

The Malaysian International Tribology Conference 2013, MITC2013

Preliminary Study of CST in Malaysia Based on Field Optical Efficiency

S.A. Rafeq^{a*}, Z.M. Zulfattah^a, A.M. Najib^a, M.Z.M. Rody^a, S. Fadhli^a,
Mohd Fadzli Bin Abdollah^a, M.H.M. Hafidzal^a

^aFaculty of Mechanical Engineering, Universiti Teknikal Malaysia Melaka, 76100 Durian Tunggal, Melaka, Malaysia

Abstract

Solar is one of the many sources of renewable energy, and Concentrating Solar Tower (CST) is one of the most potential technologies in extracting solar energy. Thermal efficiency of CST is high and suitable to be implemented in a tropical climate country such as Malaysia which is located between at 1^o to 7^o North latitude and 100^o to 120^o east longitude. Further, Malaysia's direct normal irradiation (DNI) in tropical climate is almost constant throughout a year with the irradiation around 1500 to 2000 kWh/m². Therefore the aim of this paper is to mathematically calculate the CST field layout in Malaysia in term of thermal efficiency based on cosine efficiency, atmosphere efficiency and mirror efficiency. The preliminary result from this paper shows Malaysia is a suitable location to develop CST with average of atmospheric transmittance efficiency and cosine efficiency of 94% and 63% respectively and the overall optical field efficiency is 52%. In addition, the atmospheric transmittance and cosine efficiency has high value but the efficiency gradually decreases whenever the distance increases. Nevertheless further investigation in term of solar irradiation and raining pattern in Malaysia is needed.

© 2013 The Authors. Published by Elsevier Ltd.

Selection and peer-review under responsibility of The Malaysian Tribology Society (MYTRIBOS), Department of Mechanical Engineering, Universiti Malaya, 50603 Kuala Lumpur, Malaysia

Keywords: Solar concentrating power (CSP); solar concentrating tower (CST); solar energy; renewable energy

Nomenclature

θ	latitude angle of the sun
ϕ	longitude angle of the sun
δ	declination angle
ω	sun hour angle
n_d	number of days in 365 day a year
α	elevation angle of the sun relative to earth position
A	azimuth angle of the sun relative to earth position
η_{field}	optical Field Efficiency
$\eta_{sh\&bl}$	shadowing & blocking of heliostat efficiency
η_{at}	atmospheric transmission efficiency

* Corresponding author. Tel.: +6 06-2346794 ; fax: +606-2346884.

E-mail address: rafeq@utem.edu.my

η_{ref}	heliostat mirror reflectivity
Θ_H	azimuth angle of the heliostat relative to the receiver
λ	angle between the reflected ray incident on the heliostat center relative to tower base
S_0	Slant distance between center of heliostat to receiver

1. Introduction

In recent years the development of cleaner and renewable energy is emerging rapidly from various countries and various types of sources. The reasons are due to the depletion of fossil fuels and as a result of environmental impact of fossil fuels usage. Besides that, renewable energy has the potential to be lucrative business in the near future and as a result most researchers investigate new source of energy and lastly, in order to be in aligned with worldwide energy development. Solar is one of the many sources of renewable energy, and Concentrating Solar Power (CSP) is one of the most potential technologies in extracting solar energy. Thermal efficiency of CSP is high and suitable to be implemented in a tropical climate country such as Malaysia. In addition, Malaysia is located between at 1^0 to 7^0 North latitude and 100^0 to 120^0 east longitude, which is almost at the equator line [1]. Further Malaysia has the tropical climate that is hot and humid throughout the year, means that the direct normal irradiation (DNI) in tropical climate is almost constant throughout a year with the irradiation around 1500 to 2000 kWh/m² per year. Even though Malaysia is a strategic location for CSP, but developments toward this area is less numerous. Therefore the aim of this paper is mathematical calculation of CST field layout in Malaysia in term of thermal efficiency based on three factors that are cosine efficiency, atmosphere efficiency and mirror reflectivity efficiency of heliostat.

