

Energy Comparison of the Optics and Tracking System for Evacuated Solar Thermal Collector by using Ray Tracing Analysis

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Abstract

Evacuated tube solar collector is one of the feasible alternatives for heating demand application such as absorption chiller. They are mostly suitable for supplying outlet temperature up to 100°C. In this paper, we present a tracking evacuated tube solar collector with semi-parabolic reflector to improve the efficiency of glass tube solar collector. Firstly, the ray tracing analysis is employed to design the suitable optics for non-tracking glass evacuated tube solar collector. Next, the intensity and beam pattern on heat absorber of each optic is determined to select the appropriate optics. Then, to comparing the energy between non-tracking and tracking tube solar collectors with reflector system, the total power on heat absorber and the total power per installation area during the daytime are figured out by using the sun position referring to the solar equation. According to the analysis, the presented tracking evacuated glass tube solar collector with reflector can drastically increase the power on heat absorber and power per installation area especially in the morning and evening. This model can be used to understand and predict the efficiency of the prototype for the better evacuated tube solar collector.

Keywords: evacuated tube solar collector, ray tracing analysis, solar thermal

1. Introduction

Due to Thailand's renewable energy development plan coupled with the global warming and oil price crisis, solar energy becomes one of the renewable sources that play a crucial role in the economic development of Thailand. However, the research and development on solar energy is still modest in quantity compared to other countries. To keep pace with the rapid growth in solar technology and rising energy demand, the evacuated tube solar collector is focused in this study as an

indispensable component in renewable thermal cooling system [1].

Compared to conventional flat plate collectors, evacuated tube solar collectors have lower heat losses thanks to the vacuum envelope surrounding the heat absorber fins [2–3]. The evacuated tube solar collector operates by transferring thermal energy from the heat absorber fins to the working fluid within the heat pipe.

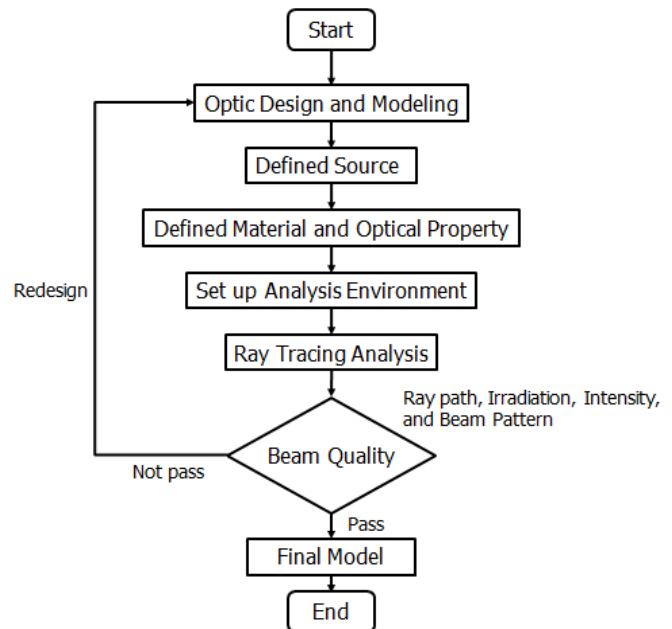
In order to promote the solar energy utilization for heating demand application such as

solar absorption chiller in Thailand, the evacuated tube solar thermal collector should be developed to increase concentration's efficiency, improve thermal quality, lower the manufacturing cost and higher the energy per installation area. Therefore, in this paper, the proper optics for non-tracking evacuated glass tube solar collector is designed and selected by employing ray tracing method to improve the beam quality on the heat absorber. Then, the power on heat absorber and the power per installation area during the operating hours between a non-tracking and tracking glass tube solar collectors with reflector system are figured out and compared by using the sun position referring to the solar equation. As the results of the analysis, the tracking evacuated glass tube solar collector with reflector presented in this paper can drastically increase the power on heat absorber and power per installation area especially in the morning and afternoon comparing to the typical evacuated tube solar collector. Consequently, the model gained from this project can be used to understand and predict the efficiency of the prototype for the better evacuated tube thermal collector in solar heating demand application.

2. Solar Thermal Collector Optical Model

For ray tracing analysis, we have used the ray tracing software "SPEOS" by OPTIS. This software is a physical based optical modeling by applying optical properties to all surfaces, materials and light sources. By calculating with user defined optical properties, the software can predict the ray paths, calculate the intensity and beam pattern with diffused and directly reflecting

surfaces. The solar thermal collector analysis is shown in the following flow chart diagram.



