Parametric Study of Double Axes Tracking Heliostat to Optimize Heliostat Field Efficiency

by

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Dissertation submitted in partial fulfilment of
the requirements for the
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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
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(MECHANICAL)

Approved by,

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TRONOH, PERAK
JANUARY 2020

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 person.

MOHD HAQIMI IZWAN BIN NOR SHAHARIM

ABSTRACT

The paper presents the research on optimization of heliostat field in terms of distance of heliostat relative to the receiver. The heliostat field consist of sun tracking mirror (heliostat) that reflects the sun radiation to the receiver at the top of the tower. Heliostat field efficiency is related to cosine loss and atmospheric attenuation loss. Increasing the distance of heliostat relative to the receiver, results in higher cosine loss and atmospheric loss. The heliostat field is located in Ipoh, Malaysia (latitude 4.340 N). The angle of incidence is calculated using sun position and heliostat position related equations that had been established in the mathematical model. The cosine efficiency of the heliostat field and atmospheric attenuation efficiency are calculated using the mathematical model that is done through Matlab simulation for one day and one week period starting from 13th January 2020 until 19th January 2020. The cosine efficiency of the heliostat at 6 meter, 9 meter and 12 meter when the heliostat is facing directly north of the receiver are 76.9%, 72.4% and 69.6%.The atmospheric attenuation efficiency is the highest at 6 meter at 99.25% while 9 meter and 12 meter are 99.22% and 99.18% respectively. Shading and blocking is not focused in this paper and The overall field efficiency that includes cosine efficiency, atmospheric attenuation efficiency and mirror reflectivity is optimized when the heliostat is placed at west side of field relative to the receiver at a distance of 6 meter and at facing angle of 45^0 that yields value of 88.7%.

ACKNOWLEDGEMENT

First of all, I would like to express my deepest gratitude to my supervisor, Dr. Syed Ihtsham Ul-Haq Gilani, that had been helping me since the first day that I was given the project during my Final Year Project 1 until the completion my project in Final Year Project 2. He would always spend some of his time for a brief meeting every week in order to clear any misunderstanding that I have throughout my project and guide me slowly to the desired goals of the project. This allows me to be able to complete the project with according to the objectives.

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CHAPTER 1: INTRODUCTION

One of the challenges faced by the society nowadays is finding adequate supply of clean energy. The current technology development that we are living in it today causes a disastrous result of pollution from the rate of energy consumption produced by the fossil or chemical sources that are known to be non- renewable energy [1]. The alternative for this issue is utilizing renewable energy sources for example sun energy.

The land on the Earth is covered with a system that utilize conversion of solar power having 10% efficiency, would generate 20TW of power that is almost twice consumption rate of fossil fuel by the world [2].In China, the power generated from coal-fired power plant are estimated to be over 60% and it also contributes to 40% of total national emissions. This leads them to focus more on generating power using renewable energy preferably solar energy.

Solar energy is the most easily obtained among other renewable sources of energy. Generally, The Sun can emit energy at a rate of 3.8 x 1023 Kw where taking 10% of the energy and converted at efficiency of 10% would generate about four times the world's total generating capacity of 3000 GW. The amount of Sun radiation falling on the Earth is more than 7500 times the world's total annual primary energy consumption of 450 EJ [3].

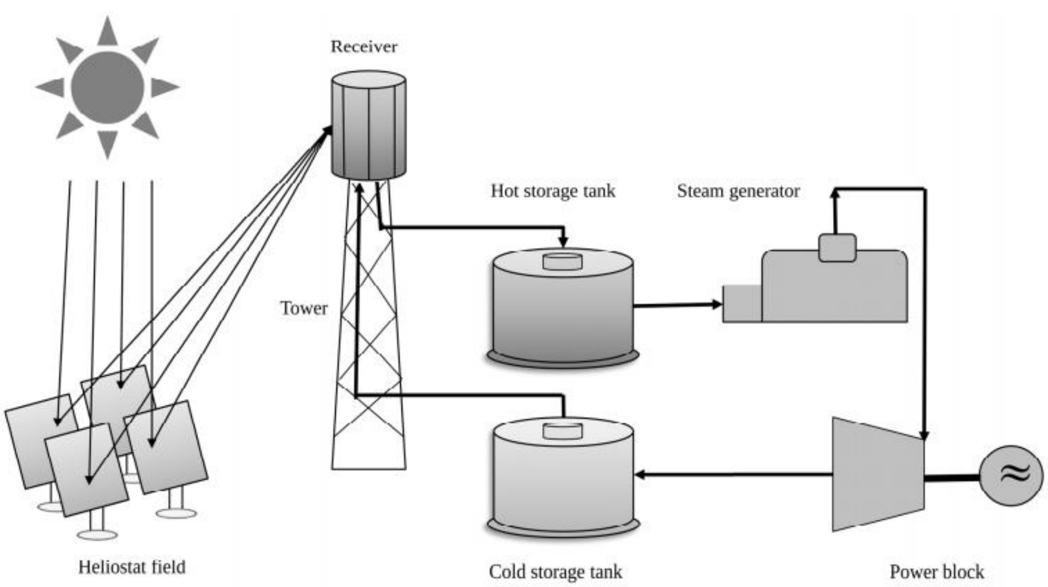

Figure 1.1 The schematic diagram of CSP technology[4]

Concentrating solar power (CSP) is the new and are currently researched by scientists. This is due to its ability in generating large scale electricity. By 2050, the CSP can reach 11% of electricity demand over the world. Between other CSP technologies, the solar central receiver technology has the most unique advantages compared to others due to its great potential for high efficiency and scalability [5].

Solar central receiver system utilizes a sun-tracking mirror (heliostat) that concentrates the solar radiation and reflects it to a receiver at the top of the tower [7]. The heliostat is a reflecting mirror with single or double axes tracker that can track the position of the Sun rays. The high concentration of solar power is translated into thermal energy that will be used to generate electricity.

The main components present in the system are the collector, receiver and power generation parts [8]. The essential subsystem is the heliostat field as it contributes fifty percent to the total capital investment of the plant and also causes loss by up to forty percent in power [6-10]. The high-power loss is closely related to the heliostat field. The heliostat field efficiency is usually affected by the field layout, tracking control system and heliostat design.

The performance of the system can be observed through the efficiency that is explained as the net absorbed power by tower receiver to the normally incident power. The layout of the heliostat field give rise to optical losses that can be classified as cosine loss, atmospheric attenuation, shadowing and blocking, receiver spillage, mirror reflectivity and losses due to other factors [11].

1.1 Problem Statement

The research on the heliostat field is still ongoing and requires more improvement to enhance the optical efficiency of the heliostat field. One issue that arise is related to the distance of the heliostat from the tower. When the distance increases, the atmospheric attenuation increases. Another issue that had been observed is when the distance increases, the cosine loss will increase. The relationship of the heliostat field can be defined to be directly proportional as when one parameter is increase, the other parameter will increase. Therefore, it is imperative to carry out study on the optimum distance between the heliostat with the receiver that will result in the best heliostat field efficiency.

1.2 Objectives

The objective of the research is:

- To develop mathematical model in Matlab for calculating the heliostat field efficiency
- To determine the optimum distance of heliostat between 6 meter, 9 meter and 12 meter and the facing angle relative to the center of receiver.

1.3 Scope Of Study

The study involves the research on the optimization of the heliostat field. The parameters that are used in the mathematical models that had been established are taken from experimental values from a solar site located in Universiti Teknologi Petronas, Tronoh, Malaysia. The duration of this simulation is set to be for 1 day simulation and 1 week simulation period starting from 13th January 2020 until 19th January 2020. Excel Spreadsheet is the software used in order to keep the parameters that is used in Matlab for to computing, analyzing and tabulating the results of heliostat field efficiency.

CHAPTER 2: LITERATURE REVIEW

2.1 Sun Tracking Method

Two sun tracking method that are commonly used in heliostat is the conventional method: Azimuth-Elevation (AE) and Spinning-Elevation (SE) method. In SE tracking method, the tracking axis of heliostat points towards spinning axis or also known as target that keeps the tangential plane normal to heliostat. Another axis is tangential to frame heliostat and perpendicular to the first axis until it bisects with the vector position of the sun (elevation axis). In AE tracking method, one axis of heliostat is perpendicular to first axis and tangent to frame of heliostat (elevation axis) while another axis is pointing towards zenith (azimuth axis). As the tracking is independent of receiver and the Sun, the incident angle is achieved equal in AE and SE method but the difference is in utilization of mechanism. Figure 2.1 shows the two types of tracking method:

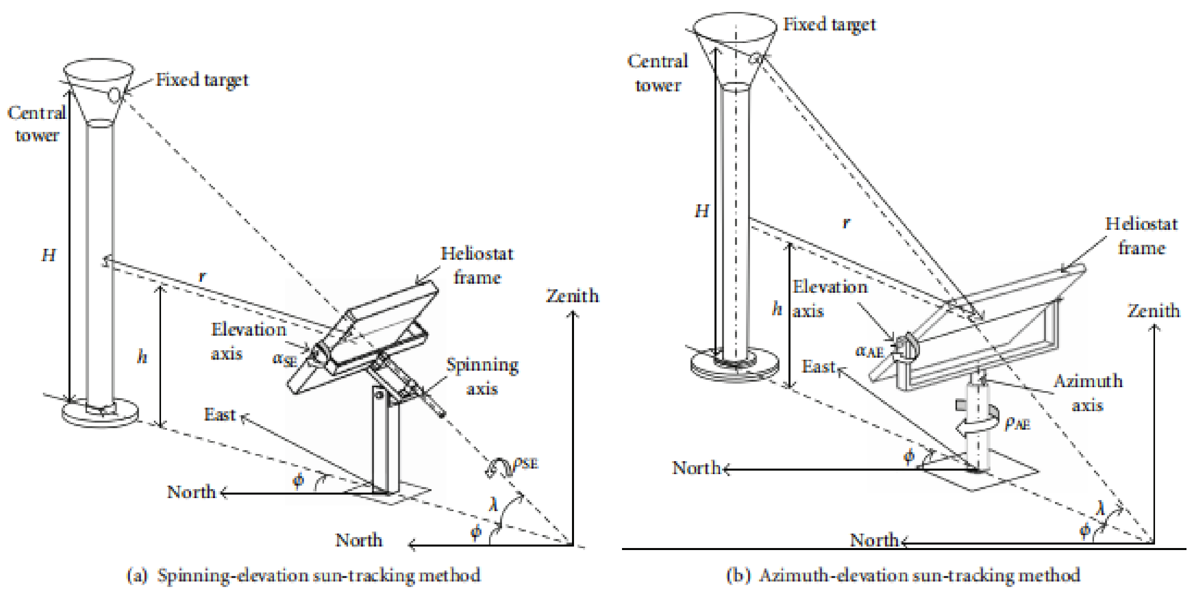

Figure 2.1 Two different sun tracking method [11]