1.1. Concentrating Solar Power

Concentrating solar power (CSP) is defined as a method of using solar sunlight to produce power. Unlike photovoltaic that manipulate photoelectric effect to produce electricity, CSP uses heat generated from sunlight to produce electricity. CSP uses lenses, mirror and tracking system to reflect and focus large area of sunlight to a small beam. Generally, CSP has three types of system that are trough system, dish system and central receiver. Referring to Fig. 1, trough system use parabolic mirror to collect and concentrated the sunlight to a tube and fluids-carrying receiver located at the focal point of the mirror, as for dish system it uses dish shaped parabolic mirror to reflect and focus sun rays onto a receiver and lastly the central receiver use reflector that called heliostat to reflect solar energy onto a receiver [2]. From previous study in tropical climate shows that central receiver generate and collect the highest electricity and solar energy respectively compared to the other two system even though it has the lowest solar to electricity efficiency [3].

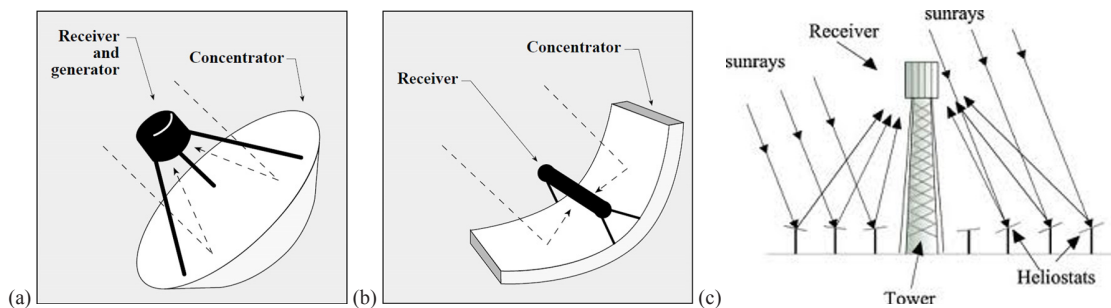


Fig. 1. Type of CST (a) Parabolic trough system, (b) Dish System, (c) Central System.

1.2. Concentrating Solar Tower

Central tower system or also known as Concentrating Solar Tower (CST), consist of 5 major component which are heliostat, receiver, heat transport, thermal storage and lastly control system. CST generate electric by focusing solar radiation onto a receiver that placed at the top of a tower, the system uses hundreds of heliostat or mirror and

sun-tracking system to reflect sunlight onto a receiver. A heat transport is pumped from cold storage to receiver to be heated and then to a hot tank for storage. The hot tank is used to generate steam generator to produce electricity and after that the heat transport then return back to cold storage [3]. Among the suitable location for CST is near the equator line which has high and constant solar irradiation, not to mention tropical climate which has hot and humid climate throughout the year plus high solar irradiation around 1500 to 2000 kWh/m² per year. Nevertheless tropical climate has one drawback towards solar energy which is the unpredictable movement of the clouds that effects the solar irradiation and also the unpredictable raining pattern throughout the year [4, 5]. Regardless of this drawback still on average the tropical climate DNI is quite high.

Basically, the sun irradiation on earth can be measured in 2 ways first by using an equipment called pyrometer and another method is by using mathematical model that already been developed by S Janjai to estimate the Direct Normal Irradiation (DNI) in tropical climate [4, 5]. As for pyrometer, it generally measured on a planar surface and is a sensor designed to measure solar radiation flux density in watts per meter square [4].

2. Sun Location

In order to developed renewable energy that uses solar, determining the exact location of the sun is crucial. The location of the sun is measured from certain earth location. Each geographical location on earth has its own coordinates, which is latitude ϕ and longitude θ . [9, 10] Malaysia coordinates location is between 1⁰ to 7⁰ North latitude and 100⁰ to 120⁰ east longitude.

