SOLAR THERMAL MATERIAL PROCESSING

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I would like to acknowledge Professor Graham Town and my family for helping to guide me through the project and assisting with construction when needed.

STATEMENT OF CANDIDATE

I, Mathew Reid, declare that this report, submitted as part of the requirement for the award of Bachelor of Engineering in the Department of Electronic Engineering, Macquarie University, is entirely my own work unless otherwise referenced or acknowledged. This document has not been submitted for qualification or assessment at any academic institution.

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ABSTRACT

The use of fossil fuels for the processing of materials and other fuels is a challenge like no other affecting the world we live in. The creation of solar fuels is a way that could help curb emissions from fossil fuels through the use of concentrated solar power systems, creating clean energy and materials. This document provides a background into concentrated solar power systems as well as solar fuels and details the design process of this project to create a concentrated solar power system. Simulations and results are presented to explain the design decisions taken in the project. A CSP system is then constructed and tested with the aim of reaching 500°C. This temperature sets a good base temperature for future work on processing solar fuels. In order to reach the desired temperature, different strategies were tested to try and raise the temperature. Due to losses to convection and problems with the tracking system, the desired temperature was not reached. There is however scope to reach 500°C in the future by upgrading parts of the system.

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Abbreviations

CNC	Computer Numerically Controlled
CPC	Compound Parabolic Concentrator
CSP	Concentrated Solar Power
Insolation	Incident Solar Radiation

Chapter 1

Introduction

Worldwide there is a growing demand for materials and fuels, many of which are produced and used at traditional fossil fuel powered factories and power plants. This is creating a problem for the world in the form of pollution and climate change which effects the environment around us and impacts on the lives of everyone. In order to continue living the way we do, changes in the way that we produce fuels and materials need to be made. Using the sun to produce materials and fuels is one such way that this can be achieved and concentrated solar power (CSP) is one way of doing this.

Using CSP materials can be processed using the power of the sun instead of other fuels. These materials are called solar fuels. Solar fuels are fuels that are made by the processing of materials in a collector in a CSP system. These solar fuels can then be stored and transferred to places they are required to be used, lowering the environmental impact of producing them. Some solar fuels that can be produced through the use of energy from the sun are hydrogen, methane and bio-char.

1.1 Project Outline

This section will provide an outline of what will be completed in the project as well as a timeline of when these tasks will be completed, an overview of the budget for the project and an outline of this document. Supplementary documents for this section such as the project timeline can be found in Appendix A. Throughout the project meetings were held once a week with the project supervisor to ensure that progress was being made each week and so that advice on how to proceed could be given if necessary.

1.1.1 The Project

This project aims to build a fully functioning parabolic solar trough reflector that will be capable of reaching temperatures of over 500°C, which will give it a good base temperature to work with for the future processing of materials to form solar fuels. The system will have a reflective surface of at least two meters wide in order to receive enough sunlight to

reach the stated temperature goal. The project will be conducted with a budget of $300 in mind, but if extra funding is needed due to the size of the project then more funding will be applied for. This project will be completed over a fifteen week period spanning from August to November and a presentation will be given at the completion of the project.

Time Line

Each task that makes up the whole project has been allocated a certain amount of weeks to be completed in throughout the fifteen week period. A time line for the project can be found in Appendix A.

Budget Review

For this project the university allocated $300 for expenses. A table has been prepared below to show the costings of the project and can be found in Appendix A. As the total cost of the project exceeded the $300 budget, more funding was requested. This funding went towards building the tracking system for the reflector allowing it to be more efficient and reach higher temperatures.

1.2 Contribution

During the project a working system was built to concentrate solar radiation on an absorber and attempt to achieve a temperature of 500°C. While the intended temperature was not reached, a system has been constructed that will allow further testing to commence. This allows for upgrades that may push the maximum temperature higher. The results from this project also show that focusing on lowering losses at the absorber of the system has more of an effect on the temperature than trying to improve the reflector. This means that future work should be focused on reducing losses due to things like convection and ensuring the tracking system is as accurate as possible.

1.3 Document Outline

This section presents an overview of what each chapter of this document will contain. Presented in this document will be an introduction to the project, an explanation of the background plus a literature review, the process of designing a parabolic reflector, construction, results, future work and conclusions. A quick summary of each chapter is presented below.

Chapter Two: Chapter Two contains the background information on different types of CSP systems, solar fuels and important factors in material choice for the system.

Chapter Three: This chapter contains an analysis of the simulations done on a few different types of solar reflectors in a program called Soltrace. The design process for the final design is also discussed.

Chapter Four: Chapter Four contains a brief explanation of how the system was constructed and the various setbacks that were encountered and how these were overcome during the project.

Chapter Five: Chapter Five details the different tests that were conducted over the duration of the project and discusses the findings from these. All the results are then compared and a discussion is presented.

Chapter Six: Conclusions about the results and work done on the project are presented in this chapter. A summary of future work is also presented.

Chapter 2

Background and Related Work

CSP systems can be made up of different types of solar reflectors that can be placed in different types of arrays. Each style has its own benefits and draw backs, such as some systems have a stationary point that receives the energy while others move with the reflectors. The main types of CSP systems, which are shown below in Figure 1, that are in use today are solar towers, linear Fresnel reflectors, parabolic dishes and troughs. Parabolic trough and dish reflectors have receivers that are at the focal point of the reflector and move with the reflector tracking the sun across the sky throughout the day. These systems produce more energy than linear Fresnel reflectors, which have stationary receivers, however this complicates transferring the energy away from the receivers.

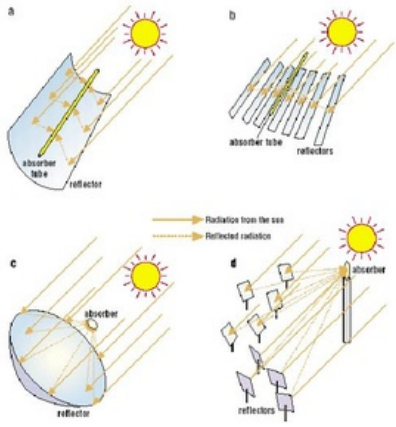


Figure 2.1: Common types of CSP system. Clockwise from top left: trough, linear-Fresnel, tower and dish reflectors [11].

The table below compares these four types of CSP systems in terms of how large they are, how easy it is to process materials in them and if the receiver moves throughout the day or not.

System	Receiver Type	Focal Point	Ease Of Processing Materials	Number Of Reflectors
Parabolic Trough	Mobile	Line	Simple	1
Parabolic Dish	Mobile	Point	Difficult	1
Linear Fresnel	Stationary	Line	Simple	1 - Many
Tower	Stationary	Point	Simple	Multiple

Table 2.1: Comparison of four common CSP systems.

As shown in the table above each system has its own strengths and weaknesses. For this project maximum heat wasn't the only factor that was important in the design of the system. Equally important was how easily materials could be processed in the system and how large the system had to be. We can see that solar towers and linear Fresnel systems take up far too much space as towers require many flat reflectors placed around them to reflect the heat to the tower and linear Fresnel collectors need to be larger to achieve the same results as parabolic collectors due to their stationary design. This leaves us with parabolic troughs and dishes. Parabolic dishes are able to create higher temperatures at their focus points due to the focus being a point instead of a line, receiving all the incoming radiation instead of it being spread along a line. While the higher temperatures of a parabolic dish are desirable, it is harder to get materials to the focal point for processing as it is constantly moving along two axes to track the sun. Because of this fact the parabolic trough reflector was chosen for the project over the parabolic dish reflector as it has more potential in the future for the processing of materials. The parabolic trough and dish reflectors are explained in more detail in their respective sections in the document.

All of these systems aim to achieve the highest concentration ratio (CR), which is the concentration of energy achieved by the receiver in the system. The equation that gives us the ideal concentration ratio of a system is:

$$CR = \frac{4}{\theta^2} \sin^2 \phi_{rim}$$

For which ϕ is the rim angle of the reflector and θ is the angle subtended by the sun and the surface of the earth [17]. This equation only gives us the ideal concentration ratio however, as realistically things such as irregularities and imperfections in the reflective surface or the shape of the parabola would affect this ratio. This provides one of the goals of this project, to attempt to maximize the concentration ratio in order to achieve the highest temperature possible at the receiver.

An important factor that influences the amount of energy that a CSP system can generate on any given day is the daily insolation level. The daily insolation is the incident solar radiation averaged over the entire day, meaning it is the watts per square meter received by a surface over the course of the day [16]. The amount of insolation varies throughout the year due to the angle of the sun, atmospheric conditions, altitude and location on the earth. The greatest amount of insolation is achieved when the sun is directly overhead, minimising the amount of atmosphere that the solar radiation has to pass through to reach the surface.

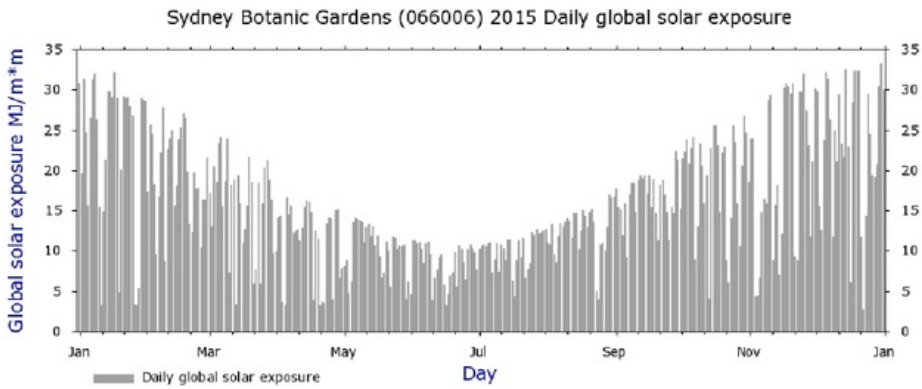


Figure 2.2: Graph of insolation levels throughout 2015 [10].

This is why insolation levels are significantly higher in the summer months, sometimes being nearly three times higher than the lowest levels in winter [10]. Insolation is important to CSP systems, as it is a factor that is used in the calculation of the mean flux concentration ratio of the system. This ratio is often measured in suns, with one sun being equivalent to 1000W/m2. The mean flux concentration ratio can be found using the following equation.

$$C = \frac{Q_{solar}}{IA}$$

The mean flux ratio, C, is equal to the solar power input, Q_{solar} divided by the insolation I, multiplied by the area A at the focal plane [18].

2.1 Solar Fuels

One aim of CSP systems and for this project in particular is the production of solar fuels. The production of solar fuels mainly focuses on the goal of producing fuels usually produced through the use of fossil fuels using the energy from the sun instead [2]. This

is extremely useful as solar fuels can be used to store energy imparted by the sun in chemical bonds, allowing the energy produced from CSP systems to be easily stored and transferred for use in other areas away from the CSP plant. Some methods of producing solar fuels through CSP systems include the production of hydrogen and carbon dioxide through electrolysis and thermochemical production [9, 22].

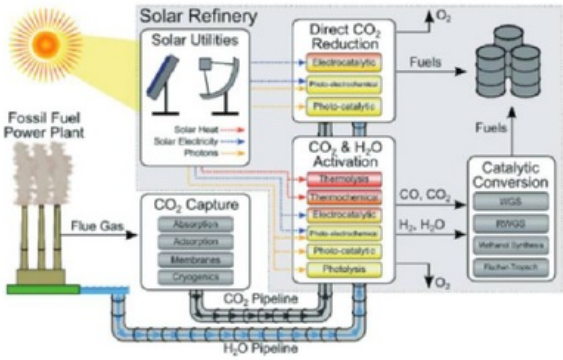


Figure 2.3: Example of processes for creating solar fuels [22].