2.2 Types Of Sun Tracker

The tracking of solar position can be carried out using one-axis and two-axis tracking system. In order to obtain a higher accuracy tracking, two-axis is commonly used and they are categorized into two types which are polar tracking and azimuth/elevation tracking[2]. The figure 2.2 shows the energy lost with respect to the maximum tracking angle in comparison with the ideal tracking. From the graph, it is observed when tracking angle is bigger than 60^0, there is no energy loss.[2]

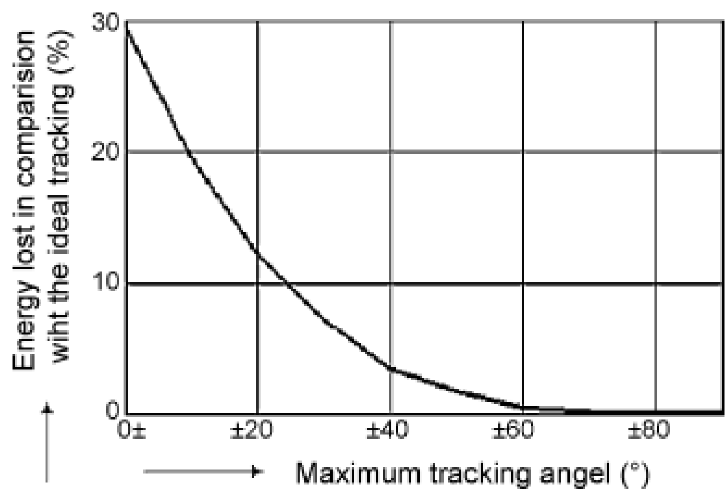

Figure 2.2 Energy lost with comparison to ideal tracking [2]

The categorization of the sun trackers is solely based on one and two axis devices. However, sun tracking devices also includes active and passive as shown in Figure 2.3.

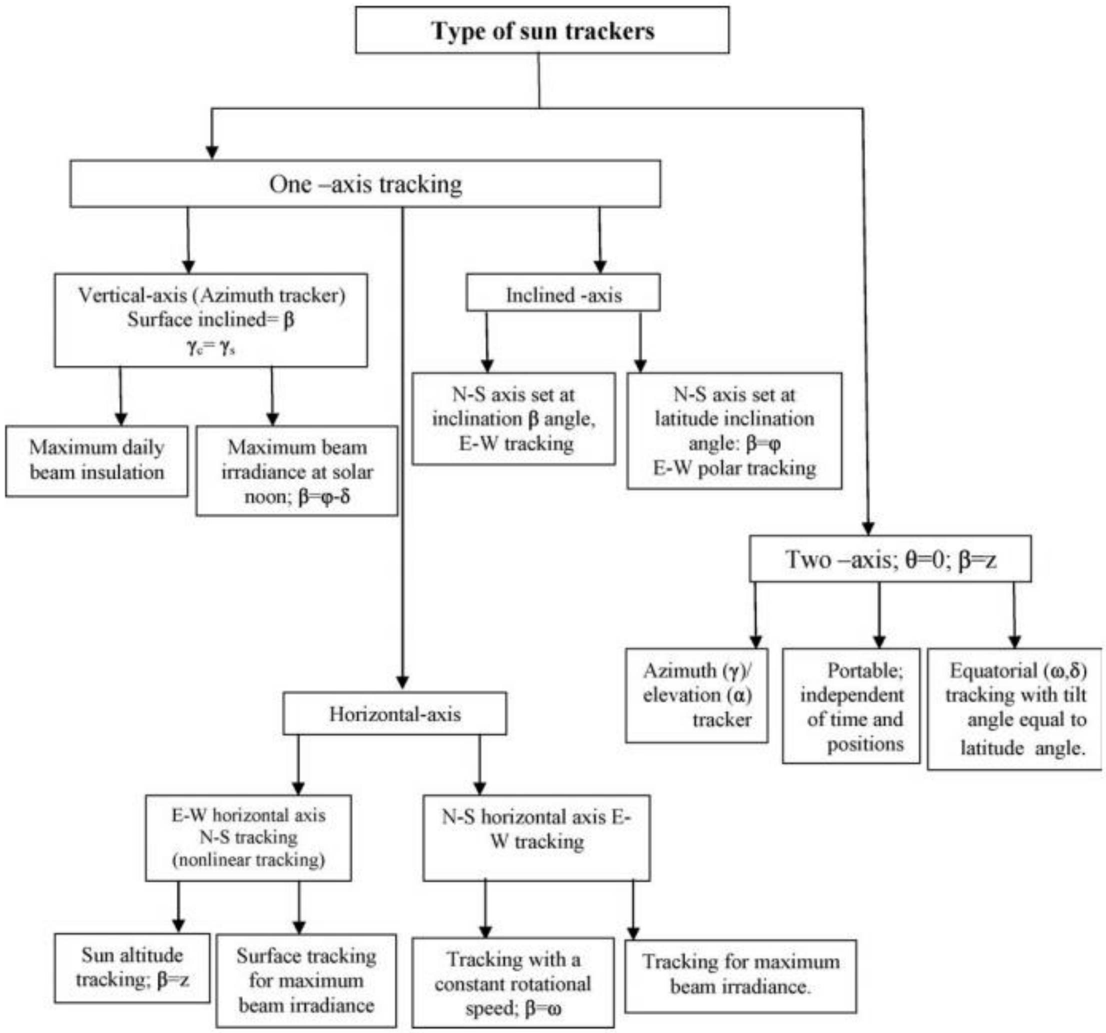

Figure 2.3 Types of Sun Tracker [2]

2.3 Sun Angle Definition

Latitude angle, φ is the vertical angle between a line joint by point of location to the center of the Earth with projection on equatorial plane ($-90^\circ \leq \varphi \leq 90^\circ$). **Declination angle**, δ is the angle between line from center of the Sun to the Earth with the projection of the line on the Earth equatorial plane; ($-23.45^\circ \leq \delta \leq 23.45^\circ$). **Slope**, β is the angle between plane of measured surface and the horizontal line ($0^\circ \leq \beta \leq 180^\circ$ where $\beta > 90^\circ$ denotes that the surface is downward) [12].

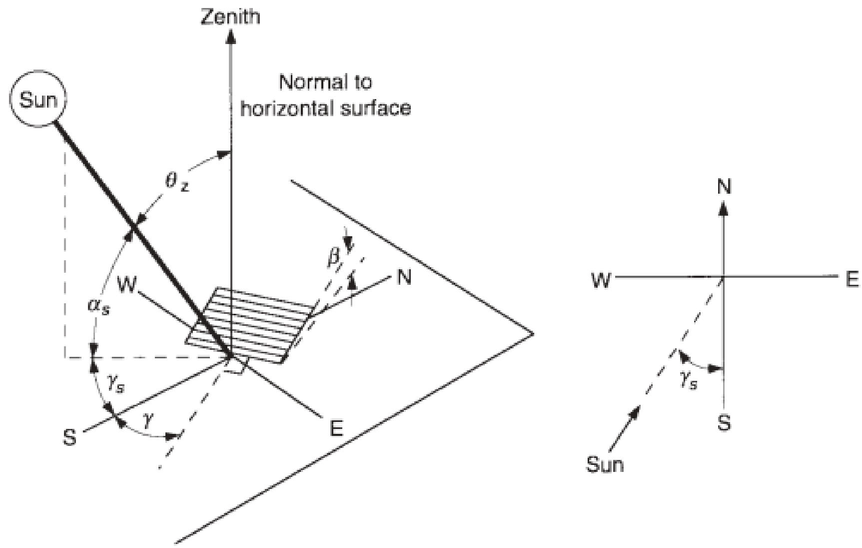

Figure 2.4 (a) Slope, Zenith , Surface Azimuth and Solar Azimuth angle (b) solar azimuth angle [12]

Surface azimuth angle, γ is the deflection of projection from the local meridian on a horizontal plane that is normal to the surface; having positive(west), negative (east) and zero (south); ($-180^\circ \leq \gamma \leq 180^\circ$). **Hour angle**, ω is the angle representing the position of the sun with respect to clock hour at approximately 15^0 per hour. (morning as negative, evening as positive). **Incidence angle**, θ is the angle between radiation of the sun on a surface and normal to the surface [12].

Angles that describe the position of the Sun in the sky:

Zenith Angle, θz is angle between the sun radiation and perpendicular to the horizontal plane.

Solar altitude angle, αs is angle between sun radiation and projection on horizontal plane. It is the complement of the zenith angle.

Solar azimuth angle, γs as shown in Figure 2.4. East of south displacement (negative) while west of south are (positive).

