the field. From the table we can see that the higher the total power reflected to the receiver, the faster and easier the required fluid outlet temperature is reach by the plant. However for this project, it is only to check the feasibility of using the central tower receiver in the Malaysian weather. So the total power to the receiver is not a critical parameter in this project.

In this paragraph, the author would like to differentiate between the temperature set points. Comparing results 1 and results 5 from the table, we can see that the mass flow rate demand inside the receiver is higher for the simulation which has a lower temperature set point (300 °C) while the mass flow rate demand is lower for the simulation which has the higher temperature set point (350 °C). This is because; the fluid inside the receiver has to be circulated many more times inside the receiver to bring down the surface temperature of the receiver to 300 °C. Mean while, for the simulation with temperature set point 350 °C the fluid is circulated fewer times to maintain the surface temperature of the receiver at 350 °C. The circulation of the fluid from the simulation is obtained from the mass flow rate demand of the receiver.

4.4 Data Verification

The data which is stated on the table below are based on 60 units of reflectors and each reflector having a surface area of $1m^2$.

Table 4.2: Verification of data between spread calculation results and simulation results

Parameters	**Spread sheet Calculation**	**TRNSYS Simulation**
DNI (W/m^2)	700	666.67
Fluid Outlet Temperature ℃	310	300
Useful Energy W	22867.59	23611.11
Mass Flow Rate (kg/hr)	144	150

From the data obtained above we can clearly see that there is not much difference between the calculated data and the simulation results. There is slight difference between the mass flow rate, surface temperature and the useful energy because in the calculation not all the receiver and filed losses are taken into account (conduction losses not taken into account). However, for the simulation, real time results would be given and the reading would be more accurate compared to the calculation results.

4.5 Receiver Efficiency

Assumptions for receiver efficiency calculations

No Heat loss to the backside of the receiver due to insulation

Solar Irradiation: 800 W/m^2

Ambient Temperature: 30 °C

Fluid Intel Temperature: 80 °C

Fluid Outlet Temperature : 300 °C

Conduction Heat Losses are neglected

All useful energy are transferred into the heat transfer fluid

Heat Transfer Fluid used for this calculation is Synthetic Oil

Efficiency = Energy Collected / Incident Solar Energy from Heliostat field

Energy Collected = $\dot{m}$Cp ΔT

Incident Solar Energy from Heliostat field,

Qa = $I \times Ag \times \varphi \times \rho \times \eta \times \alpha$

Where

Qa = Total energy reflected

I = Solar Incident Radiation

Ag = Total Field ground area

φ = Fraction of ground area

ρ = Mirror utilization factor

η = fraction of solar reflection received by the receiver

α = Absorptance value of receiver

η_{solar} = $Q_{collected}$ / Qa

= 18333.33 W/ 40176 W

= 0.456

4.6 Preliminary Design (Receiver Section)

From the reading and researches done in chapter 2, the preliminary design of the receiver is modeled in Autodesk Inventor. The design of the receiver consists of 4 main parts, which are the cold oil tank, the hot oil tank, the distribution pipes and finally the downcomer tubes. Before the modeling process was done a series of calculations which was discussed in Chapter 2 was undertaken to obtain certain values such as the maximum surface temperature of the receiver's surface and the useful energy that can be absorbed by the receiver at different levels of solar radiation

In the preliminary design, the cold oil tank and hot oil tanks functions to store the cold oil and hot oil respectively. The cold oil is directly from the outlet of the Heat Recovery Steam Generator while the hot oil transfers the heat absorbed in the receiver to water in the Heat Recovery Steam Generator to produce Steam. The tanks are made of aluminum alloys to which are insulated with ceramics to store the heated oil and cold oil. Aluminium alloys are used because it has high melting point, low emissivity value and it is lighter compared to other types of metals. In addition, the tanks are insulated to avoid heat loss to the atmosphere.

For the downcomer tubes, copper is chosen as the material of the pipes to efficiently absorb heat from the concentrated solar radiation into the working fluid which would be flowing inside the pipes. The size of the down comer pipes are 20mm in outer diameter and a total of 65 down comer tubes are used for the heat transfer area. The size of the tubes is small and many tubes are used to enlarge the heat transfer area of the receiver and efficiently transfer the concentrated heat flux to the working medium (synthetic oil) inside the receiver's tubes. In addition to that the distribution pipes are used to evenly transfer the working medium into the down comer tubes and create a constant flow rate in all of the down comer tubes. The material that has been chosen for the preliminary design of the down comer tubes is copper-black oxidized in ebanol C. This material is chosen because it has high heat absorptivity and low emissivity value. Besides that, copper also has high melting point and it would be safe to use it in the design of the central receiver.