2.1. Solar Position

In order to calculate the instantaneous efficiency of heliostat field efficiency the sun position need to be determined. The sun location from earth can be calculated based on declination, hour, azimuth and elevation angle [3-9]. The position can be calculated based on equation (1) and (2) as shown below:-

$$\delta = \frac{23.45\pi}{180} \sin\left(2\pi \frac{284 + n_d}{365}\right) \quad (1)$$

$$\omega = \cos^{-1}(\tan\phi \tan\delta) - \pi \quad (2)$$

where, δ is declination angle of earth, n_d is number of day in 365 day a year, ω is sun hour angle, and ϕ is latitude angle of the sun. These equation accurately measure sun position from earth [9, 11].

2.2. Azimuth & Elevation Angle

The sun position relative to an observer on the earth ground was based on 2 angle which are elevation/altitude angle and azimuth angle. Both of the angles can be calculated using equation (3) and (4) for latitude angle and azimuth angle respectively:-

$$\alpha = \sin^{-1}(\cos\phi \cos\delta \cos\omega + \sin\phi \sin\delta) \quad (3)$$

$$A = \operatorname{sgn}\left(\frac{\sin\alpha \sin\phi - \sin\delta}{\cos\alpha \cos\phi}\right) \quad (4)$$

where α is latitude angle and A is azimuth angle, this two angle can be used as references to determine the suitable location for CST development [9, 11].

3. Efficiency

There are numerous source of energy loss in a CST, the combination of all this losses can be define as total system efficiency of certain location for CST development. Even though there are many kind of energy loss the major losses which are considered in the calculation of the total optical efficiency are define as cosine efficiency, atmospheric transmission efficiency, reflectivity efficiency, and blocking and shading efficiency. Total optical efficiency is the ratio of the net power absorbed by the receiver to the power incident normally on the field. It can be calculated based on equation (5) as shown below [7, 9, 13]:-

$$\eta_{field} = \eta_{cos} \eta_{sh\&bl} \eta_{ref} \eta_{at} \quad (5)$$

3.1. Cosine efficiency

Cosine efficiency is the efficiency of a single heliostat in certain location on the CST field which relate to the azimuth and elevation angle of the sun. The cosine efficiency of a heliostat depends on the sun location and heliostat position itself on the heliostat field. In this study the tower height is fixed and the calculation was based on single heliostat. Therefore the cosine efficiency of a heliostat equal to the cosine of incident angle θ relative to the heliostat center is given in equation (6) as shown below [7, 9, 11, 12]:-

$$\cos \theta = \frac{\sqrt{2}}{2} (\sin \alpha \cos \lambda - \cos(\theta_H - A) \cos \alpha \sin \lambda + 1)^{1/2} \quad (6)$$

3.2. Atmospheric Transmission Efficiency

The atmosphere efficiency depends on the distance of the heliostat to the receiver and also the weather condition on certain location. Based on previous study by Vittitoe and Biggs (1978) they approximate that for a clear day is 23km visibility whereas for hazy day the visibility is 5km visibility. For a clear day the visibility is calculated as shown in equation (7) for heliostat to receiver distance below than 1000m and equation (8) for heliostat to receiver distance more than 1000m [7,12]:-

$$\eta_{at} = 0.99321 - 0.0001176S_0 + 1.97 \times 10^{-8} S_0 \quad S_0 \leq 1000m \quad (7)$$

$$\eta_{at} = e^{-0.0001106S_0} \quad S_0 > 1000m \quad (8)$$

3.3. Heliostat Reflectivity Efficiency

Heliostat reflectivity is due to the design itself which also have some energy losses. The heliostat mirror surfaces reflect most of the solar energy or the sun ray but it also absorbs some of the energy. A standard value for the heliostat reflectivity is 0.88 which means 88% of the solar energy is reflected to the receiver. [14]

4. Results

4.1. Location Selection

The data collected from this study were based on one location in Malaysia, and to be more specific in Malacca around Bemban area, which have latitude 102.372665405273 and longitude 2.2564202962028. Bemban area was selected due to its topography which has huge area and has almost level ground. On top of that the area is

surrounded by plantation of palm oil and rubber oil which were far away from human civilization. As a result from all justification above it shows that this area is a suitable location for CST development.