Declination angle can be calculated using Table 2.1 and Equation 2.1 as reference that shows the value for estimating the number of days, n according to the date and month of the year.

$$\delta = 23.45 \ \sin\left(360 \ \frac{284+n}{365}\right) \tag{2.1}$$

Table 2.1 Average Days in a month and year [12]

Month	n for ith Day of Month	For Average Day of Month		
		Date	n	δ
January	i	17	17	−20.9
February	$31 + i$	16	47	−13.0
March	$59 + i$	16	75	−2.4
April	$90 + i$	15	105	9.4
May	$120 + i$	15	135	18.8
June	$151 + i$	11	162	23.1
July	$181 + i$	17	198	21.2
August	$212 + i$	16	228	13.5
September	$243 + i$	15	258	2.2
October	$273 + i$	15	288	−9.6
November	$304 + i$	14	318	−18.9
December	$334 + i$	10	344	−23.0

[a]From Klein (1977). Do not use for $|\phi| > 66.5°$.

2.4 Heliostat Layout Design

The heliostat is arranged in radius shape although there is different arrangement of the heliostat field possible [13]. The layout is best for solar power plant as it reduces blocking and shadowing losses [3]. This arrangement allows the heliostat to be placed strategically without blocking heliostat that is place adjacently over the tower. The beam that was reflected from the heliostat will go through the other heliostat heading to the receiver. It has been proven that arrangement in staggered of radial pattern is more efficient as it reduces land usage and atmospheric losses.[11, 13]

The radial spacing is the distance from the heliostat to the tower receiver. According to [13], there are three views on the minimum radius of the heliostat with respect to the tower. The three opinions are shown in Equation 2.2, 2.3, 2.4:

$$R_{0,0} = R_{\min} = H_t \qquad (2.2)$$

$$R_{0,0} = R_{\min} \cong 0.75H_t \tag{2.3}$$

$$R_{0,0} = R_{\min} \cong 0.8H_t - H_t \tag{2.4}$$

2.5 Types Of Losses

The field efficiency comprises of cosine, reflection, shading, blocking, spillage and atmosphere attenuation. The relation is given by the equation 2.5 below [4]:

$$\eta_{\text{optical}} = \eta_{\text{cosine}}\eta_{\text{shading}}\eta_{\text{reflection}}\eta_{\text{blocking}}\eta_{\text{spillage}}\eta_{\text{atmosphere}} \tag{2.5}$$

The figure 2.5 is the representation of the losses that are observed in a Solar Central Receiver (SCR) system.

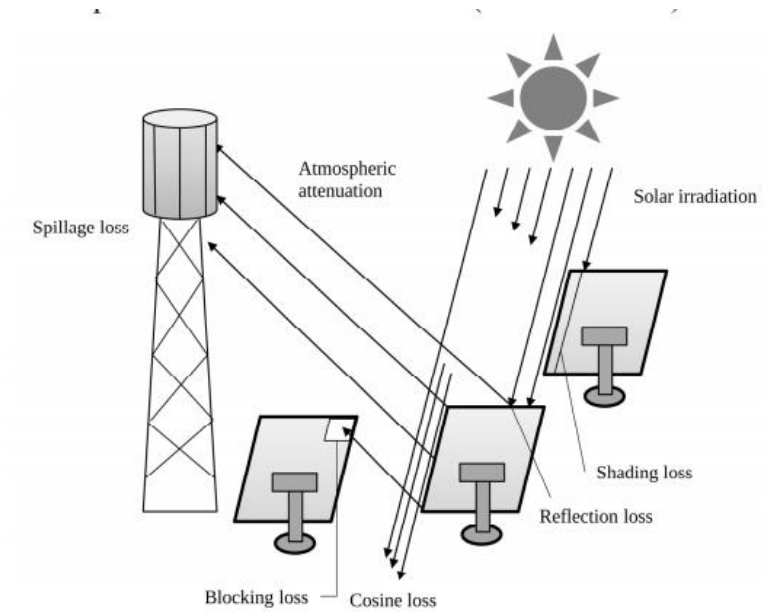

Figure 2.5 shows the types of optical losses in a SCR system that relates to the optical efficiency[4]

2.5.1 Cosine Loss

The cosine loss has the biggest impact on reflected solar power of the heliostat due to the dependency on position of the Sun and heliostat location relative to the receiver [3, 11]. By definition, cosine loss is ratio of projection area by the heliostat in solar radiation way to the surface.[11] The heliostat is required to be tilted at angle in order to direct solar radiation towards the receiver. This results in lower amount of energy obtained by receiver and is known to be cosine loss.

As shown in Figure 2.6, Heliostat A have a small reflecting angle that results in lower loss while Heliostat B have higher loss due to bigger angle of reflection. The sun rises from east and sets in the west. In the morning, heliostats placed at the west of the tower (receiver) will have lower cosine loss in comparison with heliostats at the east of the tower. However, the situation is reversed in the evening as the cosine loss is higher in east of the tower compared to the west side of the tower.[14] Equation 2.6 shows the relation between angle of incidence with the cosine loss efficiency.

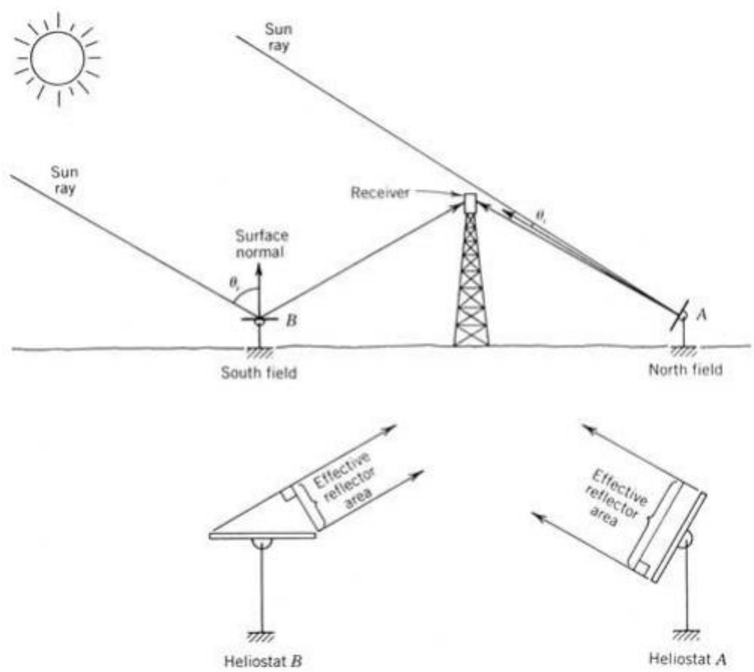

Figure 2.6 Cosine effect of heliostat A and B in opposite direction

$$n_{cos} = \cos(\theta_i) \tag{2.6}$$

2.5.2 Atmospheric Attenuation

Reflected rays on the path of heliostat mirror to the receiver are always affected by the atmospheric attenuation. This loss relates between distance of heliostat and receiver located on the tower [6]. The mathematical model below shows the calculation for atmosphere attenuation efficiency [15]:

$$n_{atm} = \begin{cases} 0.99321 - 0.0001176\ x\ dist + 1.97\ x\ 10^{-8}\ x\ dist^2 & ,\ dist < 1000m \\ \exp(\ -0.0001106\ x\ dist) & ,\ dist \geq 1000m \end{cases} \tag{2.7}$$

2.5.3 Shading/ Blocking

Shading is the phenomena where sunlight radiation reflected by one heliostat is received by a neighboring heliostat. Blocking is the obstruction of one heliostat from receiving sunlight radiation by a heliostat [16]. The heliostat that is placed behind its neighbor is not able to fully reflect its entire surface to the receiver as some part of reflected sun rays is blocked by the back side of the heliostat placed in front of it [6].

2.5.4 Mirror reflectivity

It is defined as quality of the surface reflectivity. This factor depends on cleanliness and degradation of the surface. The value is usually taken to be constant equal to 0.88 [6, 15].

2.5.5 Spillage

This occurs when a part of the reflected radiation from the heliostat deviate from its path and does not focused on the receiver. The likely caused are due to tracking accuracy and mirror quality [6, 17]

2.6 Efficiency Distribution

According to [3], the cosine efficiency of the heliostat field varies with the position of the heliostat. In Figure 2.7, three heliostats (1, 2 and 3) are observed at their own position where heliostat 1 is at the north of the tower, heliostat 2 is at east and heliostat 3 in the west of the tower. The cosine efficiency for heliostat 1 is in parabolic shape where it increases slightly and decreases to its original value. For heliostat 2, cosine efficiency is higher during the day and it decreases in the at the end of the day. Heliostat 3 have lower cosine efficiency in the morning and increases in the evening.