The design below is only the preliminary design. The design would be changed to have a better design technically in the final design of the central receiver

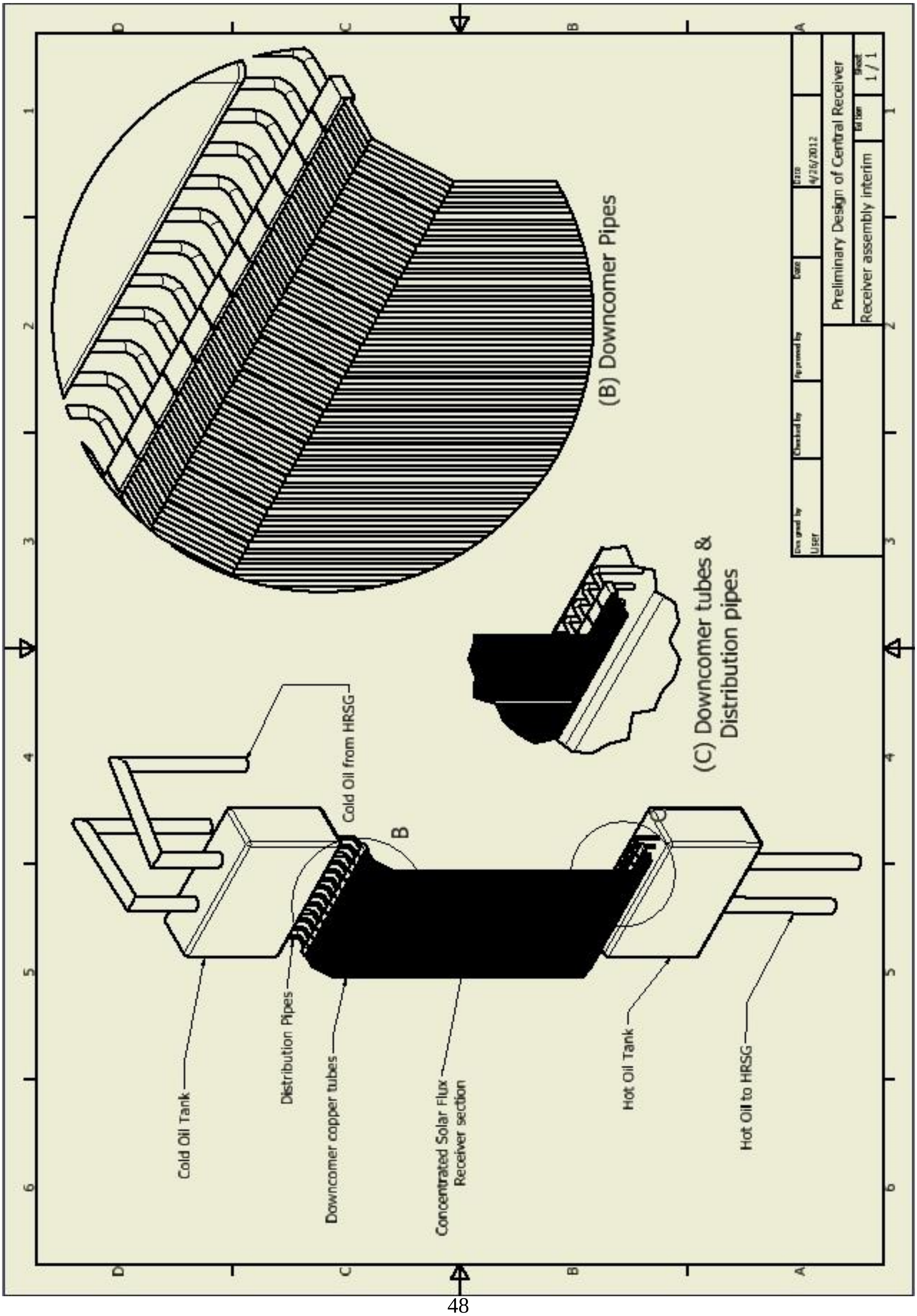
4.6.1 Bill of Materials for Preliminary Design

Table 4.3: Bill of materials

No.	Description	Units	Remarks
1	Hot Oil tank	1	Aluminium Alloy 2100mm x 1500mmx 700mm
2	Cold Oil Tank	1	Aluminium Alloy 2100mm x 1500mmx 700mm
3	Distribution Pipes	13	Steel Pipe Insulated 40mm OD
4	Down comer Pipes	65	Copper pipes Insulated at the backside 20mm OD

4.6.2 Design Problems with the preliminary Design.

- No allowance given for the copper and steel pipes to expand when the receiver is being heated by the solar flux from the heliostats. This would lead the pipes into buckling and damage the receiver.
- The Down comer copper tubes are bent at the top and the bottom to be fitted to the distribution pipes. The bent copper tubes will have high thermal stress when the copper tubes are heated up and the lifecycle of the tubes will decrease as it will leak easily at the bent parts.
- The oil tanks in this design are square in shape. Tanks with square shape are cheaper to manufacture however, the flow of the fluid inside the tanks are uneven because the pressure is distributed unevenly.
- Cheaper material can be used for the design; Instead of using aluminium steel can be substituted.