In order for these processes to work efficiently, high temperatures must be achieved at the receiver of the CSP system. in order for this to happen the absorption efficiency of the receiver must be as high as possible. The absorption efficiency, $\eta_{absorption}$ is given by:

$$\eta_{absorption} = \frac{\alpha_{eff} Q_{aperture} - \epsilon_{eff} A_{aperture} \sigma T^4}{Q_{solar}}$$

With $Q_{aperture}$ being the amount intercepted by the aperture which has an area $A_{aperture}$, Q_{solar} represents the total power from the reflector, ϵ_{eff} and α_{eff} are the effective emittance and absorbtance of the receiver, with T being the receiver temperature and σ the Stefan-Boltzmann constant [12, 17].

The absorption efficiency is used with the Carnot efficiency to find the ideal exergy efficiency, $\eta_{exergy,ideal}$. The Carnot efficiency is the theoretical most efficient heat engine cycle, and when multiplied with the absorption efficiency of the receiver gives the ideal exergy efficiency of the system [12, 17, 18].

$$\eta_{exergy,ideal} = \eta_{absorption} * \eta_{Carnot}$$

Exergy is the maximum amount of work that a system is able to do before it reaches equilibrium state [15]. So if the ideal exergy of the system can be found then the ideal conditions for creating solar fuels can be created.

2.2 Potential Applications and Requirements

CSP systems have the potential to change the way that we process certain materials and create fuels. Some of the possible applications of these systems are as follows.

2.2.1 Electricity Generation

While the technology to produce electricity from the sun is nothing new and has been around for years in the form of solar panels, producing electricity through solar fuels is a new and convenient way to do this. As mentioned in the Solar Fuels section, CSP systems can take the suns energy and store it in the form of chemical bonds in various gasses such as hydrogen, methane and carbon monoxide. In a system where CSP is used to produce power, water is split into hydrogen and oxygen at the CSP plant in a process called thermochemical water splitting, which is a series of chemical reactions that end up with the decomposition of water into oxygen and hydrogen [13].

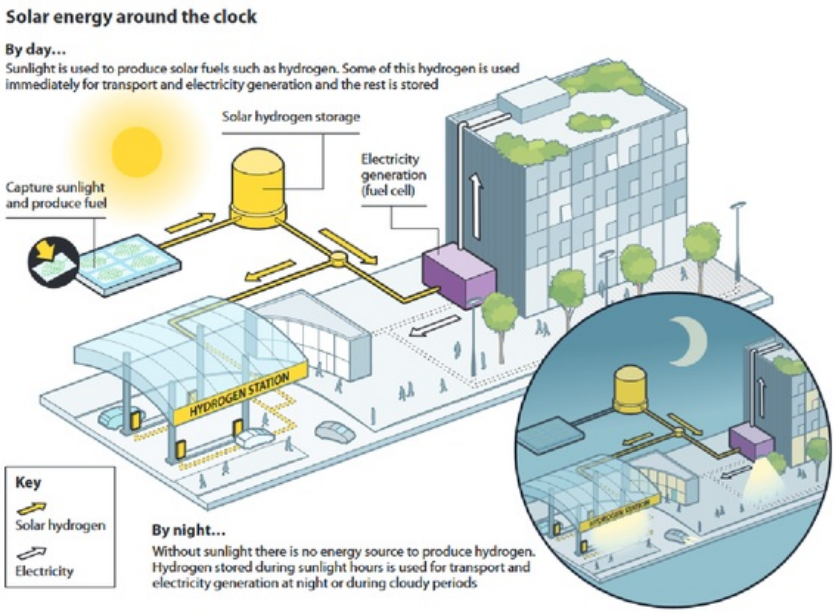


Figure 2.4: Uses of a hydrogen producing CSP plant [4].

This hydrogen that is produced at the CSP plant can then be transferred to where it needs to be used, such as in power stations or as fuel for hydrogen vehicles. This system has the advantage over traditional solar electricity generating plants in that the stored hydrogen can still be used at night to produce electricity, effectively allowing the plant

to run 24 hours a day instead of only when the sun is up. The downsides of this system however is that relatively high temperatures are required to drive the chemical processes ($> 800°C$). This means that when it is cloudy the system will not reach these temperatures and so enough excess hydrogen must be produced to cover for extended periods.

2.2.2 Pyrolysis

Another possible use for CSP is the production of materials through pyrolysis. Pyrolysis is the thermal decomposition of materials, usually organic, in the absence of oxygen [6]. Pyrolysis is an important technology when paired with CSP, as like hydrogen production from water, various materials that can be used as substitutes for conventional fuels can be obtained by breaking down basic organic matter such as wood at temperatures of 650-1000°C in the absence of oxygen. These fuels can then be transported to places where they are required, meaning that when they are used they are a greenhouse gas neutral source of energy [24].

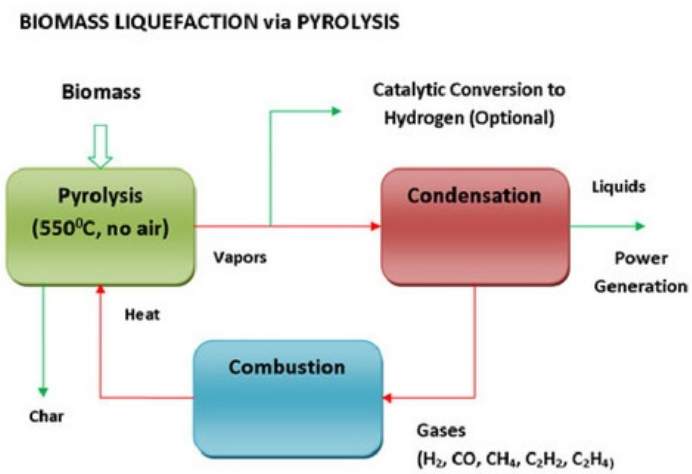


Figure 2.5: Conversion of biomass into different products through pyrolysis [25].

Pyrolysis can also produce a material known as bio-char, which is a carbon rich solid produced at lower temperatures through pyrolysis, usually around 400°C [24]. Bio-char is a particularly useful product to produce from CSP as it can be used to increase the organic contents of soil in ares that have suffered from erosion or over-farming, making them more fertile. On top of this, when bio-char is stored in the soil after being produced through renewable methods such as CSP, it results in a negative carbon cycle, meaning

that it actually takes carbon dioxide out of the atmosphere.

2.3 Heat Absorbing Materials

In order to create the best CSP system possible that is capable of producing high temperatures, preferably in the 500°C range, the best possible material must be chosen to be the receiver of the system. Every material has an emissivity coefficient (ϵ) that determines the amount of heat it re-radiates. This coefficient is between 0 and 1, with 0 being a perfect reflector absorbing no heat and 1 being a black-body that re-radiates no heat. For this reason materials with a higher emissivity coefficient are preferable as they absorb more of the incoming heat from the reflector. While emissivity is very important in the design process, there are other factors that influence the choice of material for the receiver, namely the melting point of the material, its price and how well it conducts heat. There are many basic materials such as concrete and clay that have high emissivity coefficients (ϵ =0.85-0.91) [20]. However they are obviously not ideal materials to make a receiver out off as they are not easy to make into a tube nor do they conduct heat particularly well. Silver and copper are good conductors of heat, having conductivity of 429W/(m K) and 401W/(m K) respectively [21]. While these two materials are both excellent conductors, copper has some significant advantages over silver. Firstly, copper costs around $2USD per pound as of October 2016 where as silver costs over one hundred times as much at around $272 per pound, significantly increasing the cost of building a system. Secondly, and more importantly, silver has a very low emissivity constant at just 0.03, meaning that it reflects most of the heat that hits it. Silver is therefore an excellent reflector, but not a very good absorber regardless of its conductive properties.

Material	Emisivity (ϵ)	Thermal Conductivity (W/(m K))	Price ($USD)
Copper	0.2-0.3	401	$2/lb
Steel	0.79	43	$0.13/lb
Silver	0.02-0.03	429	$272/lb
Aluminium	0.2-0.3	205	$0.75/lb

Table 2.2: Comparison of four common materials that could be used as absorbers.

The emissivity coefficient of the absorber can be increased by coating it with another material that has a high emissivity coefficient. A good example of this is matte black paint. This paint is a very dull black that has little to no reflectivity and usually a emissivity co-efficient close to 1, allowing it to absorb nearly all of the incoming heat. While these paints can be applied to almost any material, the material that it's applied to must have a high thermal conductivity in order to take the heat away from the paint and transfer it to the middle of the pipe as fast as possible so that as little heat as possible is wasted.

2.4 Heat Reflecting Materials

As with the materials for the absorber, there are a range of different materials with differing properties that can be considered for the reflector of the system. The emissivity co-efficient is again used when considering the reflectivity of materials for the system, but this time a lower emissivity co-efficient is desired. This is because the closer to 0 the emissivity co-efficient is the lower amount of incoming energy is absorbed and instead reflects off the material. Two common materials that have a low emissivity co-efficient are aluminium and silver with emissivity co-efficients of 0.09 and 0.03 [20] respectively. With emissivity co-efficients this low these materials can sit in the full sun and stay relatively cool, as the vast majority of the incoming energy hitting them is reflected off. This means that even though these materials have high thermal conductivity, 205-429W/(m K) [21], they are able to stay cool due to their reflectivity. The cost of these materials must again be considered because as stated in the section on heat absorbing materials, silver is extremely expensive compared to other materials. It can however be used as a coating on cheaper materials giving them a reflective property, but an even and consistent coat must be applied to this material to ensure that the reflection is as concentrated as possible onto the focus of the system so that no energy is lost.

Another option that is cheaper than using silver is to use aluminium and polish the aluminium as much as possible. Through this method it is possible to nearly reach the low emissivity co-efficient of silver, with aluminium reaching 0.04-0.05 [20]. The downside to this method however is that depending on how large the reflector is it may take quite a while to polish the entire surface and this could add to costs. the polish also does not last indefinitely and must be reapplied at regular intervals as the aluminium oxidises over time forming a thin white film on its surface. Again this could add to costs and time lost during the polishing process and so must be considered when deciding which material to use as the reflector in a CSP system.

2.5 Parabolic Dish Reflectors

Realistically for this project, of the above CSP systems, dish or trough based systems are the most viable systems to design, construct and test with on the budget and time frame given. Parabolic dish systems consist of a parabolic dish that focuses all incoming energy to a designated point above its surface depending on how the parabola is defined. The major advantage of the parabolic dish reflector over all of the trough based systems is that as the entire surface area of the dish focuses to just one point, much more energy is collected at that point compared to the collection of energy along a line in the trough reflectors. This allows for higher temperatures to be produced at that point than along a tube in a trough based system [7].

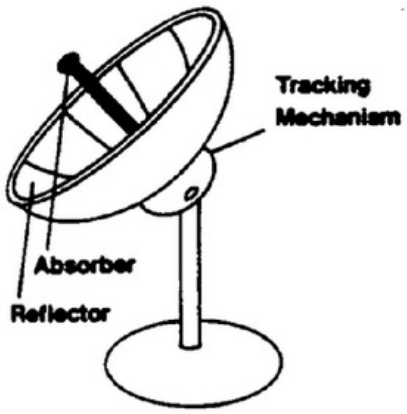


Figure 2.6: A Parabolic Dish CSP System [7].

While this system is capable of producing higher temperatures at its focal point than the trough based systems, it also has a few disadvantages compared to the troughs. Firstly while parabolic dish reflector systems can produce high temperatures at the focal point, this may not be as useful for material processing as a tubular focus. When using a tube materials can be slowly passed through the tube and be exposed to consistent heat the whole way along the length of the tube, where as in a point based focus materials would need to be stopped at the heated point to expose them to the heat.