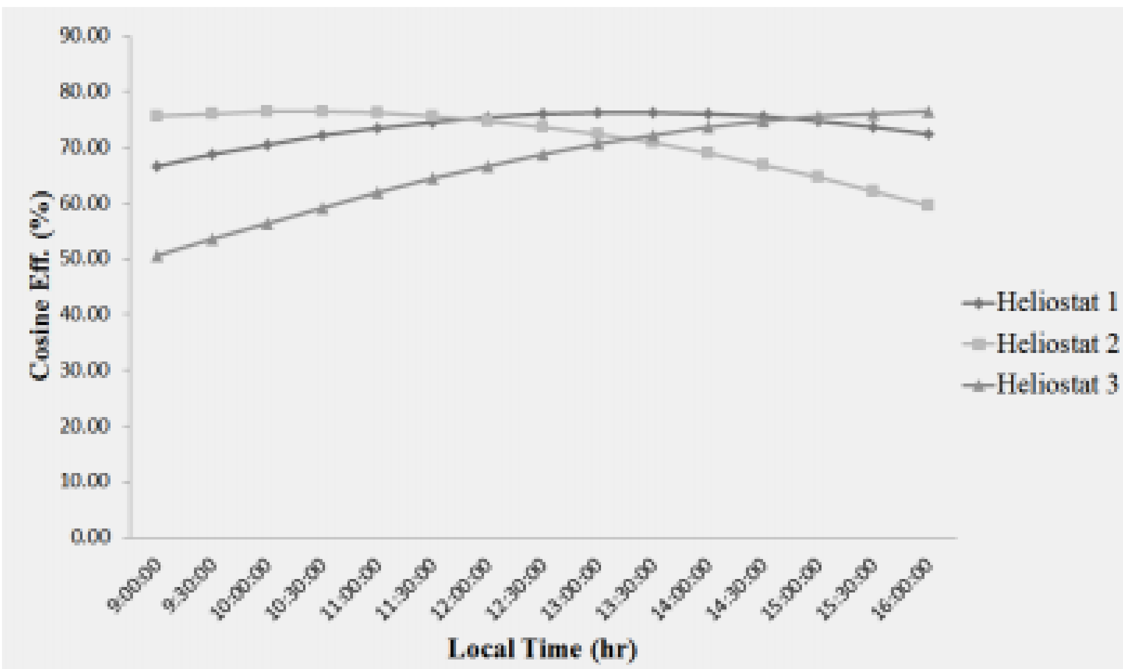

Figure 2.7 Cosine efficiency vs local time [3]

CHAPTER 3: METHODOLOGY

In order to design the heliostat field layout, this section will depict the derivation of a mathematical model.

3.1 Heliostat Layout Design

The chosen configuration for the heliostat field is utilizing only the North side of the field with radial staggered pattern that maximize field efficiency [18]. Figure 3.1 shows the orientation of heliostat in rings in the North side of the tower [14]

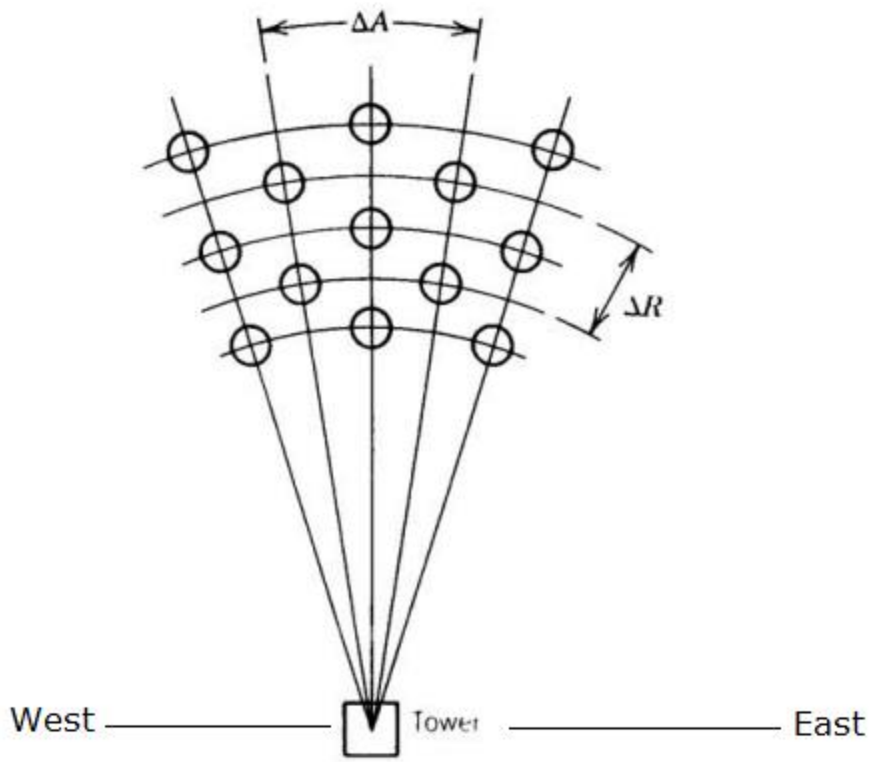

Figure 3.1 Orientation of heliostat in the field [14]

3.2 Sun Position

The position of the Sun can be tracked and determined with the aid of astronomical equations. The purpose is to lower the cosine losses and enhance the heliostat field efficiency. Some of the angles of the Sun position are tabulated in the Table 3.1:

Table 3.1 Angles in tracking Sun position [3]

Angle	Symbol
Hour angle	h_s
Zenith angle	θ_z
Solar Declination angle	δ_s
Solar altitude angle	α_s
Solar Azimuth angle	φ_s
Solar latitude angle	ϕ_{lat}
Target angle	α_{tr}
Facing angle	β_{hs}

The position of sun is always changing every day for the whole time due to both the Sun and the Earth rotating on its axis while the Earth is orbiting the Sun. Therefore, the solar angles are necessary in order to model solar coordinates system. The solar declination angle is given by [12]:

$$\delta s = 23.45 \ \sin\left(360 \ \frac{284+n}{365}\right) \tag{3.1}$$

n is the day during one year that starts from 1st January to 31st December [12].

The hour angle (h_s) is also calculated where it is the time of the day from 8.00am in the morning until 4.00pm. The equation is given below [19]:

$$h_s = (\text{Solar hour } -12) \times 15^{\circ} \tag{3.2}$$

Once hour angle (h_s) is calculated, the solar altitude angle (α_s) is calculated using equation given [19]:

$$\alpha_s = \sin^{-1} [\cos(h_s).\ \cos(\delta s).\ \cos(\phi_{lat}) + \sin(\delta s).\ \sin(\phi_{lat})] \tag{3.3}$$

where the parameters are already calculated previously. Φ_{lat} is the solar latitude angle that had been defined to be 4.34^{o} N.

The zenith angle, θ_z is the compliment of solar altitude where [19]:

$$\theta z = 90^{\circ} - \alpha_s \tag{3.4}$$

Using hour angle (h_s) ,zenith angle (θz) and declination angle, the solar azimuth angle (φ_s) can be calculated using equation [19]:

$$\varphi_s = \cos^{-1}\left(\frac{\sin\delta_s \text{ x} \cos\phi_{lat} - \cos\delta_s \text{ x} \cos h_s \, x \cos\phi_{lat}}{\cos\alpha_s}\right) \tag{3.5}$$

If $\sin h_s > 0$, then $\varphi_s = 2\prod - \varphi_s$.

3.3 Position Of Heliostat

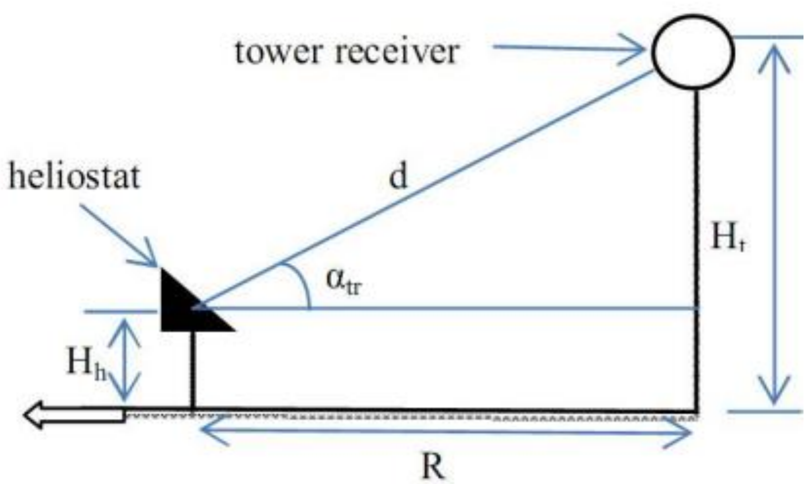

Figure 3.2 Geometric relationship of heliostat position relative to receiver

The target angle of each of the heliostat is calculated from the relationship of tower height (H_t), heliostat height, (H_h) and distance of heliostat to the receiver (R). The equation shows the formulation for finding target angle and distance, (d).

$$\alpha_{tr} = \tan^{-1}\left(\frac{H_t - H_h}{R}\right) \tag{3.6}$$

$$d = \sqrt{R^2 + (H_t - H_h)^2} \tag{3.7}$$

The angle of incidence is then calculated from all the parameters obtained using the mathematical model. The angle of incidence on the heliostat is given as [19]

$$\theta_s = \frac{1}{2}\cos^{-1}(\sin\alpha_s \, sin\alpha_{tr} + cos\alpha_s sin\varphi_s cos\alpha_{tr} sin\beta_{hs} + cos\alpha_s cos\varphi_s cos\alpha_{tr} cos\beta_{hs}) \quad (3.8)$$

3.4 Calculation Of Losses

The angle of incidence, θs is used to calculate the cosine efficiency as given in equation below:

$$n_{cos} = cos\theta_s \quad (3.9)$$

Where n_{cos} is the cosine efficiency.

The atmospheric attenuation is calculated using the distance of heliostat, where:

$$n_{atm} = \begin{cases} 0.99321 - 0.0001176 \, x \, dist + 1.97 \, x \, 10^{-8} \, x \, dist^2 & , \ dist < 1000m \\ \exp(-0.0001106 \, x \, dist) & , \ dist \geq 1000m \end{cases} \quad (3.10)$$

3.5 Simulation Parameter

The simulation is carried out for a duration of 1 day starting on 13th January 2020 and the time duration for a day are set to be from 8am to 4pm. Two parameters which are azimuthal spacing and radial spacing are determined in order to observe and analyze the effect on heliostat field efficiency at different values. Three heliostats are positioned in the field in a radius shape pattern across the field. The radial spacing are set to be at 6-meter, 9 meter, and 12 meter respectively. The azimuthal spacing between the three heliostats are fixed for three sets of simulation at angles of 15^0, 30^0, and 45^0. Figure 3.3 shows the facing angle in a heliostat field.