Cold Oil Tank
Distribution Pipes
Downcomer copper tubes
Concentrated Solar Flux
Receiver section
Hot Oil Tank
Hot Oil to HRSG
Cold Oil from HRSG
B
(B) Downcomer Pipes
(C) Downcomer tubes &
Distribution pipes
Designed by
User
Checked by
Approved by
Date
Date
4/26/2012
Preliminary Design of Central Receiver
Receiver assembly interim
Edition
Sheet
1 / 1

4.7 Final Design (Receiver Section)

During the modelling stage of the receiver section, the preliminary design is further improved. Space allowances between the metals are given for thermal expansion and the copper tubes are fixed as straight tubes to reduce the thermal stress on the tubes and for long lasting. Besides that, the oil tanks are also changed to the cylindrical shape for better fluid flow.

The design considerations for this final design stage of the receiver section are:

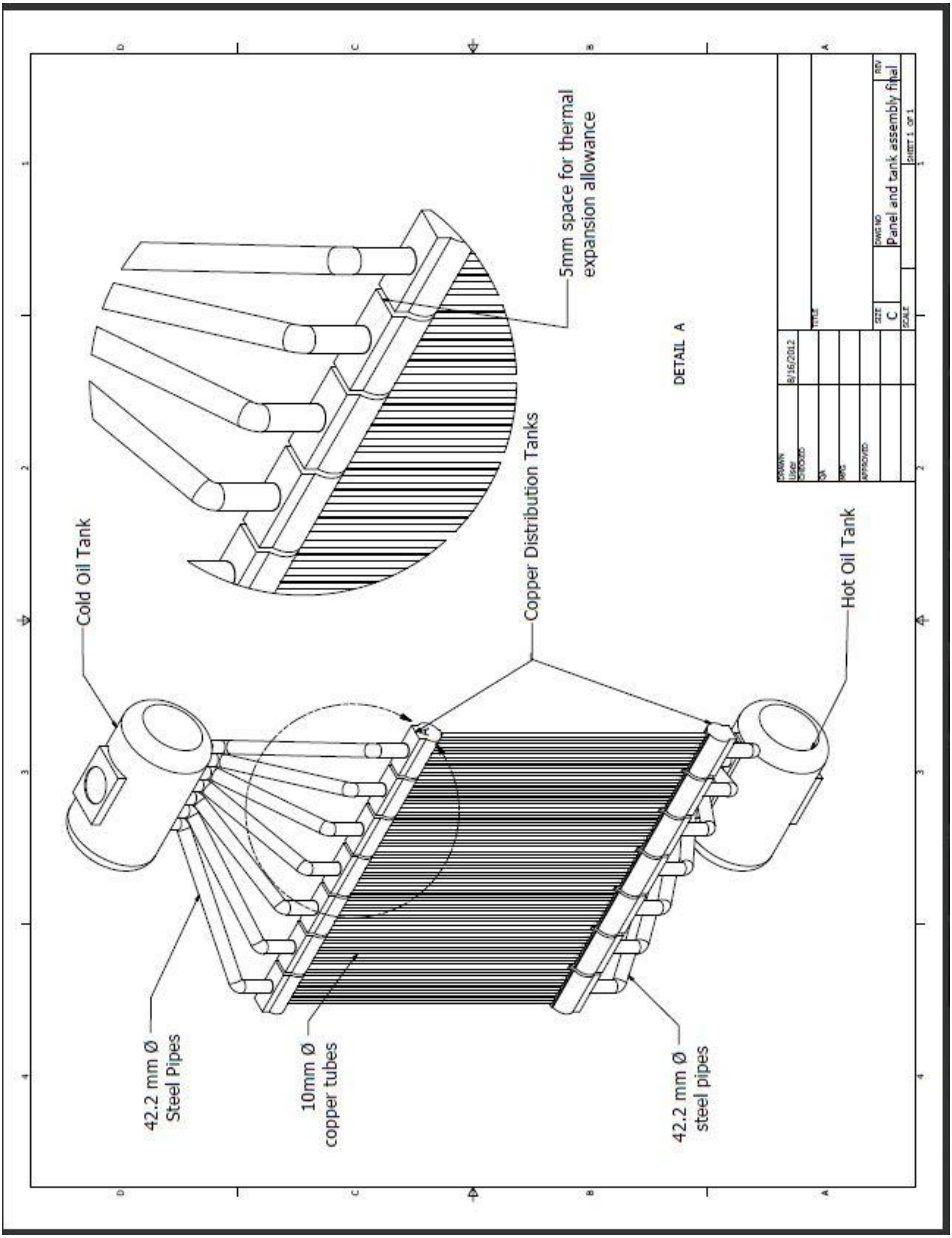
- Maximum surface temperature- 350° C
- Average temperature - 200° C
- Maximum Direct Normal Irradiation – 600 W/m^2 -700 W/m^2
- Total Number of Reflectors – 60 (4m^2 each) for each receiver
- Suitable Materials - Copper tubes coated with Ebanol C and Steel
- Thermal Stress - Straight copper tubes instead of bent ones
- Thermal Expansion - Clearance and slots to allow material to expand
- Heat Transfer Fluid – Synthetic oil
- Insulation – Fiberglass insulation at the backside and the Fluid Outlet Pipe