Additionally, if a parabolic dish reflector is chosen to process materials with due to its advantage in temperature, then a way to transport the materials to and from the focal point needs to be devised. In a trough based system materials can easily be inserted into the tube from the side of the reflector, however with a dish system tubes must be run to the focal point and back while attempting to minimise the amount of incoming energy that is blocked by this system. This means that while the increased temperature of the parabolic dish system may make it an attractive system, the possible drawbacks also need to be considered when choosing a system to process materials in.

2.6 Trough Reflectors

The parabolic trough reflector was chosen for this project due to its relative ease of construction, smaller size than other systems and its ease of processing materials. While the parabolic dish requires material to be transported up to the focus and then back after being processed, the trough system can easily just have materials slowly move through a tube absorber along the focus. If this project is successful in reaching the temperature goal with a system that is easy to process materials in it will be a step towards the easy

processing of solar fuels.

For trough based systems there are a few considerations to take into account when choosing a type of reflector, namely ease of construction, if tracking is required, maximum possible heat and accuracy. The three main types of trough reflectors are parabolic, spherical and compound parabolic concentrators (CPC's). Parabolic and spherical trough reflectors are fairly basic, being composed of a reflective material in the shape of a parabola and half cylinder respectively. CPC's however are a bit more complex, consisting of two different half parabolas pointed at each other with either a flat plate collector in the gap in between them or a cylindrical collector at the point both parabolas meet [1].

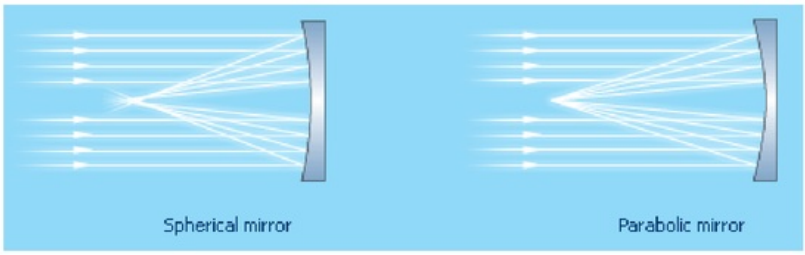


Figure 2.7: Spherical versus parabolic focus points [3].

Each shape has its advantages and disadvantages in relation to various aspects of the design of a CSP system. The strengths and weaknesses of each shape is presented in table 2.3. Spherical collectors are the easiest to build as they have a simple design, only requiring part of a circle to be made and also don't need to have tracking systems attached to them. The downside of spherical collectors however is that they have a wide focus and so receivers need to be made to be wider than those for the parabolic and CPC, giving a lower concentration ratio.

	Spherical	Parabolic	CPC
Tracking	None	Full	Limited
Accuracy	Medium	High	High
Maximum Heat	Low	High	Highest
Ease of Construction	Simple	Simple	Complex

Table 2.3: Strengths and weaknesses of different types of trough collectors [19].

CPC's give the best results as they need limited tracking and produce high heat, but are complicated to build as they require two half parabolas to be accurately built and

usually operate with an evacuated chamber between the top and bottom of the reflector to maximise heat. Parabolic trough reflectors provide a balance between the two, providing high heat, although not as much as the evacuated CPC, and relative ease of construction. For this project the trough reflector was chosen as it has the most versatility in being able to process different materials while also providing high temperatures and concentration ratio.

Chapter 3

Design and Construction of a Trough Reflector

3.1 Simulations of Reflector Styles

In order to begin testing of different methods and materials that could increase the temperature of a CSP system, a reflector must first be designed and built to facilitate this testing. This reflector will be designed to reach the project goal of 500°C (773.15°K), which will provide a good base for future work and improvements on the system. The first step in the design process was to decide which type of trough reflector would provide the best combination of maximum temperature produced and ease of construction. These characteristics were briefly covered in table 2.3 in Chapter Two, however this chapter will go into more depth about how the results on heat were found through the use of simulations. The program that was used to conduct simulations for this project was a program called SolTrace, a free program designed specifically to simulate CSP systems. In order to simulate each type of reflector a preliminary design had to be created for each reflector. For this a few different equations were needed. The first of these, the parabolic equation, is as follows.

$$y = \sqrt{4fx}$$

Where f is the focal length [19] given by:

$$f = \frac{d^2}{16h}$$

With d being the aperture and h the depth of the parabola [19]. For the spherical reflector the only equation that is required is the equation for the focus.

$$f = \frac{r}{2}$$

So by simply choosing the radius r or focus that we desire we can decide the dimensions of the spherical reflector, making design relatively straight forwards. Design of the CPC

on the other hand is a little more complex. When designing for a flat plate collector CPC (where the collector is at the bottom of the system) the following equation is used.

$$y = \frac{x^2}{2b(1 + sin(\theta c))}$$

Here θc is the acceptance half angle and b is the width of the absorber [14]. These simulations give us the flux produced at the receiver of the system. The equation that allows us to determine the average temperature from the average flux is derived from the Stefan-Boltzmann Law for grey bodies:

$$T = \sqrt[4]{\frac{F}{\epsilon\sigma}}$$

In which F is flux, ϵ the emissivity co-efficient and σ the Stephan-Boltzmann constant [23]. The results gathered from this equation are the temperatures achievable under ideal conditions and may not correlate to the same results in practice. This is because the simulations do not take into account things like convection, atmospheric conditions and imperfections in the reflector which affect real world systems.

In order to start the simulation process a few parameters of the reflector first had to be decided, namely the desired aperture of the system and the size and emissivity of the absorber. For this project an aperture of two meters was chosen with the absorber being a one inch (32mm) copper pipe with an emissivity co-efficient of 0.8. These dimensions were chosen as a wide aperture was needed to collect as much energy as possible without being too large that it was difficult to move, and an absorber was required that would be able to fit materials through it to be processed. The first type of system that was simulated in SolTrace was the parabolic reflector.

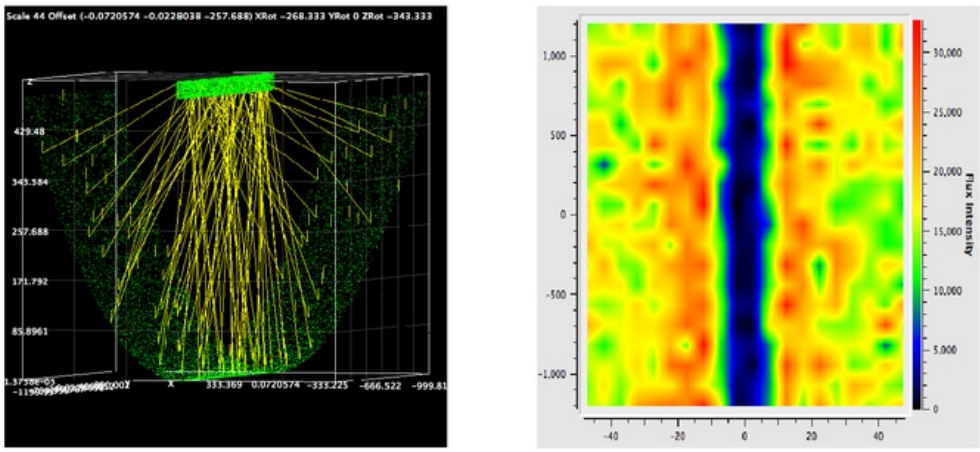


Figure 3.1: Parabolic trace and flux distributions.

Figures 3.1 above shows the path of the sun rays as they hit the reflector and reflect onto the receiver and the flux pattern produced from this respectively. As can be seen above the receiver for the parabolic reflector is a tube that sits at the focal point of the trough, 30mm above the top of the reflector. The flux pattern for the parabolic reflector is quite well spread out which creates even heating of the receiver, giving an average flux of $15976.9W/m^2$, which results in an average temperature of 770°K. The efficiency of this system in terms of the amount of collected rays from the reflector that hit the reviver is 75.7%.

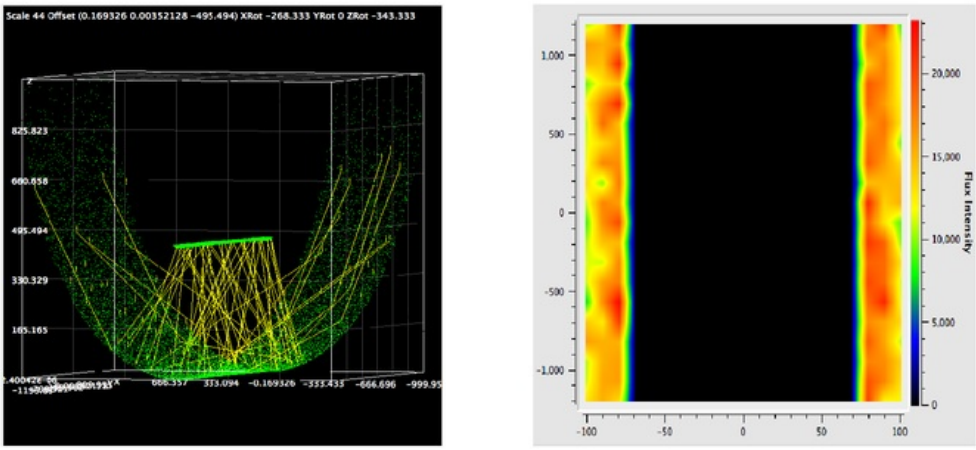


Figure 3.2: Spherical trace and flux distributions.

The flux pattern for the spherical reflector is quite different as the focus of the spherical reflector is quite a lot bigger than that of the parabolic reflector, only having an efficiency of 36.9%. This is why we see the large concentration on the bottom of the receiver instead of being all around the receiver like in the parabolic system, as it is hard to position the focus in the middle of the tube to get an even distribution of flux with the spherical collector. While the flux map may give the impression that the spherical system provides higher flux, this is not the case as it only produces an average flux of $4650.81W/m^2$ and temperature of 565.85°K, giving an average flux more than three times lower than the parabolic receiver and a significantly lower average temperature.

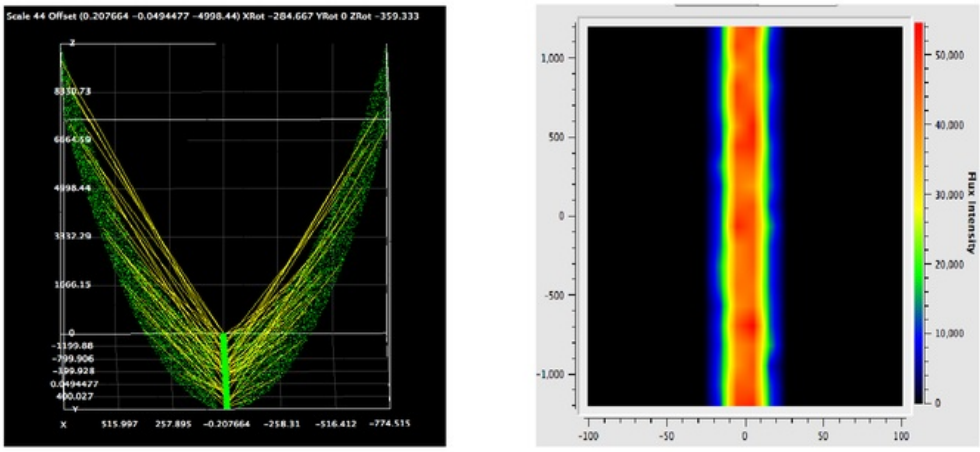


Figure 3.3: CPC trace and flux distributions.