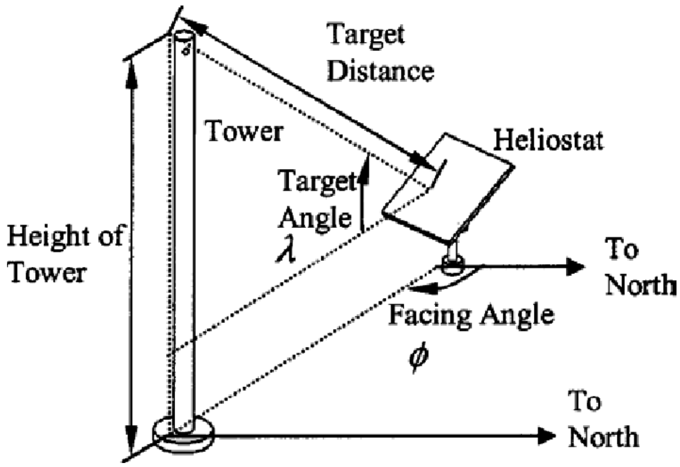

Figure 3.3 facing angle in heliostat field

In order for the simulation to be carried out in Matlab, some parameters are identified and listed out in Excel spreadsheet. The parameters are then imported to Matlab software for the simulation based on the mathematical model that had been created. Table 3.2 below shows the listed parameters that are necessary for the simulation.

Table 3.2 parameters for simulation

Parameter	Unit
Heliostat length	1.5 m
Heliostat width	1.9 m
Heliostat height	1.5 m
Heliostat distance	6m, 9 m, 12 m
Tower height	6 m
Facing angle	0, 15^0, 30^0, 45^0
Mirror reflectivity	88%
Latitude	4.34^0
Time	8am- 4pm
Date	13th -19th January 2020

3.6 Process Flowchart

The Matlab software is first opened and the parameters for the heliostat for example, heliostat length, width, height, and distance from the receiver are set inside the code. Table 3.2 shows the parameters that are established and set in matlab software. Once parameters are set, the governing equations are utilized in order to obtain the declination angle. The declination angle is then used to obtain the target angle and facing angle of the heliostat relative to its position at the heliostat field. By using the equations listed previously and translating it into matlab code, angle of incidence is obtained. The cosine efficiency is then calculated as a function of angle of incidence and atmospheric attenuation is computed as a function of distance of heliostat from the receiver. The field efficiency is calculated by considering other losses that are present in the heliostat field. The data is analyzed, and the code is simulated again for different distance of the heliostat that are 6 meter, 9 meter and 12 meter. Figure 3.4 shows the process flowchart of the simulation in Matlab software.

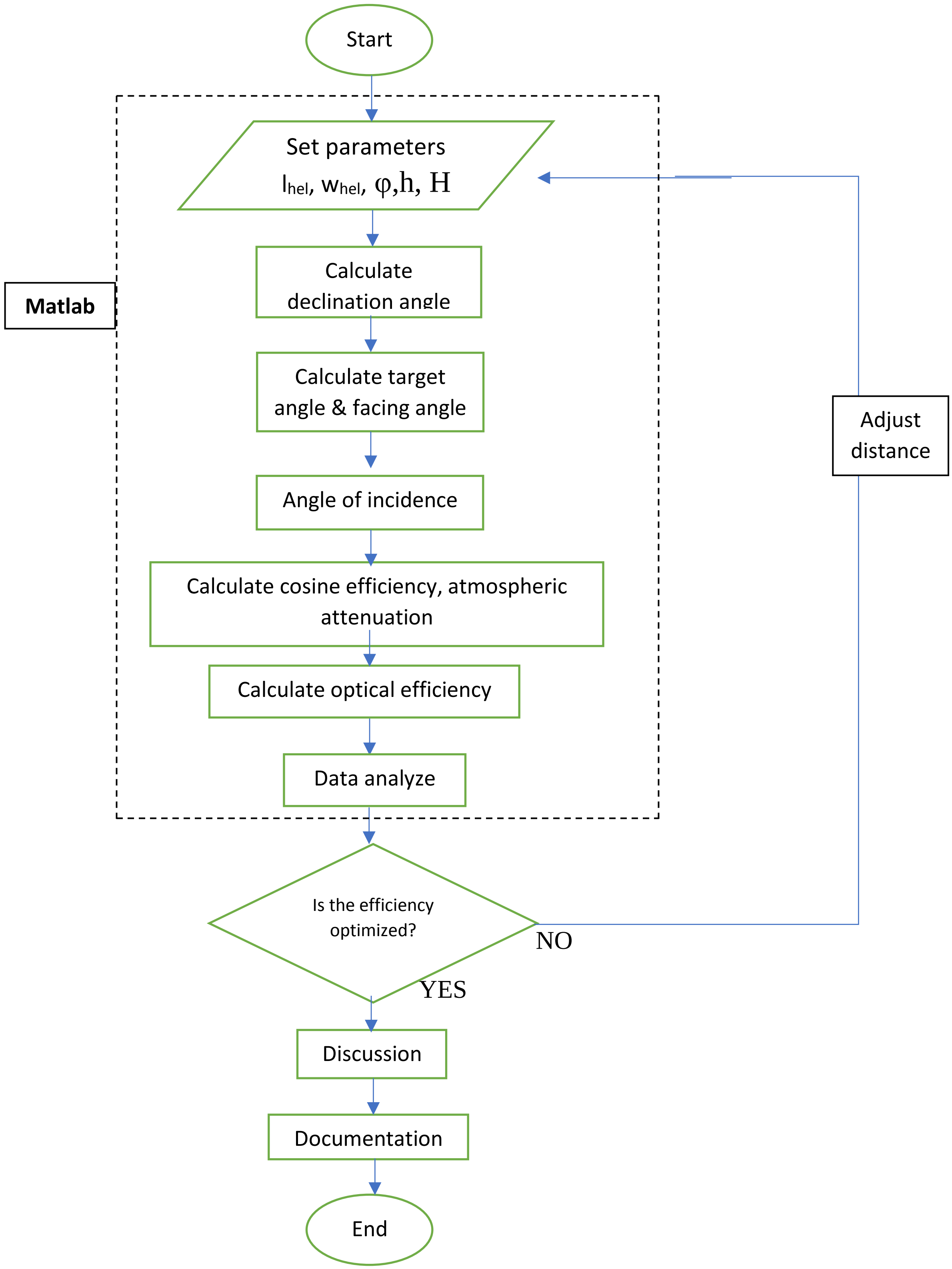

Figure 3.4 Flow chart of project

3.7 Gantt Chart

Table 3.3 Gantt chart FYP 1

Final Year Project 1

Description	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11	Week 12	Week 13	Week 14
Project selection														
Preliminary Research														
Introduction														
Literature Review														
Progress Assessment 1														
Proposal Defense														
Mathematical modelling														
Excel execution														
Interim Draft Report														
Progress Assessment 2														
Interim Report														

Mathematical Modelling & (Week 10)

Table 3.4 Gantt Chart FYP 2

Final Year Project 2

Description	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11	Week 12	Week 13	Week 14	Week 15
Project Continuation															
Matlab Execution															
Progress Assessment 1															
Result & Discussion															
Draft Dissertation															
VIva															
Progress Assessment 2															
Project Dissertation															

Result & Discussion (Week 5)

CHAPTER 4: RESULT AND DISCUSSION

4.1 One Day Simulation

The simulation is carried out using Matlab software based on the mathematical model that had been developed. The results are shown in Figure 4.1, 4.2, 4.3, 4.4 and 4.5.

In Figure 4.1, the heliostats are placed at exactly North of the tower (facing angle, $\beta_{hs} = 0$) at distance of 6 meter, 9 meter and 12 meter. It is observed that the shorter the distance between the heliostat with the receiver, the higher the cosine efficiency of the heliostat. At 12 noon, the shortest distance of heliostat (6m) have the highest cosine efficiency of 82.3% while (9m) having 77.3% and (12m) having 74.1% cosine efficiency.