4.7.1 Bill of Materials for Final Receiver Design

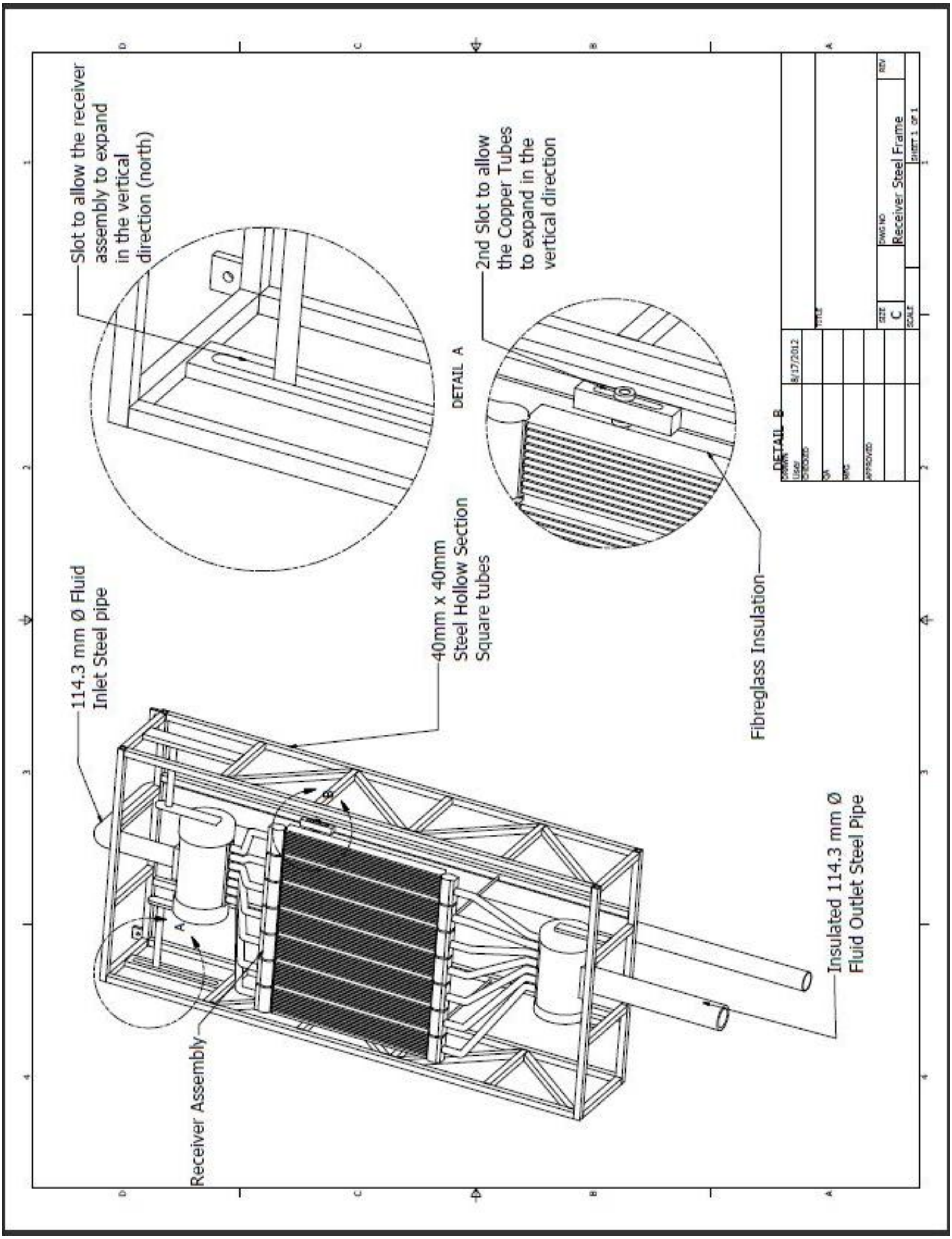
Table 4.4: Bill of materials

No.	Description	Units	Remarks
1	Hot Oil tank -	1	Alloy Steel(AISI 4340)
2	Cold Oil Tank	1	Alloy Steel(AISI 4340)
3	Distribution Pipes	14	Alloy Steel(AISI 4340) Pipe Insulated 42.2 mm OD
4	Down comer Pipes	70	Copper pipes Insulated at the backside with Fiberglass 10mm OD
5	Distribution Tanks	14	Copper