The trace map of the CPC shows that the rays hit the receiver fairly consistently, giving it a high efficiency at 77.6%, the highest of the three. The flux distribution is very narrow like the spherical collector, giving high flux in one region of the pipe, this time the top, and none at the other parts. This is probably due to the fact that CPC's are optimised to work with flat plate collectors not tube collectors. The average flux in this system is $5685.98W/m^2$ (595.01°K), which is also lower than the parabolic system. Of note however is the peak flux in this system, which peaks at $54642.6W/m^2$, giving a peak temperature of 1047.63°K, far above either of the others.

After analysing the results of the simulations it was decided that the parabolic system was the best to conduct this project with as it has the best flux distribution for a tube type receiver, highest average flux and is not too hard to construct, as the parabola can be as flat or steep as desired with a two meter aperture, with just the focus moving. It does however mean that a full tracking system needs to be implemented on the system as the parabolic reflector must always be pointing directly at the sun for maximum efficiency.

3.2 Focus Placement

After deciding on using a parabolic system for the project, a more specific design had to be created. The main point of concern for this part of the design was ensuring that the focus of the reflector was at a height that maximised temperature as well as minimising losses due to convection and being easily accessible for testing. To find out which focus height gives the highest amount of flux, various heights were inputted into SolTrace to see how flux and efficiency were effected while keeping the aperture the same size for all simulations. The main point of these simulations was to see if flux increased if the receiver was brought down inside the reflector which would possibly lower the convection losses as there would be less air flow around the receiver to take the heat away. To accomplish this simulations were done by adjusting the depth of the reflector starting at a depth of 50mm and increasing the depth in 50mm increments until the reflector depth reached 300mm. As the aperture was kept the same size, when the depth was increased the focus eventually moved from high above the reflector to down inside the reflector.

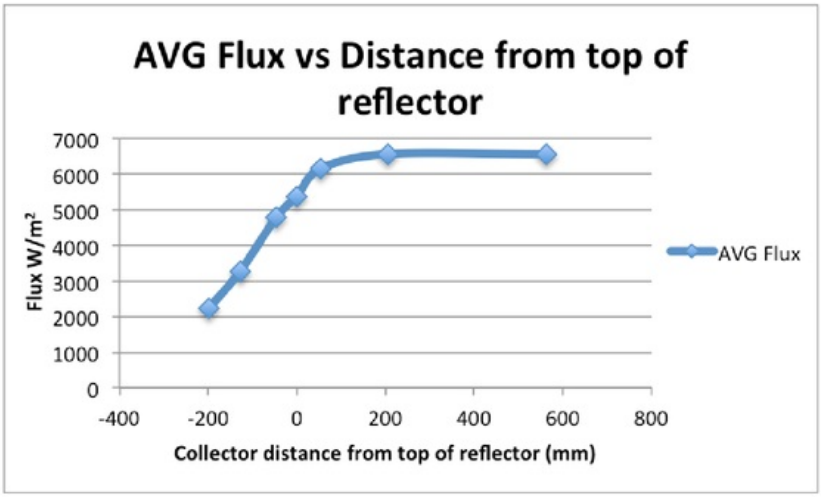


Figure 3.4: Flux versus receiver height. Values start negative as the receiver starts below the top of the reflector.

The flux distributions of the simulations are shown in Appendix B. These results show that the flux distribution starts off focused on the bottom of the tube, as the first simulation at a reflector depth of 50mm has the receiver far above the reflector, and then gradually becomes more evenly spread as the receiver nears the top of the reflector, before becoming more concentrated again as the receiver drops down into the reflector. Figure 3.4 above illustrates the increase in average flux as the receiver is brought out of the re-

flector. The negative distance indicates that the receiver is below the top of the reflector and so the tube is inside the parabola. As shown in this figure, the flux steadily increases as the receiver is raised up until just after it clears the top of the reflector where the average flux stabilises.

The efficiency of the system is also low when the receiver is beneath the top of the reflector and again steadily rises and stabilises after rising above the reflector as shown in table 3.1. The most likely reason for this is that when the receiver is below the top of the reflector, the reflector actually blocks some of the energy coming from the sun from reaching the receiver due to the tall sides of the system. The parabola could be truncated to avoid this problem, but then reflective surface would be lost and it would be better to just have a wider shallower parabola instead.

Distance from top of reflector (mm)	AVG flux (W/m^2)	Efficiency %
562.5	6556.79	97.7
206.25	6564.99	97.6
54.17	6162.63	92.5
0	5380.53	80.6
-46.87	4781.19	58.7
-127.5	3281.79	33.3
-197.92	2243.99	19.8

Table 3.1: Results of simulations of different focus points.

This leaves us with the four simulations that are either level with or above the top of the reflector. Within these simulations there is a noticeable increase in efficiency and flux between the reflector being 0mm and 54.17mm above the reflector, but the increase drops of after that. Because of this the best route to take in designing the system is to chose a height that is above the top of the reflector, but also easily accessible and convenient for the construction process.

3.3 Alignment

An important part of the design of a parabolic trough reflector system is deciding how it will track the sun. There are two main types of tracking that are used for parabolic trough reflectors which are 2d systems and 3d systems. For 2d systems the reflector rotates on one axis throughout the day while 3d systems have the reflector rotating on 2 axes. 3d systems have increased accuracy due to the system being able to track the sun in two directions across the sky. This in turn leads to higher concentration ratios and higher temperatures at the absorber. The downsides of 3d tracking however is that it is more expensive than 2d tracking, requiring another actuator or motor to drive the system, and

that it adds complexity to the design requiring more motors and a more complex sensor.

Trough absorbers can be placed along either the east-west or north-south axis depending on what style of tracking they are using. For systems that use 2d tracking or just manual adjustment, placement with the focus running along the east-west axis is preferable. As the sun travels across the sky in a arc from east to west, these systems can gather at least some energy throughout the day as even at shallow angles some radiation is reflected onto the absorber. Tracking in the north-south direction allows 2d systems to collect more energy than stationary systems as they are able to track the sun as it moves up and down the sky from sunrise to sunset. This system is not ideal however because as mentioned earlier when the sun is not directly overhead on the east-west axis, some energy will be lost. This is due to the angle it hits the reflector as the angle will be too shallow or deep and reflect into the wall or out of the system. Tracking systems that utilise 3d tracking avoid this problem however as they are able to rotate along both axes. This allows them to keep the sun directly above the focal point at all times throughout the day, maximising the amount of energy collected and minimising losses due to shallow and deep angles.

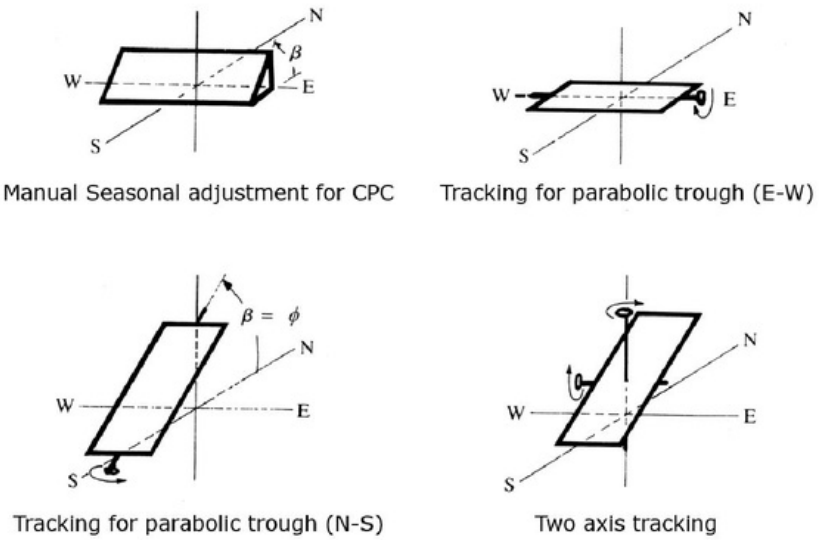


Figure 3.5: Four diferent options for solar tracking on a trough system [8].

For this project a system that is in between 2d and 3d tracking was chosen. In this system the reflector would be placed along the north-south axis as if it was a 3d tracking system. This system however will only contain automated tracking rotating about the north-south axis and will have manual adjustment about the east-west axis. A system

similar to this is shown in the bottom left image in the figure above. The reason for this design choice is that while the tracking system being used on the project allows tracking in two dimensions, a feasible way to allow the system to track about the east-west axis could not be found that was within the project budget and easy to construct. While this system will obviously not be as accurate as a full 3d tracking system, it will still provide a higher concentration ratio than a 2d system, resulting in higher temperatures and less losses.

Chapter 4

Construction and Setbacks

For this project a CSP system had to be designed and constructed from scratch as nothing suitable was available in the scale or price range to purchase pre-made. The system was designed based on the potential uses and requirements of solar materials processing with input from the project supervisor Dr. Graham Town when problems arose. The final design of the system ended up being a parabolic trough reflector two meters wide by 1.2 meters long with a height of 1.2 meters as well. This trough would sit on top of a base with rollers on it that allowed the whole system to be easily moved around and also allowed it to rotate in place while tracking the sun. This chapter will detail the design process through each stage of design and also the setbacks that occurred during design and construction that caused the building of this system to take so long and limited testing time.

4.1 Initial Construction

Early on in the project it was decided that the reflector had to be large to achieve the high temperatures desired. This meant that large quantities of material had to be sourced such as aluminium which required traveling to large distributors away from where research and construction were to take place. Sourcing these materials and transporting them took longer than expected and unfortunately set the project back a week or two. Another early setback was finding a way to create the parabolic shape of the reflector. This shape could be made by hand using calculations and then cutting it out of the wood, but this would have resulted in an imperfect shape meaning that energy would have been lost. Instead it was arranged to use the Computer Numerical Control (CNC) mill at university to cut a parabolic slot in the three pieces of wood that would make up the frame of the reflector. This however also took longer than expected as a suitable time had to be found where the wood could be transported to university and cutting of the wood could be overseen. During this process the wood had to be cut half a piece at the time due to the large size of the wood, increasing the possibility for error.

Figure 4.1: Wood on the CNC being cut half a piece at a time.

After the parabolic shape was cut each piece of wood had a half circle cut into it to allow the system to roll while tracking the sun. The three pieces were then connected using cross beams to give it support and stop the wood from warping. Pictures of this process can be found in Appendix C. The end product of all of this was a parabolic reflector mounted in a half circle with a radius of 1.2 meters that could roll to track the sun. The aluminium sheet was then slotted through the parabolic slots to form the reflective surface and a copper pipe placed at the focus, completing the initial design.

4.2 Implementing the Tracking System

Originally it was planned that the system would roll on its half spherical base in order to track the sun, removing the need for complicated tracking systems. As pointed out by Dr. Graham Town however, this was impractical as the system would need several meters of space to roll from side to side instead of staying in the same place. From this a design was created where the system would sit on six rollers evenly spaced out on a base. This base would sit on wheels allowing it to be moved easily with a jockey wheel at the front to allow the system to be tilted in order for tracking to properly function. This system took longer than expected to build however as the parts had to be sourced on the tight budget while also being strong enough to support the system. In the end a plywood base was used with wheels underneath this base allowing it to easily roll. Rollers for boat trailers were used as the rollers for the system as they were cheap and also sturdy, being made out of hard rubber. The actuator was then attached to the base and to the middle piece of wood on the reflector. However due to how the reflector was constructed, the actuator

had to be attached close to the outside of the spherical shape, limiting how far the system can rotate compared to if it was further in on the sphere.