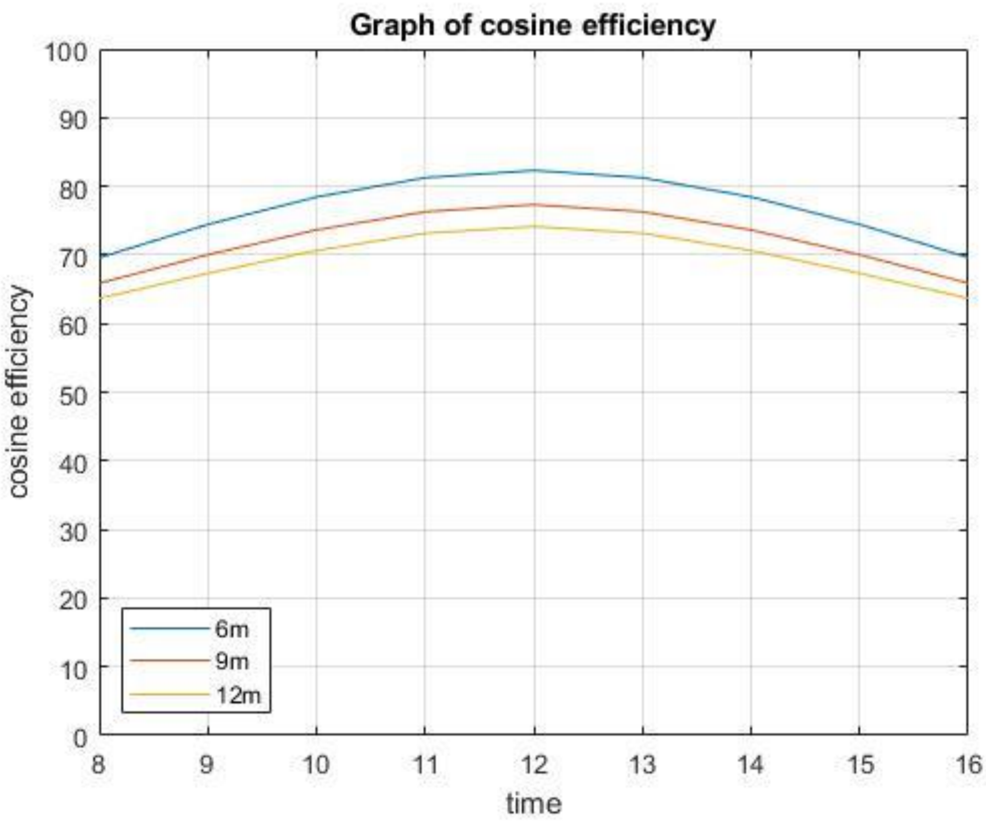

Figure 4.1 Graph of Cosine efficiency at 6,9 and 12 meters

In Figure 4.2 (a), heliostats are placed in the west part of the receiver at distance of 6 meter from the receiver in a radial staggered pattern. It is observed that the cosine efficiency is higher in the morning and it starts decreasing throughout the day. The intersection points as shown in Figure 4.2 below shows that the cosine efficiency is the same for all the position of heliostat. This is due to the position of the Sun that is exactly on top of the heliostat at noon. The highest cosine efficiency obtained by the heliostat is at facing angle of 45^0 with value of 90% and reach the lowest in the evening at 55% of cosine efficiency. The high cosine efficiency that is observed in the morning is because the surface normal is pointing towards the receiver and the Sun is at the opposite side of heliostat (sun rise from East to West).

In Figure 4.2 (b), the heliostats are placed in the opposite direction (east) of the receiver at 6 meter. The cosine efficiency is observed to be lower in the morning due to the Sun rises from East. This results in a bigger angle of incidence of sun rays. The cosine efficiency of the east side heliostat shows the highest value at 45^0 position relative to the receiver at 12 noon that managed to reach up to 90% efficiency.

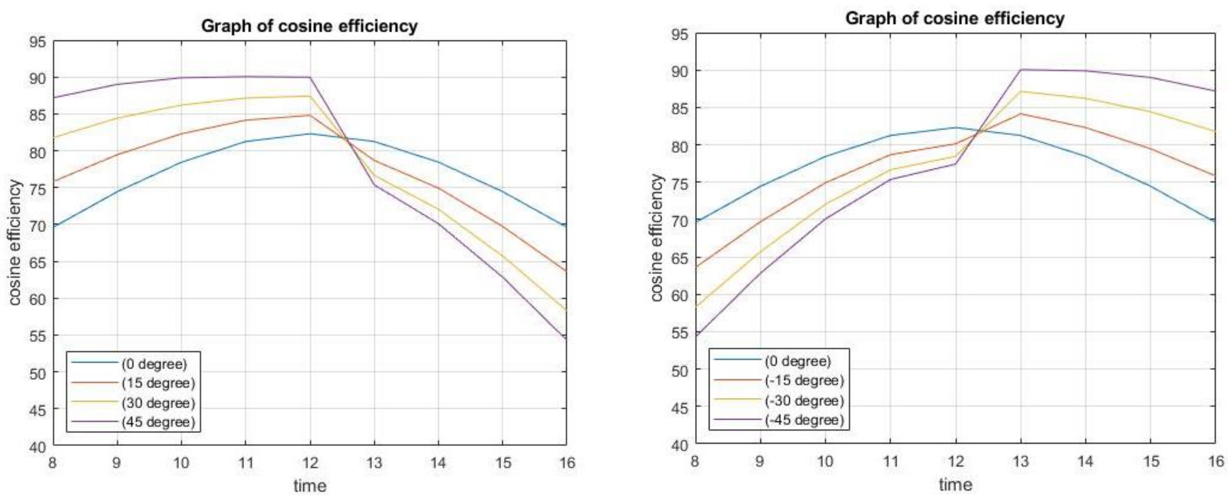

Figure 4.2(a) Heliostat at west side and at (b) east side of the receiver for 6 meter

In Figure 4.3 (a) and (b), the distance of heliostat is increased to 9 meter from the receiver. It is recorded that the cosine efficiency is highest in the morning at west side of the receiver and highest in the evening at the east side relative to the receiver. The cosine efficiency shows slight decrease from 90% at 6 meter to 87% at 9 meter during the afternoon which has the highest cosine efficiency. The distance of the heliostat to the receiver affects the cosine efficiency of the heliostat field as such that the further heliostat from the receiver, the higher the cosine loss. The result obtained are reversed for west side and east side because the position of heliostat at the heliostat field are symmetrical where the heliostat is fixed at 0, 15^0, 30^0 and 45^0 azimuthal spacing.

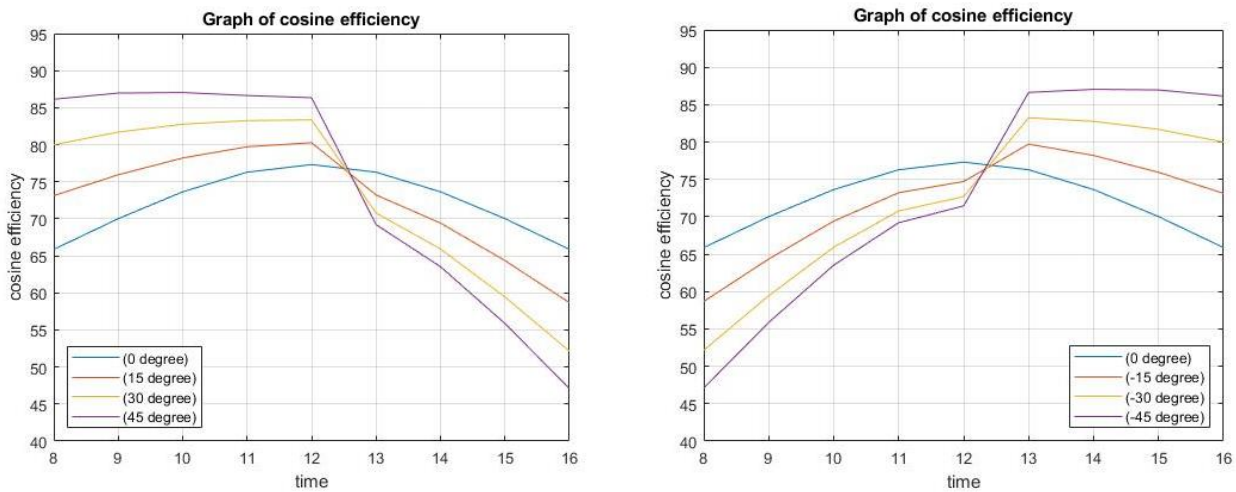

Figure 4.3(a) Heliostat at west side and at (b) east side of the receiver for 9 meter

From figure 4.4 (a) and (b), the cosine efficiency is observed to be slightly decreasing from 87% to 85.2% when the distance of heliostat is increased to 12 meter. The data is used based on facing angle of heliostat at 45^0. The west side of receiver shows a higher cosine efficiency distribution compared to the evening. The east side is the opposite where cosine efficiency is higher in the evening and lower in the morning. The further the distance of heliostat from the receiver, the lower the cosine efficiency of the heliostat. The simulation at 12 meter shows that overall, cosine efficiency are observed to be decreasing by almost 2% compared to simulation at 9 meter, and decrease almost 4% compared to 6 meter simulation.

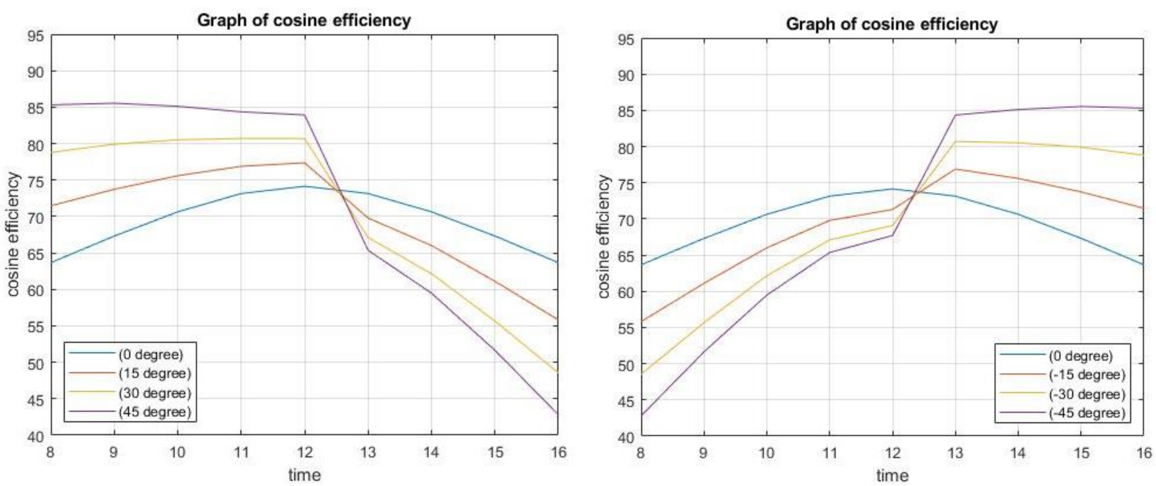

Figure 4.4 (a) Heliostat at west side and at (b) east side of the receiver for 12 meter

Based on Figure 4.5, the atmospheric attenuation efficiency is simulated for different distance of heliostat. The graph shows that for a higher distance of heliostat from the receiver, the lower is the atmospheric attenuation. The graph shows that the values do not change with time throughout the day. This is because atmospheric attenuation efficiency is a function of distance. This is proven through the mathematical model as the only parameters that can be manipulated is the distance of the heliostat in the heliostat field. The values of atmospheric attenuation efficiency are 99.25%, 99.23% and 99.18% for 6 meter, 9 meter, and 12 meter respectively.