4.2. Analysis

This study was based on one location, one heliostat but with different distance from tower. In addition the azimuth and elevation angle of the sun was taken during noon of local time and the data was calculated on weekly basis. Further in this study the efficiency of the atmospheric transmission, cosine efficiency and heliostat mirror reflectivity efficiency been calculated based on the particular location whereas blocking and shading due to each heliostat have not been considered in the study.

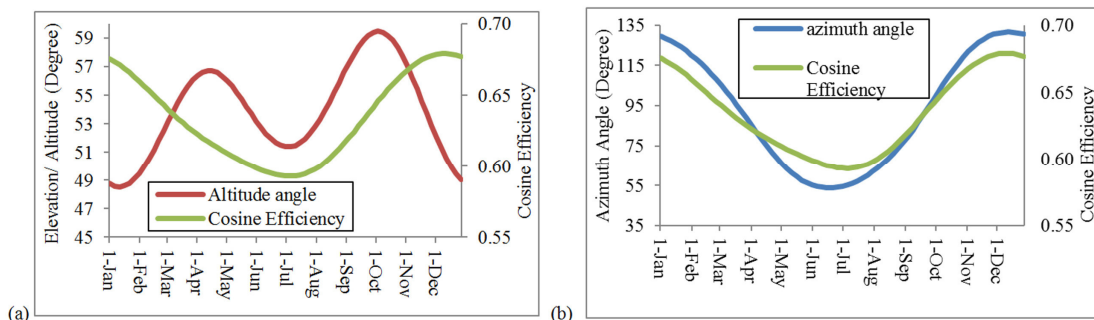


Fig. 2. Illustrate the cosine relation with (a) Elevation Angle of sun (b) Azimuth Angle of sun.

The calculated data of the azimuth and elevation angle versus day in weekly basis was tabulated in Fig 2. Referring to equation (6) the cosine efficiency depends on three data which are the azimuth angle of the sun, elevation angle of the sun and tower height, but based on this study the cosine efficiency proportional to the azimuth angle of the sun this can be seen in Fig 2(b). Meaning that whenever the azimuth angle is high the cosine efficiency also may increase, this characteristic can also be seen from the plot pattern of cosine efficiency and azimuth plot pattern.

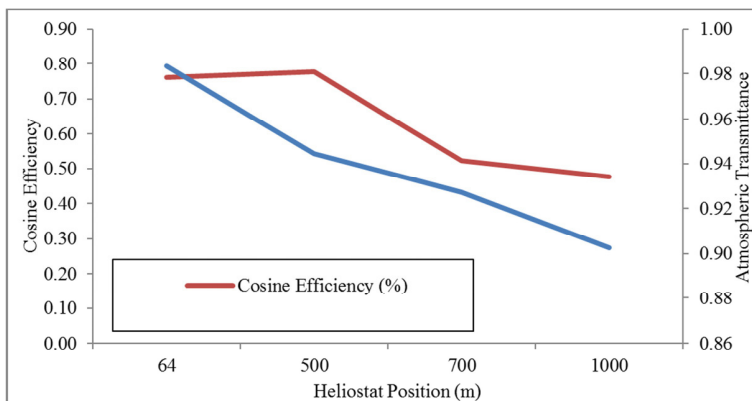


Fig. 3. Cosine Efficiency & Atmospheric Transmittance Efficiency with different heliostat distance.

The atmospheric transmittance efficiency and cosine efficiency shown in Fig 3, indicates that the efficiency versus slant distance of center heliostat to tower for both efficiency decreases as the distance of the heliostat increases. In details, the atmospheric transmittance show slight decrease whenever the heliostat distance increases, whereas for the cosine efficiency it shows major reduction. In general the overall efficiency of the optical fields is

52% as depicted in table 1, with the average of atmospheric transmittance efficiency around 94%, average cosine efficiency around 63% and mirror reflectivity equal to 88%.