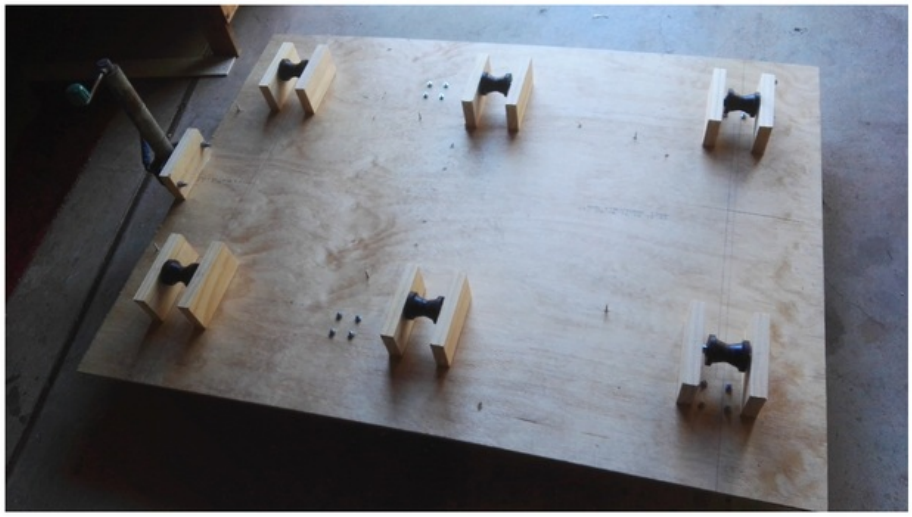


Figure 4.2: The base that the reflector rests on with rollers and jockey wheel to tilt the whole system.

4.3 Setbacks During Testing

Testing of the system relied on a couple of variables all aligning to allow testing of the maximum efficiency of the system to be conducted. Most important of these variables was the cloud cover present each day. On many days when testing was planned to take place there was significant cloud cover. This ranged from patchy clouds, in which testing could still take place but only periodically, to complete cloud cover that blocked the sun and caused testing to be delayed to another day. This was a major problem during the project as because the construction took longer than expected, testing time was limited to a few weeks and any lost testing time impacted on the reliability of the results. Another important variable that had the potential to delay testing of the project was the amount of wind present during testing. While the wind generally did not stop testing unless there was a lot of wind, it did increase the amount of heat loss due to convection, and the higher the wind the more loss there was. This means that it was difficult to find the maximum heat and efficiency of the system as the system was not able to be isolated from the wind. Due to the limitations of the tracking system as described in the section above, the system was only able to be tested utilising the tracking system when the sun was close to the middle of the sky. During tests this ended up being from around 10:30am-

2:30pm, although this may change with the time of year. This limitation along with the weather limitations detailed above made it so that testing relied on all these variables being favorable in order for it to be possible.

Chapter 5

Testing And Results

Throughout the project three main tests were conducted. In order that they occurred, these tests were:

- Initial Testing - This stage tested the system with a basic uncoated copper pipe and untouched aluminium sheet and determined the maximum temperature attainable as well as the concentration ratio and absorption efficiency of the system.
- Coating the Absorber - In this stage the absorber was coated and testing carried out to determine if this made any differences.
- Polishing the Aluminium - Finally the aluminium will be polished and testing again carried out to see if this improves on the results of the coated pipe tests.

Throughout all these tests the FLIR TG165 infrared imager and a thermocouple was used to record the temperature of the absorber. The infrared imager works by absorbing the incoming infrared radiation from object and turning this into a picture. This is like how a regular camera turns visible light into a normal picture. The infrared imager however assigns different colours or shades of colours to different intensities of infrared light that it receives, allowing us to see which objects are hot and which ones are cold. This incoming infrared radiation also allows it to calculate the temperature of the object being measured as the intensity of the incoming radiation can be converted into a temperature. This feature depends on the emissivity of the object being measured which can be set in the imager, and so this must be know in order to use the TG165 to receive accurate measurements. The temperature of the absorber was the primary measurement taken as the temperature achieved at the absorber was the result of many different variables, some controlled and some not. For each test the system was manually raised or lowered about the east-west axis until the focus of the reflector was as concentrated as possible on the absorber.

5.1 Initial Testing

Before attempting to improve on aspects of the system, initial testing took place to determine the temperatures that could be reached with the system without any improvements. For these tests the very basic initial system was used. As these tests took place before the tracking system was fully implemented, the system was manually maneuvered to track the sun on its base. The aluminium reflector was unpolished and the copper absorber tube unpainted during these tests to ensure that a good base temperature was set before improvements to the system were made. It should be noted that the results that the system is able to produce are affected by a number of different variables that change every day, such as angle of the sun, cloud cover, wind, time of day and temperature. Because of this many tests need to be done over a variety of different conditions to get a definitive result and unfortunately lack of time prevented this from happening during this project. Future testing should hopefully yield more concrete results for all stages of testing.

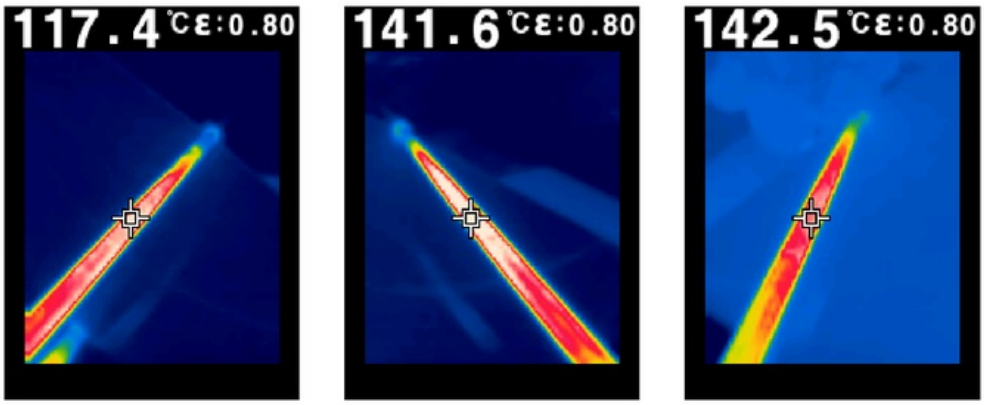


Figure 5.1: Results of three tests with an unmodified absorber and reflector.

On the day of testing there was an average solar exposure level of 4.9kWh/m^{-2}. Wind speed on the day of testing was light with an outside temperature of 22°C with minimal cloud cover. Through this initial testing temperatures of 200°C were recorded. This temperature was lower than hoped for the initial test, however it was not unexpected for a day with relatively low insolation and with no improvements made to the system yet. Through the use of the equations shown in the Background section for mean flux concentration ratio (C) and $\eta_{absorption}$ we can determine the concentration ratio in suns for the system and its absorption efficiency. Calculating the mean flux concentration ratio using a Q_{solar} of 3727.708W/m^2, $Q_{aperture}$ of 3226.12W/m^2 and insolation (I) of 4.9kWh/m^{-2}. The result of this was a concentration ratio of 322.35 Suns, which is in the typical range for trough reflectors. The absorption efficiency of this system using a effective emittance

(ϵ_{eff}) and effective absorbtance (α_{eff}) of 0.2 and 0.8 respectively was calculated to be 33%, meaning that 33% of the suns energy that hit the reflector was converted into heat at the absorber.

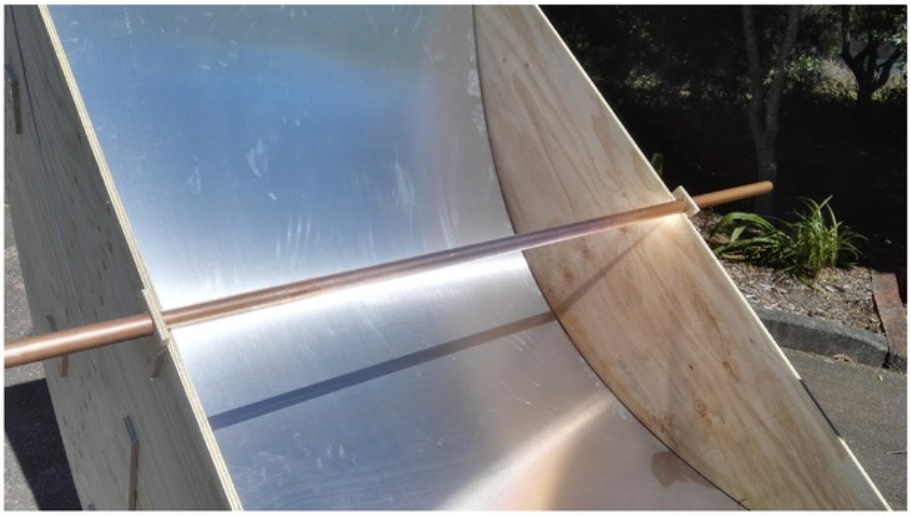


Figure 5.2: Black oxide forming on the pipe during initial testing.

Some of the reasons for this low level of efficiency is because of how basic the system is in this first test. The most obvious reason is that the tracking system had not been fully implemented yet and so the system was not able to keep the sun completely centered so that maximum concentration was on the focal point. This would have had a fairly large effect on how much heat was being generated by the system. The parabolic shape of the reflector requires the system to be pointing directly at the sun to focus the incoming energy on the absorber. Slight variations away from this centering can result in a wider focal point and a more dispersed concentration of the energy on the absorber. Another reason that the efficiency may be low is that the aluminium had not been polished and the copper had not been coated. This is important as unpolished aluminium has a higher emissivity co-efficient than polished aluminium. As stated in the Background section, this means that the aluminium will absorb more of the incoming energy than if it was polished, affecting the amount of energy reaching the absorber. More importantly than this however is that the copper absorber had not been coated with anything and was still relatively shiny. This gives it a lower emissivity meaning that it reflects more of the incoming energy from the reflector than if it was coated with a high emissivity co-efficient material. These two issues combined with the lack of tracking would contribute to the low efficiency of the system at this level. One unexpected result of the heating which may have helped the copper pipes absorbing ability however was its oxidisation at high

temperatures. After around a minute of being exposed to the heat the pipe started to produce a black coating on its outside. First starting in the middle where the heat was the most intense, it then spread along both ends of the pipe to near where it met the wall of the reflector. This black oxidisation should have helped raise the emissivity co-efficient of the pipe allowing it to absorb more but was still not as dull as a matte black paint could make it.

5.2 Coating The Absorber

Once initial testing was complete it was decided that the absorber would be improved first to see the effect that this had on the output temperature of the system. Before this was done however, the tracking system was to be completed in order to provide more accurate results for this stage of testing. For this test the reflector was left the same, being an unpolished aluminium sheet but the absorber was coated with VHT flame proof black paint, which is capable of reaching temperatures of up to 1200°C. The point of applying this paint is to raise the emissivity co-efficient of the material receiving the incoming radiation from the receiver. In this case the paint can raise the emissivity co-efficient to 0.9-0.94 [5] allowing it to absorb a significant amount more incoming energy than just the copper alone. This method works due to the coppers high level of thermal conductivity, 401(W/(m K)). This means that heat in the black paint can be transferred away from the surface touching the paint and into other parts of the copper pipe such as the middle.

Figure 5.3: Reflector and tracking system combined to form the final system.

On the day that the tests took place with the coated absorber there was a solar exposure level of 7.1kWh/m^{-2} with winds being moderate with strong gusts. Cloud cover was again minimal and the outside temperature was 29°C, although it felt much cooler due to the wind. Test one, conducted at 11:30am, yielded a temperature of 229°C after being in the sun for five minutes. The second test conducted ten minutes later at 11:45am again for a time of five minutes gave a maximum temperature of 276°C, a large increase over the first test. Finally at midday the third test was conducted with a time of five minutes in the sun and produced a result of 281°C, a modest increase on the result of test two. These results were slightly lower than what was wanted, as it had been hoped that temperatures in excess of 300°C could be reached with the absorber coated in matte black paint. Calculating the mean flux concentration ratio using the same Q_{solar} and $Q_{aperture}$ as in the initial testing section along with an insolation (I) of 7.1kWh/m^{-2}, the concentration ratio of 222.47 Suns. The absorption efficiency for this system using a effective emittance (ϵ_{eff}) of 0.1 and effective absorbtance (α_{eff} of 0.9, was calculated to be 44%.