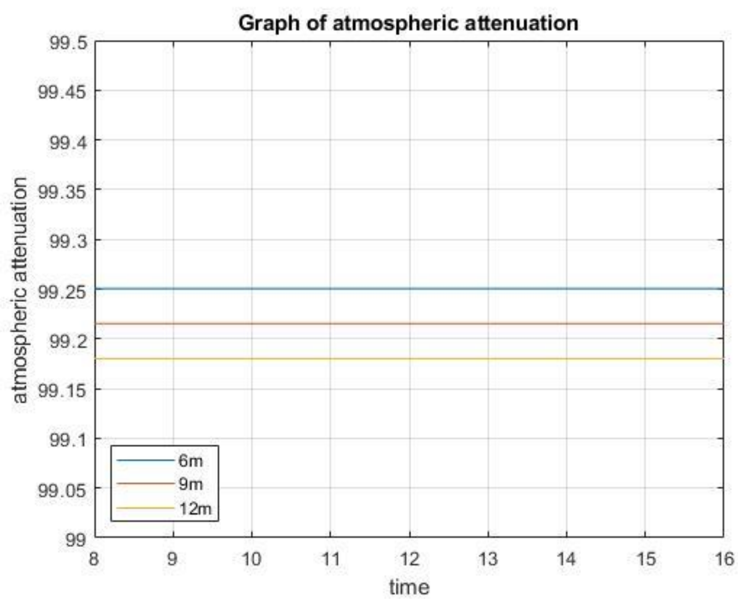

Figure 4.5 atmospheric attenuation at different distance

4.2 One Week Simulation

The simulation is also carried out for a duration of 1 week from 13th January 2020 until 19th January 2020.Table 4.1 below shows the cosine efficiency obtained for different distance and position of heliostat with respect to the receiver (tower) at the west side of the tower.

Table 4.1 Cosine Efficiency for 1 week at west side of tower

Position of heliostat relative to receiver, facing angle (Degree)	Cosine Efficiency (%)		
	6 meter	9 meter	12 meter
0	76.9	72.4	69.6
15	77.3	72.8	70.0
30	77.9	73.5	70.7
45	78.9	74.5	71.7

It is observed that the cosine efficiency is different based on the distance of heliostat and position relative to the receiver. The further the tower from the heliostat, the lower the cosine efficiency as shown in table 1 for 6 meter, 9 meter, and 12 meter. The facing angle of heliostat also affects the cosine efficiency. The facing angle of the heliostat that have the highest cosine efficiency is at 45 degree for all three different sets of distance of heliostat from the receiver. Table 4.2 below shows the cosine efficiency at the east side of the tower with respect to heliostat position.

Table 4.2 Cosine Efficiency for 1 week at east side of tower

Position of heliostat relative to receiver (Degree)	Cosine Efficiency (%)		
	6 meter	9 meter	12 meter
0	76.9	72.4	69.6
-15	76.8	72.2	69.3
-30	77.0	72.3	69.4
45	77.5	72.9	70.0

It is observed that the cosine efficiency of heliostat at the east side of the tower is slightly less compared to the cosine efficiency at west side of the tower. From analyzing the simulation data in Table 5, the optimized distance of heliostat for both sides of the tower is at 6 meter where the cosine efficiency is the highest at 77.5% compared to 9 meter (72.9%) and 12 meter (70.0%).

4.3 Heliostat Field Efficiency

Efficiency of heliostat field is computed by taking all the efficiency that had been calculated such as cosine efficiency, atmospheric attenuation, shading and blocking, and mirror reflectivity. The simulation project is focused on cosine efficiency and atmospheric attenuation efficiency. The atmospheric attenuation efficiency is constant throughout the one week simulation at 6 meter (99.25%), 9 meter (99.18%) and 12 meter (99.15%) as the efficiency is a function of distance of heliostat. The value of mirror reflectivity efficiency is assumed to be at 88% while shading and blocking are not focused in this research. Table 4.3 and 4.4 below shows the heliostat field efficiency for one-week period for west and east side at their respective position.

Table 4.3 West side Heliostat field efficiency

Position of heliostat relative to receiver (Degree)	Heliostat Field Efficiency (%)		
	6 meter	9 meter	12 meter
0	88.1	86.5	85.6
15	88.2	86.7	85.7
30	88.4	86.9	86.0
45	88.7	87.2	86.3

Table 4.4 East side Heliostat field efficiency

Position of heliostat relative to receiver (Degree)	Heliostat Field Efficiency (%)		
	6 meter	9 meter	12 meter
-0	88.1	86.5	85.6
-15	88.0	86.4	85.5
-30	88.1	86.5	85.5
-45	88.3	86.7	85.7

From the result obtained, the optimized heliostat field is achieved by placing the heliostat closer to receiver, the efficiency can be increased by more than 1 %. When the distance of heliostat are placed 6 meter from the receiver, it has the highest efficiency of 88% while 9 meter and 12 meter are only at 86% and 85%. Once heliostat at 6 meter is chosen as the optimized heliostat field, by analyzing the azimuthal spacing, the efficiency can be further increased by more than 0.1%. The highest field efficiency is found to be at the west side of the receiver when the heliostat is placed 6 meter away from receiver and at facing angle of 45 degree that yields 88.7%.

CHAPTER 5: CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The mathematical model for determining the solar position have been gathered and developed. By utilizing the mathematical model, the solar and heliostat field position are calculated, and the heliostat field efficiency are recorded. The further the distance of heliostat from the receiver, the lower the cosine efficiency resulting in lower heliostat field efficiency. The optimum distance of heliostat is 6 meter from the receiver at the west side based on the parameters that had been used and the facing angle of heliostat that contributes to the highest cosine efficiency is at 45 degree relative to the center of receiver that yields 78.9%. The atmospheric attenuation efficiency is higher for heliostat that are placed at 6 meter distance compared to 9 meter and 12 meter from the receiver at 99.25%, 99.22% and 99.18% respectively. The further heliostats are placed, the bigger the atmospheric attenuation loss. The overall heliostat field efficiency by taking account of atmospheric attenuation, cosine efficiency and mirror reflectivity that is optimized is found to be at west side of tower, 6 meter distance from heliostat, and at facing angle of 45 degree that yields 88.7% for the parameters that had been set.

5.2 Recommendation

Throughout the progress to complete my project, there are some recommendations that I believe would be able to increase the quality of my project. First of all, my project are solely focused on heliostat field efficiency that includes cosine efficiency, atmospheric attenuation and mirror reflectivity. My project does not focus on shading and blocking effect of heliostat on the heliostat field efficiency. I believe that the data obtained when I include shading and blocking would increase my project credibility.

Besides, my simulation was carried out for two sets of time period, which are one day and week. As a recommendation, it would increase my data collection and analyzing project if I were to increase the simulation period to 1 year starting from 1^{st} January until 31^{st} December. This would make me able to analyze the heliostat field efficiency thoroughly throughout the whole year. I would also be able to further increase the credibility of my project.

Finally, another recommendation is that I believe it would better if the project was able to be carried out in simulation and alongside with experimental. This is to ensure that the project that are carried out can be analyzed directly to match with the experimental value. This will make the project have a strong reference for the simulation part.