Flow chart diagram of solar thermal collector analysis

In this paper, SPEOS was employed to calculate the solar intensity and its beam pattern on the heat absorber to validate the different optic designs in non-tracking and tracking mode for quantifying the performance of the evacuated tube solar thermal collector.

For ray trace modeling, as shown in "Fig. 1", the geometry of all evacuated glass tubes were built with identical physical materials to have a length of 1.957 m and a diameter of 0.100 m. The glass tube with index of refraction 1.5 is made of anti-reflective coating borosilicate glass with 0.100 m. in diameter and 2 mm. wall thickness. The 0.355 m² double side aluminum planar heat absorber plate is modeled to have aluminum nitride coating with 92% absorption coefficient.

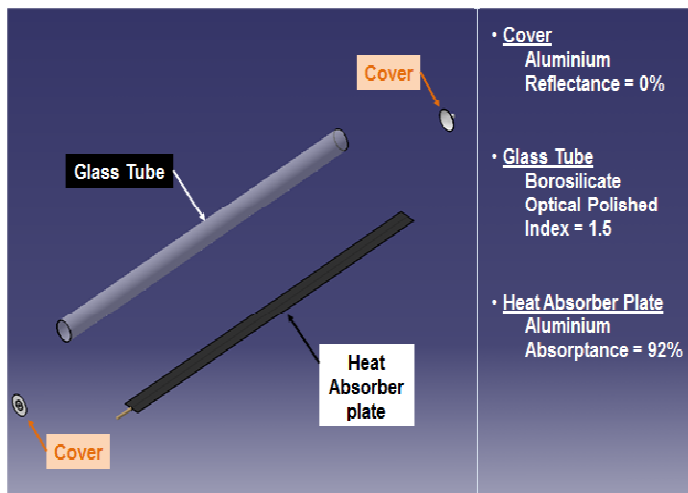


Fig. 1 Ray tracing model and optical properties of evacuated glass tube thermal collector

In simulation, the evacuated tube solar collector was positioned such that the tube was aligned in a north-south orientation at the center of the solar surface source. Each concentrating collector was positioned, facing the solar surface light source at a tilt angle of 30 degree to simulate a typical operation as shown in "Fig. 2"

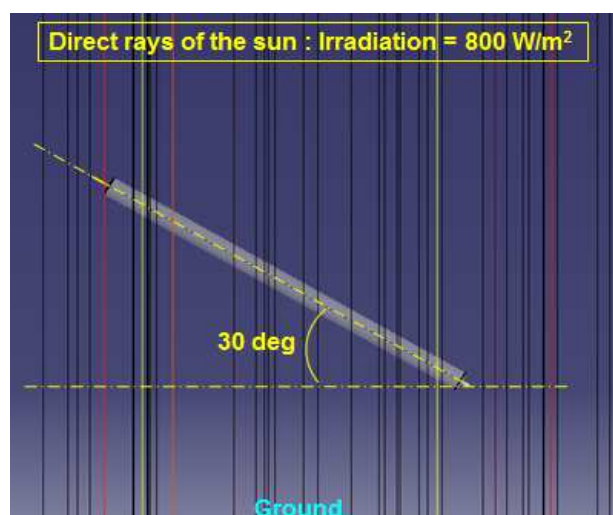


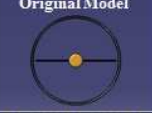
Fig. 2 Evacuated tube solar collector installation for ray tracing simulation

The sun light was modeled by a surface light source generated collimated direct rays and normal incident to ground with uniform irradiation at 800 W/m^2 at the ground surface. With ray tracing analysis, the ray paths, irradiance and beam pattern of the solar rays on the heat absorption plate has been calculated and used to evaluate the performance of the various solar tube collectors' configurations.

3. Optics Performance Estimation

In this section, the ray tracing analysis was applied to design and estimate the performance of three optical configurations for evacuated solar tube thermal collector, which are semi parabolic reflector with 87% reflectance, concentrating PMMA lens with index of refraction 1.49 and the combined lens and reflector system. For ray tracing analysis, the solar thermal collector optical model in "Fig. 2" was employed. The solar irradiation was input at 800 W/m^2 and normal incident to ground plane. The 100,000,000 rays were used in calculation. The refraction inside the glass tube and the reflection at the reflector due to Fresnel effects were handled by a Monte-Carlo approach. The ray paths, irradiation on heat absorber, and beam pattern of each optic was figured out and compared as shown in Table. 1.

Table.1 shows the comparison results of the solar beam patterns on the top and bottom surface of heat absorber including the total irradiation from each optic configuration.