This system with the coated absorber has a significantly higher absorption efficiency than the initial test but also has a lower concentration ratio. The loss of concentration ratio is possibly because as the insolation level rises causing the reflector to be hit with more radiation. This means there would be more losses due to some energy being absorbed into the reflector, a greater proportion of radiation missing the absorber due to imperfections in the reflector, and increased losses due to reflectance off the absorber. All these minor losses add up to a greater ratio of lost energy compared to incoming energy, resulting in a lower concentration ratio. The absorption efficiency however is higher than the original test due to the higher emissivity co-efficient of the black coating on the copper pipe. Because of this more of the incoming energy is absorbed instead of being reflected off.

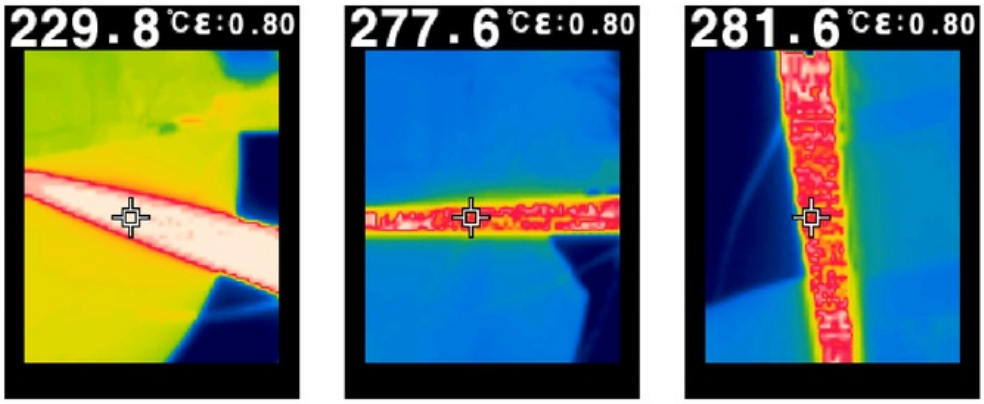


Figure 5.4: Results of three tests with the absorber coated with matte black material.

There are a few reasons for why these test results may not have reached the desired temperature. Firstly is that during the first test and part of the second test the paint started to emit steam as it heated up. This is most likely because it was curing, meaning it was the first time it had been heated up after being applied or it was foreign objects stuck in the paint while burning off. As the paint made steam the steam may have aided in the convection of heat away from the absorber and also may have blocked or reflected/refracted some of the incoming radiation from the reflector. Most of this steam had disappeared by the second test, helping to produce the higher temperature and was gone altogether by the third test. The other factor that had a larger impact on the temperature however was the wind on the day. The wind was moderate with average speeds of 12Km/h and gusts reaching up to 30Km/h and was a cool wind. This wind helped the convection take place as the constant passing of cool air over the pipe allowed heat to be constantly carried away from the system. Without this wind it is likely that the system would have surpassed the 300°C mark, so future testing may yield this result.

5.3 Polishing The Reflector

The final stage of testing involved the polishing of the aluminium that made up the reflector of the system in order to see if this would increase the systems efficiency and allow for higher temperatures to be achieved. Polishing the aluminium to make it brighter and more reflective should decrease the emissivity co-efficient of the aluminium thus allowing it to reflect more incoming radiation and send it towards the absorber. For this stage of testing polish specifically made for aluminium was originally intended the be used. However after polishing a test piece of aluminium it became apparent that this polish actually increased the emissivity co-efficient rather than lower it. Because of this the aluminium was absorbing more radiation and heating up more than unpolished aluminium. This was because the polish was making the aluminium darker while also polishing it. While the end result was aluminium that was polished it was not as shiny as the original unpolished aluminium. After assessing the reflector it was noted that it was already quite shiny but had many finger prints and marks on it from when it had been handled during construction. Therefore instead of using polish all purpose cleaner was used to clean the surface of the aluminium and remove any marks that may have been obstructing reflection.

The conditions on the day of testing the polished system were as follows. There was zero cloud cover, which helped contribute to the highest solar exposure of 7.7Wh/m^{-2}, with light winds and the occasional gust. The outside temperature was 27°C meaning the conditions were relatively close to the conditions of the coated absorber test. The first test was conducted at 9:45am and only produced a temperature of 186°C. The reason for this is that the limitations of the current tracking system causes the focus not to be focused to a point on the absorber as the angle of the sun in the sky is too shallow. Due to this low temperature, testing was delayed until 10:55am where a temperature of 236.8°C was recorded. Tests were then conducted every fifteen minutes for five minutes

each, seeing gradual gains in temperature until at 12:00pm a maximum temperature of 303.1°C was reached. Tests after this yielded lower results in the 290's°C as the wind changed to a more unfavorable direction. These results achieved temperatures of over 300°C, however it had been hoped that polishing the reflector would have made a larger improvement on the unpolished reflector. The concentration ratio of this system with an insolation of 7.7kWh/m^{-2} was calculated to be 205.13 Suns. The absorption efficiency at a temperature of 576.25°K with the same effective emittance and absorbtance as the previous test is calculated to be 38%.

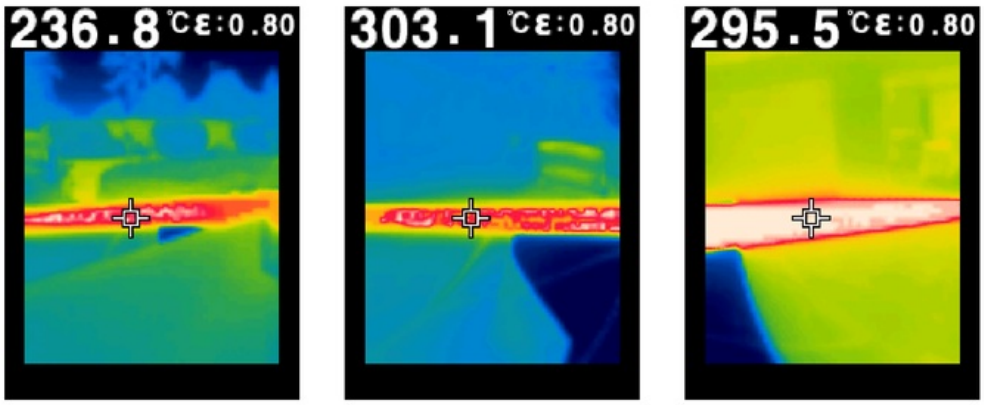


Figure 5.5: Results of three tests with the absorber coated and the reflector polished.

Even though the system managed to break the 300°C mark, this may have had little to do with the polishing of the reflector. While polishing the reflector did remove a lot of the fingerprints and dirt on the reflector, it didn't help to remove scratches and other impurities in the metal. Because of this it is more likely that the better conditions on the day of testing allowed the system to achieve the extra 20°C needed to pass the 300°C mark. The lack of any clouds at all allowed for a higher insolation level along with low wind levels for most of the testing period. These favorable conditions most likely enabled the higher temperatures on the day. This isn't to say that the polishing did nothing however. The system that was used in testing only had the aluminium on it for about two months so not much oxidation or dirt had gotten onto it. In a real life system operating outside 24 hours a day however, periodic polishing would be required to keep the surface reflective enough to allow the system to operate at maximum efficiency.

5.4 Results Discussion

5.4.1 Temperature

Through analysing the results gathered from the different stages of testing we can determine what factors allowed the system to achieve higher temperatures. The graph below shows the different temperatures recorded during three different tests for each stage of testing.

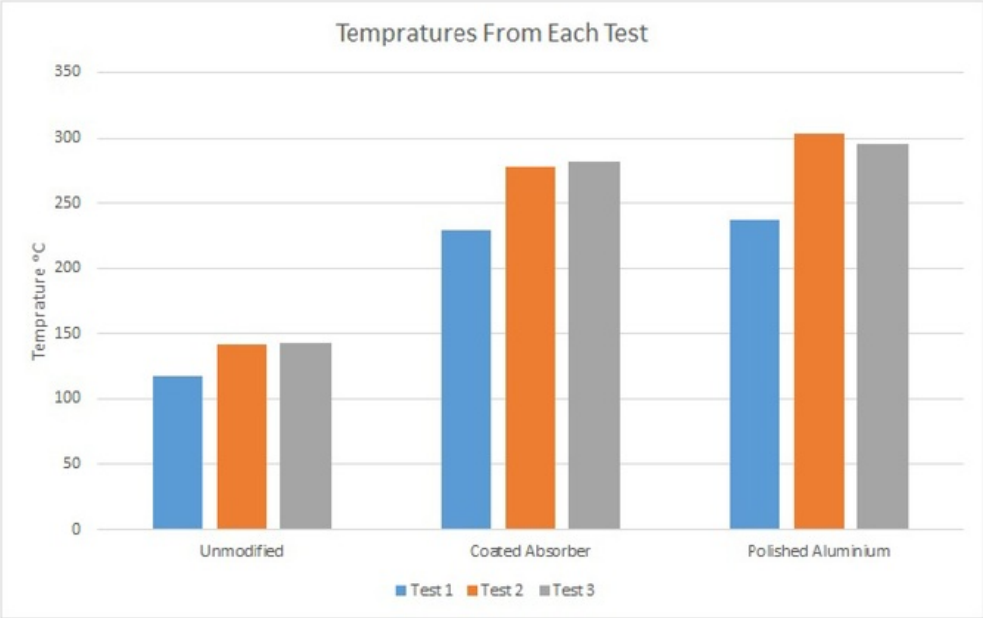


Figure 5.6: Maximum temperatures of three tests from each stage of testing.

As seen from the graph, the first set of tests while the system was unmodified produced much lower temperatures than the later tests. The main reason for this as stated in the above section is that the copper absorber was un-coated, giving it a fairly low emissivity co-efficient. This allowed it to reflect a good amount of incoming radiation. The system also suffered from having no tracking system implemented in this stage of testing, lowering the amount of time that system was able to spend with the radiation completely focused on the absorber. Interestingly the results from the second and third tests where the absorber was coated and reflector polished respectively do not show a large difference. The increase in temperature from the first test to the second one with the addition of the tracking system and coating of the tube is obvious, at times adding over 100°C to the temperature of the absorber. This vast increase is not replicated with the polishing of

the reflector however, with only an increase of 20-30 degrees being recorded. The main reason for this is that the coating of the absorber significantly increased the emissivity co-efficient of the copper, stopping much of the radiation being reflected and absorbing it instead. Polishing the aluminium however only slightly lowered its emissivity co-efficient as aluminium already has a low emissivity, only really being beaten by a small margin by silver. The increases between the second and third test could even be mostly contributed to improved conditions, although polishing the reflector would have had at least a small positive effect on the temperature.

5.4.2 Concentration Ratio

Another interesting result that was gathered from the different stages of testing was the different mean flux concentration ratios and absorption efficiencies that were achieved for each stage of testing. The concentration ratio dropped significantly between the first and second tests however only recorded a small drop between the second and third tests.