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APPENDICES

The matlab simulation code below is used in calculating and plotting the cosine efficiency of heliostat field at distance 6 meter, 9 meter and 12 meter at facing angle of 0, 15,30 and 45 degree.

```
clear
count=13;
t=1;
time=[8:1:16]
k=zeros(t,1);
%t=[9 10 11 12 13 14 15 16 17 18];
lat=4.34;
while (t<=9)
 %for t= 9:18

        hour=(t+7-12)*15;
        fprintf ('the hour angle is:%d \n',hour);
        dec=23.45*sind(360*((284+19)/(365)));
        fprintf( 'the declination is:%d \n',dec);
        sol_alt =asind((cosd(hour))*(cosd(dec))*(cosd(lat))+(sind(dec))*(sind(lat)));
        fprintf ('the solar altitude angle is:%d \n',sol_alt);
        zen_ang =90-sol_alt;
        fprintf ('the zenith angle is:%d \n',zen_ang);
        sol_azimuth= acosd((sind(dec))*(cosd(lat))
(cosd(dec))*(cosd(hour))*(sind(lat))/(cosd(sol_alt)));
        fprintf ('the solar azimuth angle is:%d \n',sol_azimuth);

        if (sind(hour))>0
           sol_azimuth=360-sol_azimuth;
        else
           sol_azimuth=sol_azimuth;
        end

 tower_h=6;
 heli_h=1.5;
 dist= 12;
 %At facing angle=0;

     facing_ang1=0;

    target_ang= atand((tower_h- heli_h)/(dist));
    fprintf ('the target angle is:%d \n',target_ang);
```

```
l1=(sind(sol_alt))*(sind(target_ang))
m1=(cosd(sol_alt))*(sind(sol_azimuth))*(cosd(target_ang))*(sind(facing_ang1))
n1=(cosd(sol_alt))*(cosd(sol_azimuth))*(cosd(target_ang))*(cosd(facing_ang1))
incident_ang1=0.5*acosd(l1+m1+n1)

facing_ang2=15;

l2=(sind(sol_alt))*(sind(target_ang))
m2=(cosd(sol_alt))*(sind(sol_azimuth))*(cosd(target_ang))*(sind(facing_ang2))
n2=(cosd(sol_alt))*(cosd(sol_azimuth))*(cosd(target_ang))*(cosd(facing_ang2))
incident_ang2=0.5*acosd(l2+m2+n2)

facing_ang3=-15;

l3=(sind(sol_alt))*(sind(target_ang))
m3=(cosd(sol_alt))*(sind(sol_azimuth))*(cosd(target_ang))*(sind(facing_ang3))
n3=(cosd(sol_alt))*(cosd(sol_azimuth))*(cosd(target_ang))*(cosd(facing_ang3))
incident_ang3=0.5*acosd(l3+m3+n3)

facing_ang4=30;

l4=(sind(sol_alt))*(sind(target_ang))
m4=(cosd(sol_alt))*(sind(sol_azimuth))*(cosd(target_ang))*(sind(facing_ang4))
n4=(cosd(sol_alt))*(cosd(sol_azimuth))*(cosd(target_ang))*(cosd(facing_ang4))
incident_ang4=0.5*acosd(l4+m4+n4)

facing_ang5=-30;

l5=(sind(sol_alt))*(sind(target_ang))
m5=(cosd(sol_alt))*(sind(sol_azimuth))*(cosd(target_ang))*(sind(facing_ang5))
n5=(cosd(sol_alt))*(cosd(sol_azimuth))*(cosd(target_ang))*(cosd(facing_ang5))
incident_ang5=0.5*acosd(l5+m5+n5)

facing_ang6=45;

l6=(sind(sol_alt))*(sind(target_ang))
m6=(cosd(sol_alt))*(sind(sol_azimuth))*(cosd(target_ang))*(sind(facing_ang6))
n6=(cosd(sol_alt))*(cosd(sol_azimuth))*(cosd(target_ang))*(cosd(facing_ang6))
incident_ang6=0.5*acosd(l6+m6+n6)

facing_ang7=-45;

l7=(sind(sol_alt))*(sind(target_ang))
```

```
  m7=(cosd(sol_alt))*(sind(sol_azimuth))*(cosd(target_ang))*(sind(facing_ang7))
  n7=(cosd(sol_alt))*(cosd(sol_azimuth))*(cosd(target_ang))*(cosd(facing_ang7))
  incident_ang7=0.5*acosd(17+m7+n7)

  cosine_eff1(t)=cosd(incident_ang1)*100;
  cosine_eff2(t)=cosd(incident_ang2)*100;
  cosine_eff3(t)=cosd(incident_ang3)*100;
  cosine_eff4(t)=cosd(incident_ang4)*100;
  cosine_eff5(t)=cosd(incident_ang5)*100;
  cosine_eff6(t)=cosd(incident_ang6)*100;
  cosine_eff7(t)=cosd(incident_ang7)*100;
  %cosine=[cosine_eff];
  %fprintf ('the cosine efficiency is %d \n',cosine_eff);
 % fprintf ('---------------------------------- \n');

  t=t+1;

end
disp(cosine_eff1)
disp(cosine_eff2)
disp(cosine_eff3)
disp(cosine_eff4)
disp(cosine_eff5)
disp(cosine_eff6)
disp(cosine_eff7)

ma=(sum(cosine_eff1,2))/9
mb=(sum(cosine_eff2,2))/9
mc=(sum(cosine_eff3,2))/9
md=(sum(cosine_eff4,2))/9
me=(sum(cosine_eff5,2))/9
mf=(sum(cosine_eff6,2))/9
mg=(sum(cosine_eff7,2))/9

disp(time)
  figure
  plot
(time,cosine_eff1,time,cosine_eff2,time,cosine_eff4,time,cosine_eff6),xlabel('time'),ylabel('cosin
e efficiency'); title ('Graph of cosine efficiency');
  ylim([40 95]);
  legend({'(0 degree)','(15 degree)','(30 degree)','(45 degree)'},'Location','southwest')
  grid on
  zoom on



  figure

plot(time,cosine_eff1,time,cosine_eff3,time,cosine_eff5,time,cosine_eff7),xlabel('time'),ylabel('c
osine efficiency'); title ('Graph of cosine efficiency')
  ylim([40 95]);
  legend({'(0 degree)','(-15 degree)','(-30 degree)','(-45 degree)'},'Location','southeast')
  grid on
  zoom on
```

The matlab simulation code below is used in calculating the cosine efficiency at different distance of heliostat at the point where it is north of the receiver.

```
clear
i=13;
t=1;
time=[8:1:16]
k=zeros(t,1);
%t=[9 10 11 12 13 14 15 16 17 18];
lat=4.34;
%dec=zeros(10);
%hour=zeros(10);
%sol_alt=zeros(10);
%zen_ang=zeros(10);
%sol_azimuth=zeros(10);
%surf_azimuth=zeros(10);
%target_ang=zeros(10);
%facing_ang=zeros(10);
%l=zeros(10);
%m=zeros(10);
%n=zeros(10);
%o=zeros(10);
%incident_ang=zeros(10);
%d=zeros(10);
%cosine=[];

 while (t<=9)
 %for t= 9:18

  hour=(t+7-12)*15;
 fprintf ('the hour angle is:%d \n',hour);
 dec=23.45*sind(360*((284+19)/(365)));
 fprintf( 'the declination is:%d \n',dec);
 sol_alt =asind((cosd(hour))*(cosd(dec))*(cosd(lat))+(sind(dec))*(sind(lat)));
fprintf ('the solar altitude angle is:%d \n',sol_alt);
zen_ang =90-sol_alt;
fprintf ('the zenith angle is:%d \n',zen_ang);
sol_azimuth= acosd((sind(dec))*(cosd(lat))-(cosd(dec))*(cosd(hour))*(sind(lat))/(cosd(sol_alt)));
fprintf ('the solar azimuth angle is:%d \n',sol_azimuth);

       if (sind(hour))>0
          sol_azimuth=360-sol_azimuth;
```

```
    else
      sol_azimuth=sol_azimuth;
    end


tower_h=6;
heli_h=1.5;
dist1= 6;
dist2=9;
dist3=12;

  facing_ang1=0;

 target_ang1= atand((tower_h- heli_h)/(dist1));
 fprintf ('the target angle is:%d \n',target_ang1);
 l1=(sind(sol_alt))*(sind(target_ang1))
 m1=(cosd(sol_alt))*(sind(sol_azimuth))*(cosd(target_ang1))*(sind(facing_ang1))
 n1=(cosd(sol_alt))*(cosd(sol_azimuth))*(cosd(target_ang1))*(cosd(facing_ang1))
 incident_ang1=0.5*acosd(l1+m1+n1)

 facing_ang2=0;

 target_ang2= atand((tower_h- heli_h)/(dist2));
 fprintf ('the target angle is:%d \n',target_ang2);
 l2=(sind(sol_alt))*(sind(target_ang2))
 m2=(cosd(sol_alt))*(sind(sol_azimuth))*(cosd(target_ang2))*(sind(facing_ang2))
 n2=(cosd(sol_alt))*(cosd(sol_azimuth))*(cosd(target_ang2))*(cosd(facing_ang2))
 incident_ang2=0.5*acosd(l2+m2+n2)

 facing_ang3=0;

 target_ang3= atand((tower_h- heli_h)/(dist3));
 fprintf ('the target angle is:%d \n',target_ang3);
 l3=(sind(sol_alt))*(sind(target_ang3))
 m3=(cosd(sol_alt))*(sind(sol_azimuth))*(cosd(target_ang3))*(sind(facing_ang3))
 n3=(cosd(sol_alt))*(cosd(sol_azimuth))*(cosd(target_ang3))*(cosd(facing_ang3))
 incident_ang3=0.5*acosd(l3+m3+n3)

 cosine_eff1(t)=cosd(incident_ang1)*100;
 cosine_eff2(t)=cosd(incident_ang2)*100;
 cosine_eff3(t)=cosd(incident_ang3)*100;
 %cosine=[cosine_eff];
fprintf ('the cosine efficiency is %d \n',cosine_eff);
```

```
  fprintf ('------------------------------------ \n');

   t=t+1;

 end
 ma=(sum(cosine_eff1,2))/9
 mb=(sum(cosine_eff2,2))/9
 mc=(sum(cosine_eff3,2))/9
 disp(cosine_eff1)
 disp(cosine_eff2)
 disp(cosine_eff3)

 disp(time)
  plot (time,cosine_eff1,time,cosine_eff2,time,cosine_eff3),xlabel('time'),ylabel('cosine
efficiency'); title ('Graph of cosine efficiency')
  ylim([0 100]);
  legend({'6m','9m','12m'},'Location','southwest')

 grid on
 zoom on
```

The matlab simulation code below is used in calculating and plotting the atmospheric attenuation efficiency of the heliostat field at different distance.

```
Clear
count=13;
t=1;
time=[8:1:16]
k=zeros(t,1);
lat=4.34;

 while (t<=9)

 tower_h=6;
 heli_h=1.5;
 dist1= 6;
 dist2=9;
 dist3=12;

   if dist1<1000
      atm_att1(t)=(0.99321-(0.0001176*dist1)+((1.97*10^-8)*dist1^(2)))*100
   else
      atm_att1(t)=exp(-0.0001106*dist1)
   end

     if dist2<1000
      atm_att2(t)=(0.99321-(0.0001176*dist2)+((1.97*10^-8)*dist2^(2)))*100
   else
      atm_att2(t)=exp(-0.0001106*dist2)
   end
```

```
  if dist3<1000
     atm_att3(t)=(0.99321-(0.0001176*dist3)+((1.97*10^-8)*dist3^(2)))*100
  else
     atm_att3(t)=exp(-0.0001106*dist3)
  end

  t=t+1;
end
disp(atm_att1)
disp(atm_att2)
disp(atm_att3)
disp(time)

plot (time,atm_att1,time,atm_att2,time,atm_att3),xlabel('time'),ylabel('atmospheric attenuation');
title ('Graph of atmospheric attenuation')
ylim([99.0 99.5]);
legend({'6m','9m','12m'},'Location','southwest')

grid on
zoom on
```