Table 1: The Efficiency of CST in Melaka

Heliostat position	(Malaysia) Average	(Aswan) Average
Atmospheric Transmittance efficiency (%)	0.94	0.95
Cosine Efficiency (%)	0.63	0.85
Mirror Reflectivity efficiency (%)	0.88	0.88
Total Optical Efficiency (%)	0.52	0.70

The efficiency calculated is been compared to the cosine efficiency of PS10 SPT in Aswan as shown in Table 1. The data were taken from M.A. Mustafa et al study, where the average Atmospheric Transmittance efficiency is 95% which is only 1% different in Malaysia, whereas for cosine efficiency shows that a huge different with 22% reduction. Even though, the cosine efficiency in Malaysia is low but the total Optical efficiency of the overall system is around 50%. Analysing from these data shows that the total optical efficiency depend closely on the cosine efficiency, whereby in this study shows that the location also plays an important role in determining the overall efficiency of the CST.

5. Conclusion

This preliminary results shows that Malaysia has the potential to develop CST in the future, nevertheless further investigation in term of raining pattern and solar irradiation in Malaysia is needed. In addition the overall system efficiency based on small scale model need to be develop and investigate. Furthermore this study uses general equation for CST, specific equation with optimization is needed in the CST development for certain location, and therefore the overall efficiency of the optical fields and overall system may be increase.

Acknowledgement

This study was supported by Universiti Teknikal Malaysia Melaka under short term research grant scheme (PJP/2012/FKM(5A)/S01075). Special thanks to all friends involved in this study.

References

- [1] S. Mekhilef, Renewable Energy Resources and Technologies Practice in Malaysia, 5th International Symposium on Hydrocarbons & Chemistry (ISH), Sidi Fredj, Algiers, 23rd May 2010 to 25th May 2010.
- [2] Energy Efficiency & Renewable Energy, DOE/GO-102001-1147, FS 128, March 2001.
- [3] S. Janjai, J. Laksanaboonsong, T. Seesaarad, Potential application of concentrating solar power systems for the generation of electricity in Thailand, Applied Energy 88 (2011) 4960-4967.
- [4] S. Janjai, P Pankaew, J Laksanaboonsong, A model for calculating hourly global solar radiation from satellite data in the tropics, Applied Energy, 86 (2009) 1450-1457.
- [5] Serm Janjai, A method for estimating direct normal solar irradiation from satellite data for a tropical environment, Solar energy 84 (2010) 1685-1695.
- [6] Francisco J. Collado, Preliminary design of surrounding heliostat fields, Renewable Energy 34 (2009) 1359-1363.
- [7] Xiudong Wei, Zhenwu Lu, Zi Lin, Hongxin Zhang, Zhengguo Ni, Optimization Procedure for Designing of Heliostat Fields Layout of a 1MWe Solar Tower Thermal Power Plant. Proc. Of SPIE Vol. 6841 684119-1.
- [8] F.MF. Siala, M.E. Elayeb, Mathematical formulation of a graphical method for a no-blocking heliostat field layout, Renewable Energy 23 (2001) 77-92.
- [9] M.A. Mustafa, S. Abdelhady, A.A. Elweteedy, Analytical Study of an Innovated Solar Power Tower (PS10) in Aswan, International Journal of Energy Engineering 2012, 2(6): 273-278.
- [10] M. Ewert, O. Navarro Fuentes, Modelling and Simulation of a Solar Tower Power Plant,

- [11] Hongli Zhang, Zhifeng Wang, Minghuan Guo, Wenfeng Liang, Cosine Efficiency Distribution of Heliostats Field of Solar Thermal Power Tower Plant.
- [12] Xiudong Wei, Zhenwu Lu, Zhifeng Wang, Weixing Yu, Hongxing Zhang, Zhihao Yao, A New Method for the Design of the Heliostat Field Layout for Solar Tower Plant, *Renewable Energy* 35(2010) 1970-1975.
- [13] A. Secal, M. Epstein, Comparative Performances of Tower-Top And Tower-Reflector Central Solar Receivers, *Solar Energy* Vol. 65, No4, pp. 207-226, 1999.
- [14] Corey J. Noone, Manuel Torrilhon, Alexander Mitsos, Heliostat Field Optimization : A New Computationally Efficient Model and Biomimetic Layout, *Solar Energy* 2012.