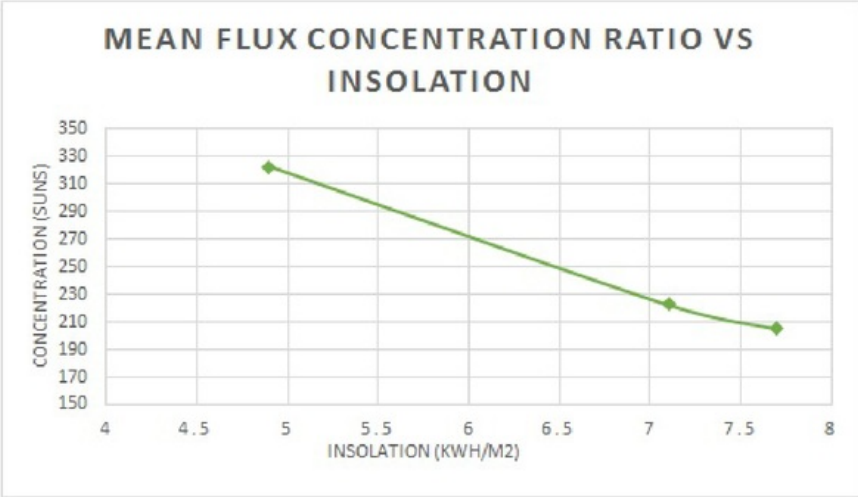


Figure 5.7: Flux concentration ratio decreases as insolation increases.

This result was mentioned briefly in a previous section but will be explained in more detail here. The reason that this happens is that as the level of incident radiation increases or decreases, different amounts of radiation hit the reflector of the system. With low insolation levels there is not as much radiation hitting the absorber. This means that there is less chance that the radiation will be reflected badly by the reflector, hit an impurity or reflect off the absorber. Because of this the amount of radiation hitting the absorber would be a higher portion of the incoming radiation. With a high level of insolation, there is more chance for an incoming ray of radiation to be absorbed, hit an

impurity or miss the absorber. Because of this the percentage of incoming radiation that reaches the absorber would be less, even though more reaches the absorber than with low insolation levels. Higher levels of incident radiation allow the absorber to reach a higher temperature even though a smaller percentage of incoming radiation reaches the absorber.

5.4.3 Absorption Efficiency

The absorption efficiency also varied during testing depending on which stage of testing it was recorded in. Between the first and second test the absorption efficiency increased dramatically by around 10%. However between the second and third test the absorption efficiency dropped by 6%, seemingly canceling out much of the gains made between the first two tests.

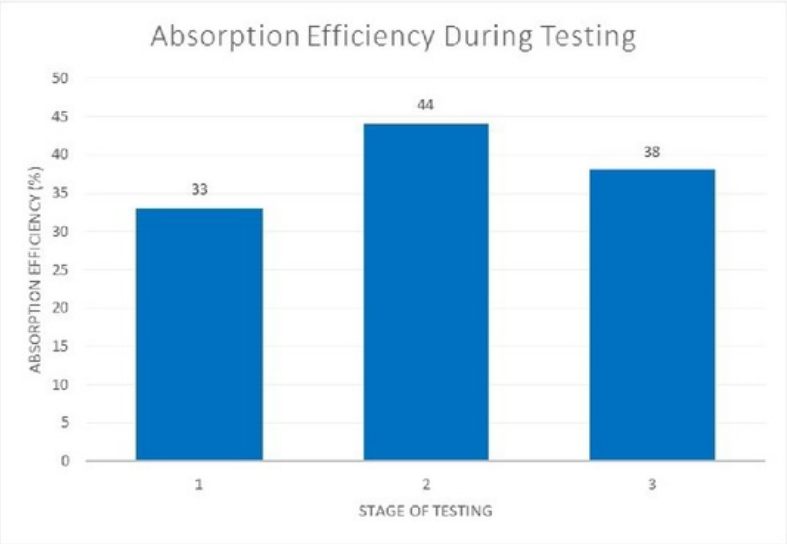


Figure 5.8: Absorption efficiency during different tests.

The fact that the efficiency jumped by so much between the first and second tests indicates the effect that coating the receiver had on the absorption efficiency of the system. Because the absorber was un-coated in the first test, much of the radiation being reflected off the reflector was also being reflected off the un-coated pipe. This was because the pipe was relatively reflective to start out with, having a low emissivity co-efficient. The radiation being reflected off the absorber is not converted into heat and so lowers the absorption efficiency of the system. When the absorber was coated for the second test it raised the emissivity co-efficient of the absorber significantly. This allowed the absorber to absorb more of the incoming radiation, minimising losses due to reflection at

the absorber. Because a greater amount of the radiation coming from the reflector was being absorbed this raised the absorption efficiency significantly, which also correlates to the increase in temperatures recorded during this test.

The third test is the outlier in the results, recording a drop in absorption efficiency after the aluminium was polished to attempt to achieve higher temperatures. One explanation for this drop in absorption efficiency is that the increased radiation being reflected from the reflector, due to the polishing of the aluminium and increased insolation, should have created a higher temperature at the absorber. The equation for absorption efficiency does not take into account the conditions of the day besides the insolation level, so if the temperature at the absorber was pushed down due to outside influences like wind, the absorption efficiency would also be lower than its ideally should be.

Chapter 6

Conclusions and Future Work

6.1 Conclusions

During this project an explanation of the background material and theories and thorough explanation of the process undertaken to conduct simulations has been completed. This was done with a parabolic CSP system designed through the methods described in Chapter Three. This system has an aperture of 2000mm, a length of 1200mm and a focal point at 515.46mm above the vertex of the parabola. The focus point is also 30mm above the top of the reflector where it receives good flux distribution, is easily accessible for testing and sits at the same level as the top of the frame so that the collector can be easily built into the system. Construction of the system began early but ran into several problems pushing back the completion time of the entire system and limiting time for testing. Three main stages of testing were carried out on the system involving the system as it was built and then two main improvements to attempt to increase the over all temperature and efficiency of the system. It was found that coating the absorber of the system with low emissivity material significantly raised the temperature and efficiency achievable with the system, however polishing the reflector did not have such a dramatic effect. While the system did not reach the desired goal of 500°C, only reaching a maximum of 303.1°C, there is certainly scope in future work to achieve this goal by making modifications to the current design. If the project could be done again with increased funding, the tracking system and absorber would be uprgraded in order to increase efficiency and accuracy of the system resulting in a higher opperating temprature.

6.2 Future Work

Future work for this system involves a lot of possibilities. The most obvious work that can be done to the system in the future is improving the tracking system to allow the system to track the sun form sunrise to sunset. The easiest way to do this would be to replace at least two of the rollers on the base of the system with motorised rollers. These rollers would replace the actuator that currently moves the reflector by pushing and pulling it

so that it moves along the rollers. This would get rid of the limitations of the actuator, allowing the system to rotate fully and track the sun all the way across the sky. It would also have the added benefit of putting less strain on the system because the load would be spread out instead of being focused on one point where the actuator connects to the reflector.

An additional upgrade that could be worked on in the future is changing the absorber to something that lowers the heat losses compared to the absorber used at the moment. One way that this could could be achieved is to replace the current matte black coated copper pipe with an evacuated glass tube receiver. Evacuated glass tubes are tubes that have an inner pipe, usually made out of copper and coated in black, and a surrounding glass tube. Between this tube and the copper pipe is an evacuated section. This vacuum allows radiation to pass through it and heat up the inner copper pipe just like it would heat up the current pipe, however due to the vacuum surrounding the pipe there are no losses due to convection as the heat cannot be transferred away through the vacuum. Because of this all the heat is either trapped in the copper or is transferred to whatever is in the middle of the pipe, whether this is air, water or materials to make solar fuels. As convection is the major reason that the system loses heat, this new type of absorber should be able to significantly increase the maximum temperature attainable from the trough system.

On top of this another object that could be added to improve the system is a solar panel and battery. Adding a solar panel and battery onto the system means that the system would be completely independent from outside power, allowing for an isolated system. This means that the CSP system does not rely on fossil fuels in order to power it, which when producing solar fuels is important to ensure that the fuels it produces are either carbon neutral or actually absorb carbon. Because the system will usually be in full sunlight, only a small battery and solar panel would be required as the system does not constantly require power and when it does require power it is only to move the system a small amount to keep up with the sun as it slowly moves across the sky.

Finally if the system was to be used regularly and for long periods of time in the future, it would be best to either upgrade the existing system or build a new system. This is due to the fact that this project was conducted on a small budget and the system was built adhering to this. Because of this plywood is the main material that the system is constructed of and so after extended use may degrade,' especially if it gets wet. The existing system is suitable for testing and experimentation but if a system was to be used for long periods of time it should be replaced. Strong materials such as metal and more advanced components should be used in order to achieve the highest efficiency and life expectancy. More advanced materials may also help to increase the temperature as with a higher budget the system could be made to smaller tolerances and allow an even more focused output from the reflector.

Appendix A

Project Overview Documents

A.1 Gantt chart

This Gantt chart shows the expected completion times of tasks throughout the project.

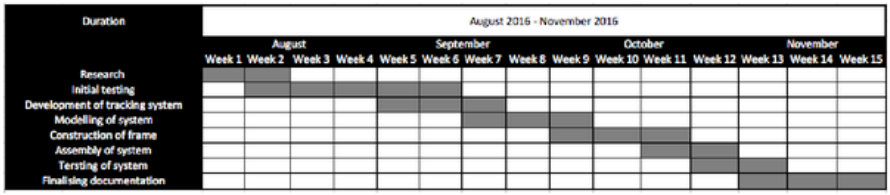


Figure A.1: Gantt chart of the project time line.

A.2 Project Approach

This flow chart shows the approach taken to complete the project.

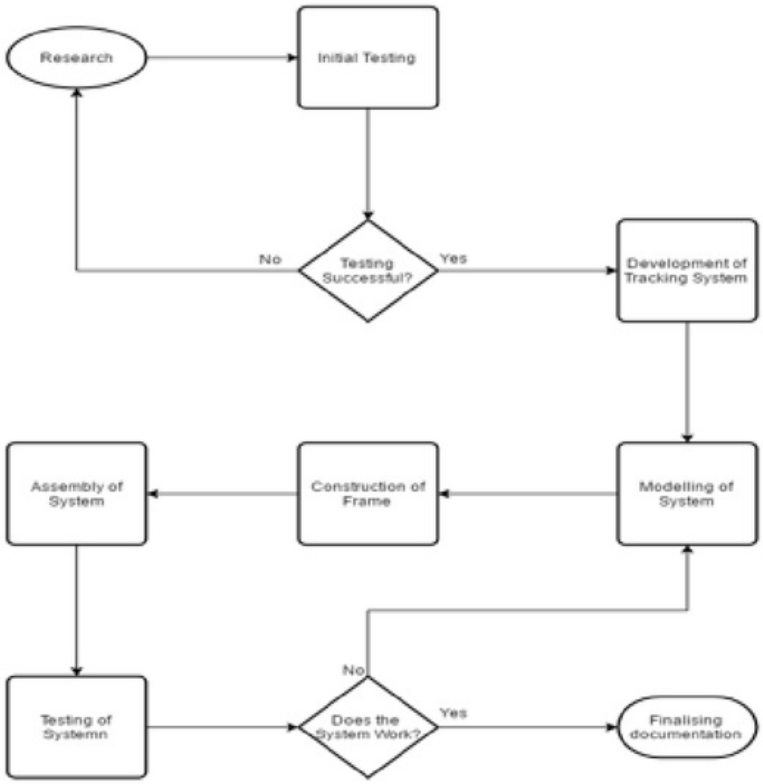


Figure A.2: Flow chart of activities undertaken throughout the project.