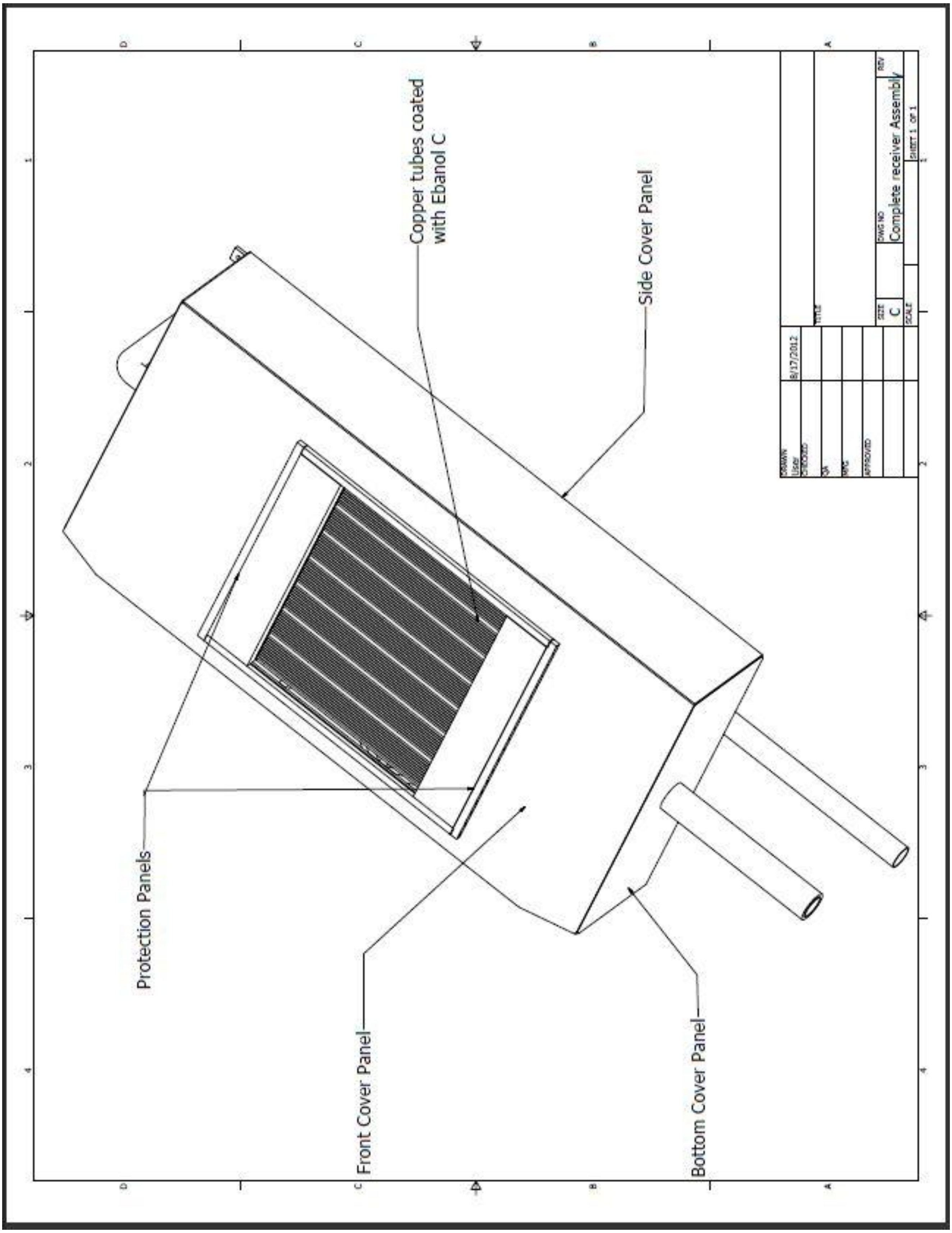
Design of Receiver Panel



Design of Receiver Steel Support Frame



Complete Receiver Assembly



4.8 Design Justification

The final design of the central solar tower receiver is based on readings and researches done on the current design of the central receiver. The Solar One and Solar Two central receiver plants are the main reference for the design of the finalized design of the prototype tower for this final year project.

Based on the design considerations above, the final design is done with the purpose of having a prototype concentrated solar central tower receiver is Universiti Teknologi Petronas, Tronoh, Perak to study the feasibility and the success rate of having a concentrated solar power plant in Malaysia. Thus, with this objective in mind, the central receiver design is done.

One of the main design considerations is the maximum surface temperature that the receiver tubes would be subjected to. From the simulation results and the calculations when the total energy to the receiver form the heliostat field is more that 20000W the maximum surface temperature of the receiver tubes would be around 350°C. From the surface temperature, the material of the receiver tubes is fixed. The material that is selected for the receiver tubes is copper. Copper is selected because it has a melting point of 1085 °C which higher than the surface temperature of the receiver. Copper is chosen because it has high absorptivity value. However, the absorptivity of the receiver tube is further increased with the solar coating of black Chrome deposition which has a absorptance value of (α=0.93) and emissivity value of (ε=0.17). By coating the copper tubes the heat loss by reflection and radiation is further decreased and the heat absorbed by the receiver tubes is increased. This increases the efficiency of the receiver.