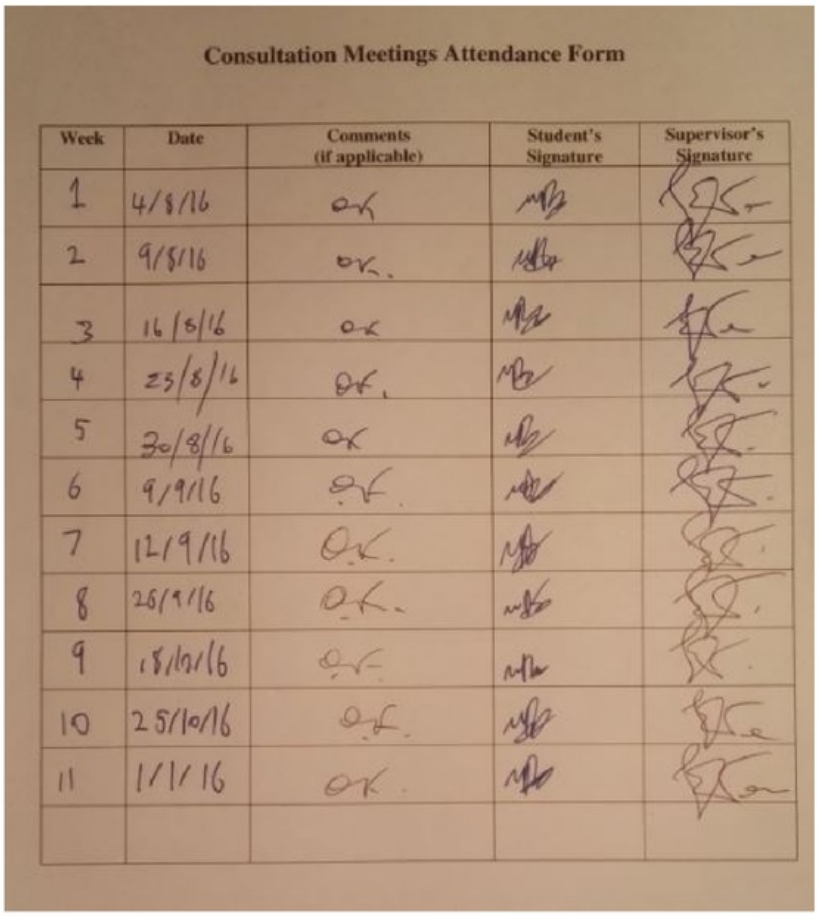
A.3 Project Budget

Item	Price
Aluminium	$67.08
Copper	$27.17
Wood	$261.51
Wheels	$32.00
Total	$387.76

Table A.1: Financial summary of the project thus far.

A.4 Attendance Sheet

This sheet shows the history of meetings during the project.



Consultation Meetings Attendance Form

Week	Date	Comments (if applicable)	Student's Signature	Supervisor's Signature
1	4/8/16	ok		
2	9/8/16	ok.		
3	16/8/16	ok		
4	23/8/16	ok.		
5	30/8/16	ok		
6	9/9/16	ok.		
7	12/9/16	O.K.		
8	26/9/16	O.K.		
9	18/10/16	ok.		
10	25/10/16	ok.		
11	1/1/16	ok.		

Figure A.3: Record of meetings throughout the project.

Appendix B

Simulations

B.1 Reflector Height Simulations

These are the flux distributions for the different reflector heights tested in Chapter Three.

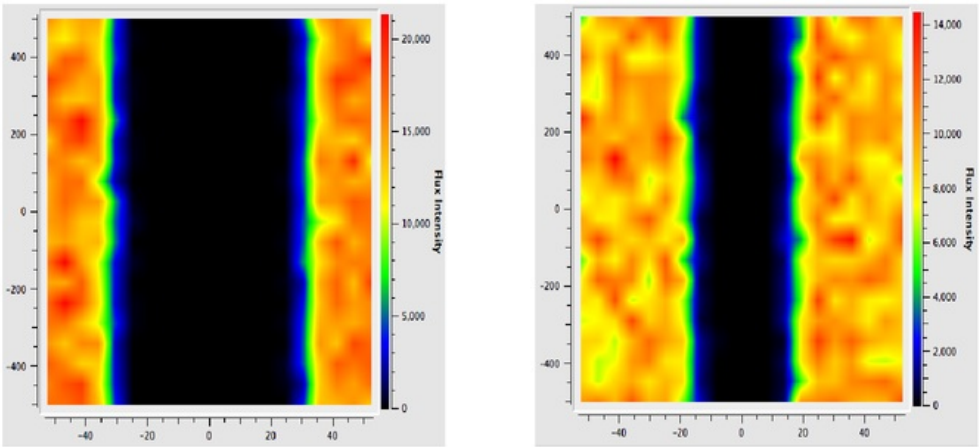


Figure B.1: Flux distributions of 50mm and 100mm tall reflector systems respectively.

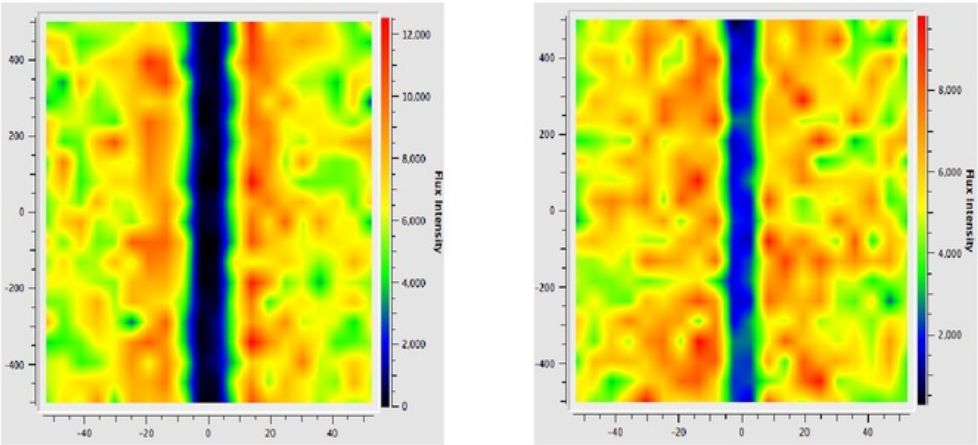


Figure B.2: Flux distributions of 150mm and 175mm tall reflector systems respectively.

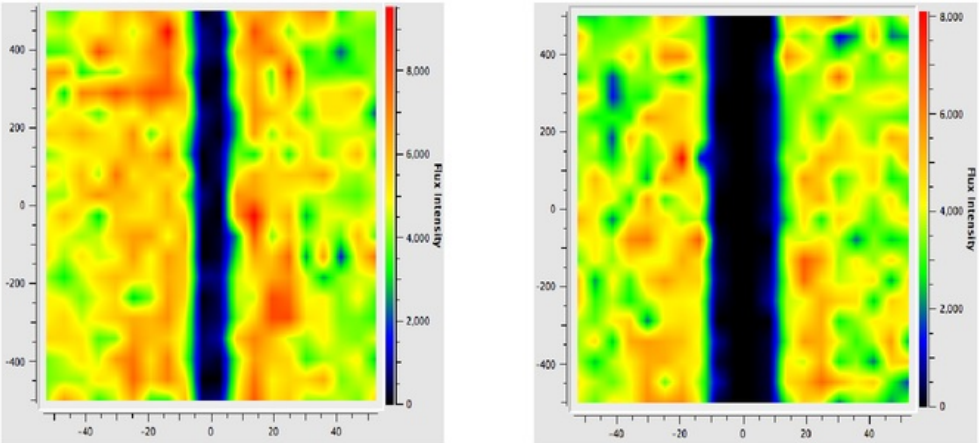


Figure B.3: Flux distributions of 200mm and 250mm tall reflector systems respectively.

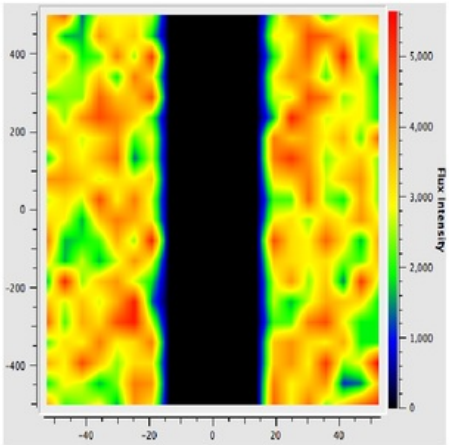


Figure B.4: Flux distribution of a 300mm tall reflector system.

Appendix C

Construction Of The System

C.1 Initial Construction

Figure C.1: The result after work with the CNC was complete.

Figure C.2: Half circles being cut out of the three wooden pieces.

Figure C.3: The result when the three pieces were combined. Two more cross beams were later added closer to the top of the reflector to increase sturdiness.

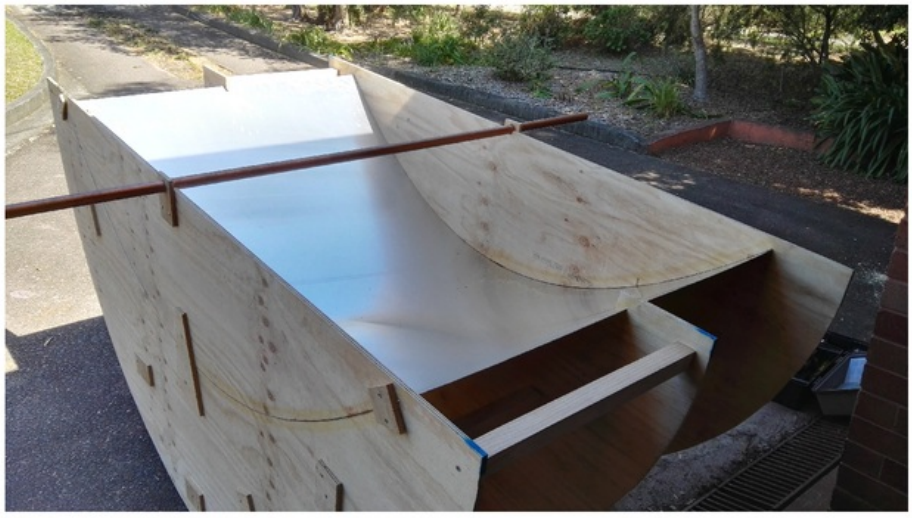


Figure C.4: The completed initial design.

Appendix D

Testing Of The System

D.1 Testing With And Without Tracking System

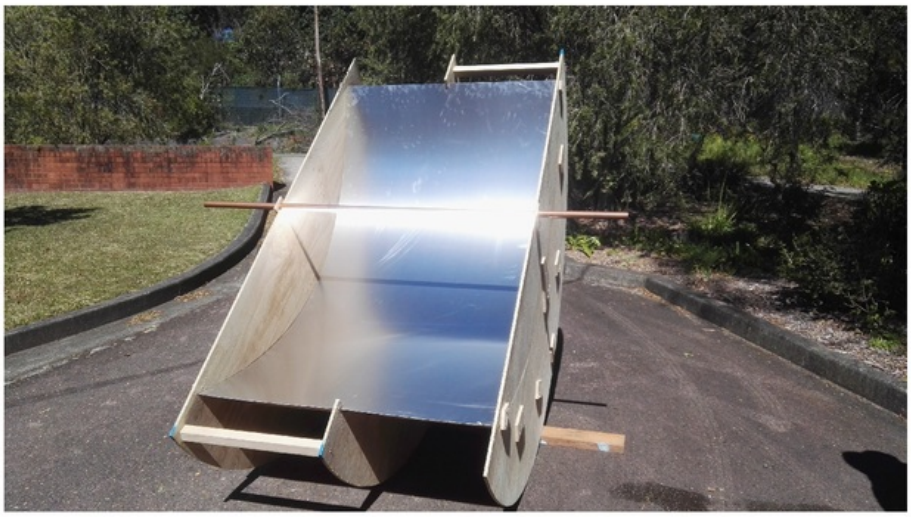


Figure D.1: Testing without the tracking system.

Figure D.2: Testing with the tracking system.

Figure D.3: Testing with the tracking system. Amount of possible tilt is something that needs improvement in future work.

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