Besides that, the other main design consideration is the thermal expansion of the receiver tubes and pipes when it is heated up to high temperatures. Copper has a linear thermal expansion of 16.5 (10-6 m/m K) while steel has a linear thermal expansion of 13.0 (10-6 m/m K). Based on the readings above and the operating temperature of the receiver, it is estimated that the receiver tubes would grow around 6mm for the copper side and around 4mm for the steel pipes. The calculations were done based on the ambient temperature of 20°C. So to allow the receiver tube to grow freely, 4 slots are designed on the supporting steel frame of the receiver to allow the receiver to grow freely in the receiver north direction. The receiver is allowed to grow freely to avoid buckling of the receiver tubes and also excessive damage to the receiver. In addition to that, the tubes panel assembly are also given a clearance space of 5mm for the copper distribution tanks to expand horizontally.

The third design consideration is thermal stress that the receiver would grow through each day. Thermal stress of the receiver would be high because the receiver would be subjected to very high temperature and suddenly when a cloud passes through the sky and blocks the sunlight, the temperature of the receiver would suddenly drop to a lower temperature. The temperature difference would be very high and this would lead to very high thermal stress that the receiver would have t undergo. From the design point of view, to reduce the thermal stress on the receiver tubes, all the receiver tubes are straight and the wall thickness is increased. The tubes are straight to minimize the stress point of the tubes and increase the operating lifetime of the tubes. Besides that, to protect the copper distribution tanks from very high temperatures, protective panels are installed around the receiver section.

The final design consideration would be the insulations for the receiver to avoid excessive heat loss to the atmosphere For this final year project fibreglass insulation is chosen because it has good insulation properties as well as it has low cost. Besides that fibreglass insulation is also easy to handle and shape to be fixed inside the receiver. The main section for the insulation to be placed would be right behind the receiver tubes. Insulation is important here because, heat would be lost to the backside of the receiver as only the front side of the receiver tubes would be subjected to heat flux from the solar radiation.

CHAPTER 5: CONCLUSION & RECOMMENDATIONS

5.1 Conclusion

Concentrated solar tower receiver is basically a heat exchanger to transfer the concentrated energy reflected from the heliostat field to the transfer fluid and into the thermal storage system for steam generation and electricity production. Based on the results obtained from the simulation and calculation, the solar central receiver tower would be feasible in Malaysia because we have an average solar radiation of 600 W/m2 throughout the year. Besides that, the maximum fluid outlet temperature of the receiver surface is around 300°C – 350°C which is high enough for steam production to generate electricity.

In addition, the design of the receiver is can be manipulated to achieve the required output from the receiver. In other words, the design of the receiver is very flexible. The material, the shape of the receiver can be always changed to satisfy the weather patent in other parts of the country. In this project, the design of the receiver is basically based on the fundamentals of the heat exchanger and boiler riser tubes, where the surface area of the absorber area is big to absorb high amounts of energy to the heat transfer fluid.

In Conclusion, based on the objectives of the project, all three objectives which are the mathematical study, running the real time simulation and designing the central receiver have been achieved for this final year project.

5.2 Recommendations

To further develop the research, future recommendation and improvements are essential. As this project concentrates on the design of the solar receiver, for future improvements, the design of the solar receiver can be changed to harvest the losses of the receiver itself and critical materials that are used on spaceships can also be used to improve the heat transfer rate of the receiver.

In addition to that, to further improve this research a simulation can be carried out in FLUENT to study the convective heat loss of the receiver. Besides that, a study on the thermal stresses on the receiver tube should be carried out in Ansys as the thermal stresses on the receiver is very high The thermal stress on the receiver is very high because the receiver cools down from 500K to 350K when a cloud passes over the sun and the receiver does not receive the concentrated heat flux from the reflectors.

Besides that, central receiver should also be fabricated and a experiment should be done to test the real capability of the Central Tower Receiver Solar Power Plant in Malaysia.

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APPENDIX A: DESIGN

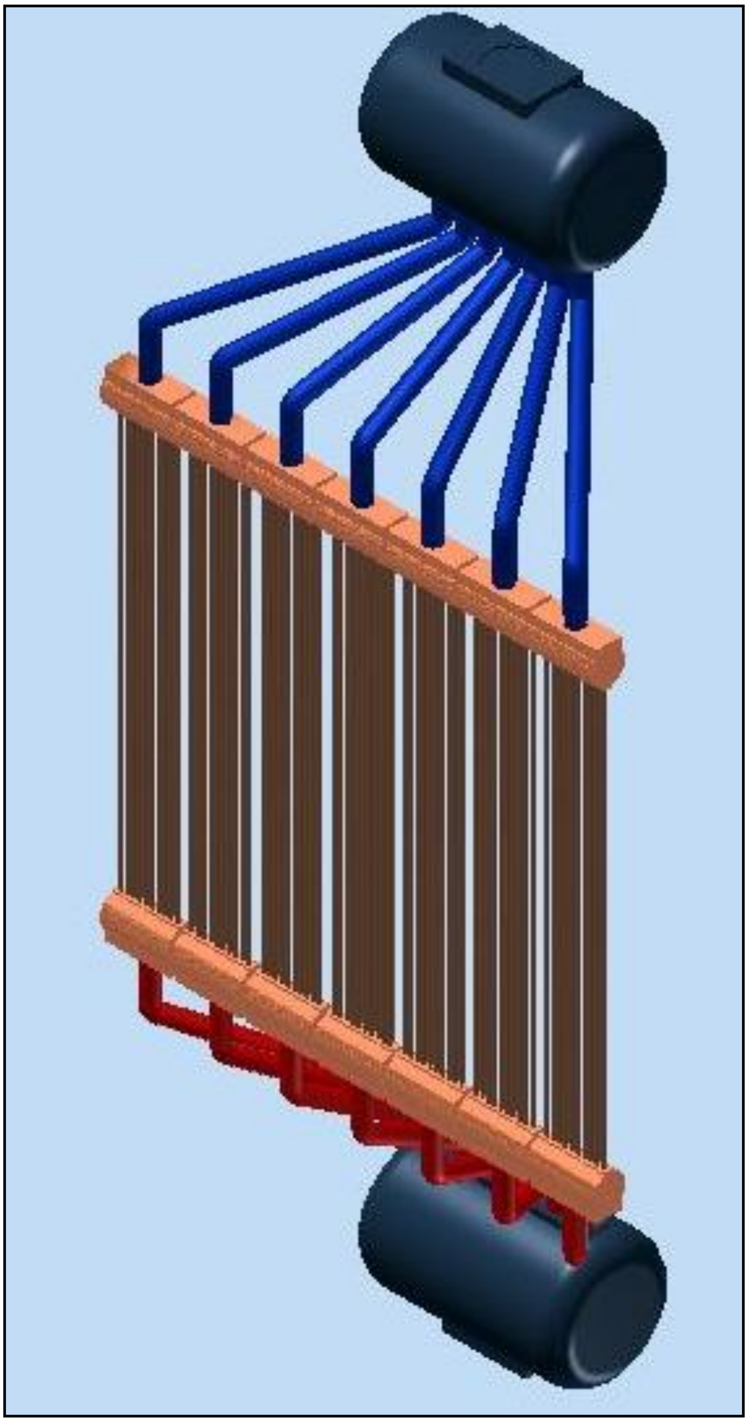

Figure A1: Final Receiver Design

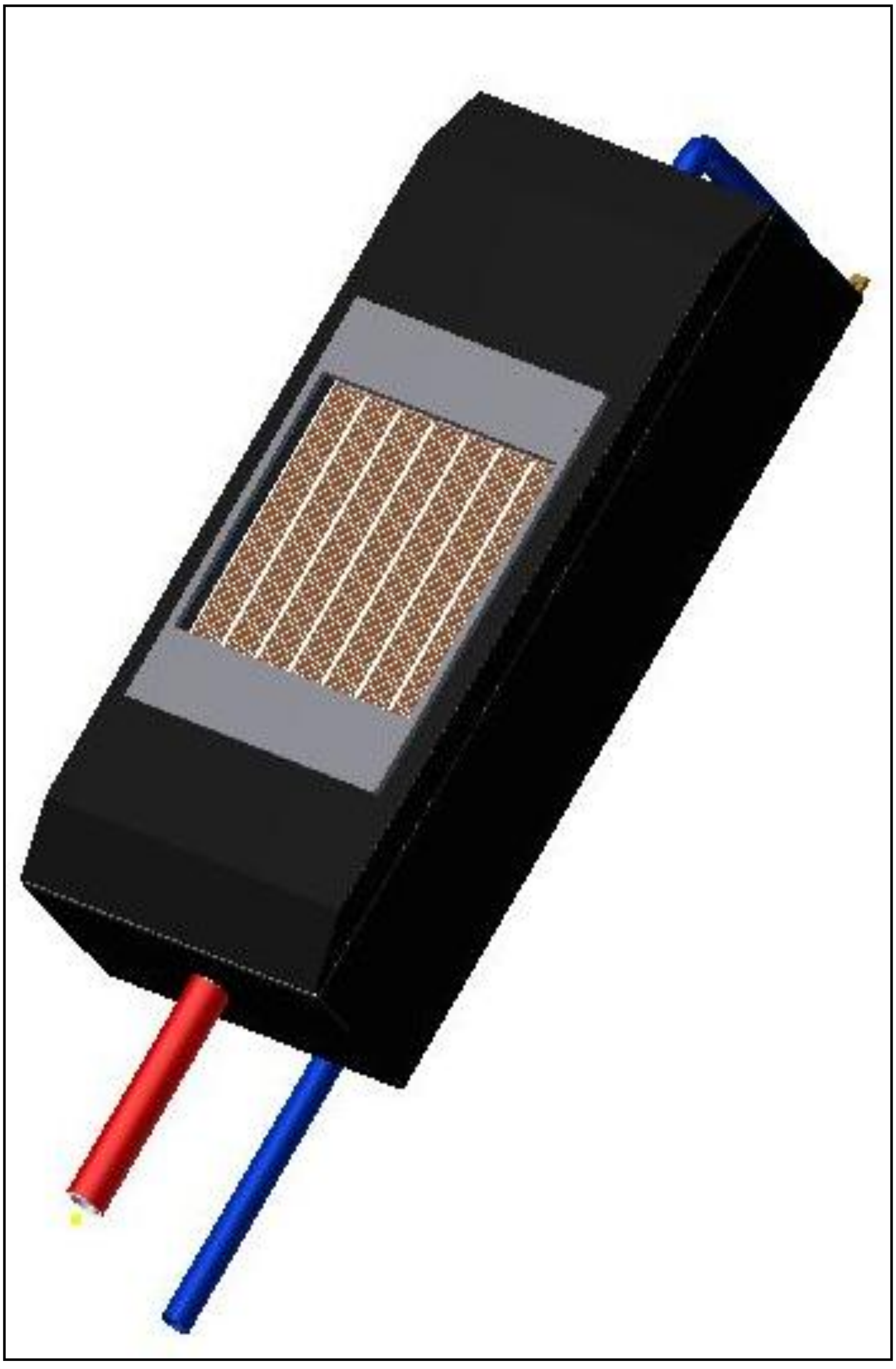

Figure A2: Complete Receiver Assembly

Figure A3: Complete Solar Tower with 6 Solar Receivers

APPENDIX B: IPOH WEATHER DATA

PERKHIDMATAN KAJICUACA MALAYSIA
Records of Meteorological Data

Station : Ipoh
Lat. : 04 ° 34 ' N
Long. : 101 ° 06 ' E
Ht. Above MSL : 40.1 m

Stnno	Year	Month	Day	Hour (ST)	Dry Bulb Temp. (° C)	Relative Humidity (%)	Mean Surface Wind Direction (°)	Speed (m/s)	Solar Radiation (MJm-2)	Solar Radiation (Whrm-2)
48625	2003	1	1	1	24.5	97	20	2.6		
48625	2003	1	1	2	24.5	97	40	1.5		
48625	2003	1	1	3	24.4	97	40	2.0		
48625	2003	1	1	4	24.4	97	30	1.5		
48625	2003	1	1	5	24.3	98	40	1.5		
48625	2003	1	1	6	24.3	97	20	2.0	0.00	0.00
48625	2003	1	1	7	24.5	94	30	2.0	0.05	13.89
48625	2003	1	1	8	25.3	90	30	3.1	0.44	122.22
48625	2003	1	1	9	27.1	79	40	2.6	1.52	422.22
48625	2003	1	1	10	28.8	76	40	2.0	2.26	627.78
48625	2003	1	1	11	29.5	73	40	2.0	1.95	541.67
48625	2003	1	1	12	30.6	68	30	2.0	1.99	552.78
48625	2003	1	1	13	30.9	64	30	2.0	1.67	463.89
48625	2003	1	1	14	31.6	67	0	0.0	1.45	402.78
48625	2003	1	1	15	31.7	67	180	0.5	1.46	405.56
48625	2003	1	1	16	31.0	72	160	0.5	0.89	247.22
48625	2003	1	1	17	29.7	79	0	0.0	0.22	61.11
48625	2003	1	1	18	26.4	95	10	3.1	0.03	8.33
48625	2003	1	1	19	25.9	95	0	0.0	0.00	0.00
48625	2003	1	1	20	25.8	98	0	0.0		0.00
48625	2003	1	1	21	25.9	98	0	0.0		0.00
48625	2003	1	1	22	25.7	98	0	0.0		0.00
48625	2003	1	1	23	25.2	99	20	1.0		0.00
48625	2003	1	1	24	24.9	100	20	1.0		0.00
48625	2003	1	2	1	24.6	99	30	1.0		0.00
48625	2003	1	2	2	24.4	99	0	0.0		0.00
48625	2003	1	2	3	24.0	100	0	0.0		0.00
48625	2003	1	2	4	23.8	100	20	1.0		0.00
48625	2003	1	2	5	23.5	100	0	0.0		0.00

APPENDIX C: FABRICATION DRAWING