	Top Surface	Bottom Surface	Ave. Irradiation
Original Model 			173.6 W/m ²
Reflector 			625.3 W/m ²
LENS 			339.7 W/m ²
Reflector + LENS 			792.7 W/m ²

According to the simulation results in Table.1, at the solar irradiation 800 W/m², the non-imaging semi parabolic reflector increases the average irradiation on both surfaces of heat absorber from 173.6 W/m² to 625.3 W/m² or 3.6 times higher than typical model due to additionally reflected solar rays collected at the bottom surface of the heat absorber, whereas the PMMA lens can enhance the concentration to intensify the irradiation from 173.6 W/m² to 339.7 W/m² on the top surface of heat absorber. Besides, by combining the previous two optic configurations, the irradiation on heat absorber is increased from 173.6 W/m² to 792.7 W/m². Although, the ray tracing results suggest that all three optic configurations can greatly improve the solar irradiation on heat absorber, however, when the manufacturing cost and the ease of maintenance are taken in to account the semi parabolic

reflector (with the additional cost of 1,200 baht per reflector sheet) is seem to be the suitable cost effective choice to apply with the existing conventional evacuated tube solar thermal collectors to improve their thermal performance.

4. Power and Power per Installation Area Comparison

Although the designed semi parabolic reflector in the previous section can reduce the number of tubes, increase the solar power and enhance the optical concentration, but the installation area is also increasingly required due to the reflector installation. Hence, the power and power per installation area must be considerably concerned for the performance and economical evaluation of the new evacuated tube solar thermal collector with semi parabolic reflector. For this paper, the power and power per installation area of six evacuated tube solar collectors without and with reflector as shown in "Fig. 3" were investigated.

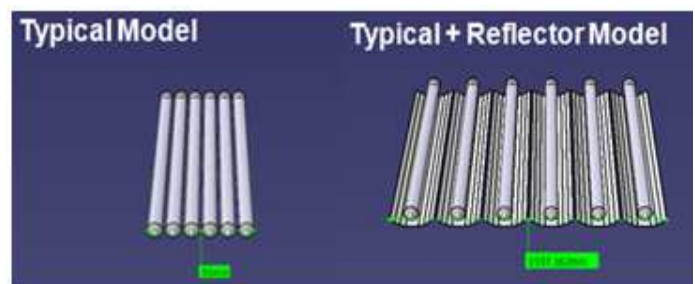


Fig. 3 The typical evacuated tube solar collector array and the one with semi parabolic reflectors

To calculated and compared power and power per installation area, the position of the sun during the operating hours (8.00 A.M. to 4.00

P.M.) on March 22nd, 2012 was calculated from solar equations and used in simulation as shown in “Fig. 4”. The constant solar radiated power of direct rays was set at 600 W/m^2 (approximately 17 MJ/m^2) for considering only the effect of the sun position to the changing of power and beam pattern on heat absorber. An array of six evacuated tube solar collectors is positioned such that all tubes are aligned in a north–south orientation at a tilt angle of 30 degree.

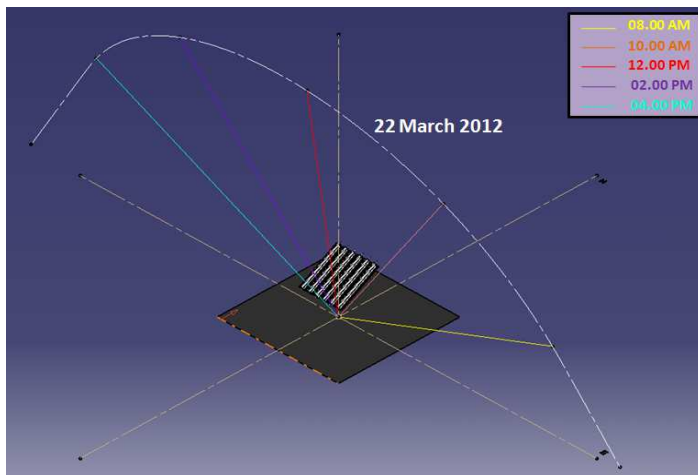


Fig. 4 The sun position during operating hours on March 22nd, 2012 and the installation of evacuated tube solar collector array for simulation

With the configuration as shown in “Fig.4”, the beam patterns on heat absorber’s surface for typical tubes and tubes with reflectors were predicted and compared in the different periods of the day as shown in “Fig. 5” and the irradiation on heat absorber surface were determined for calculating the total power and total power per installation as shown in Table.2, where the installation area is 1.19 m^2 for typical model and 3.29 m^2 for reflector model. Then, the chart of total power and operating time for typical and

reflector model was plotted in “Fig. 6”, and the chart of total power per installation area was presented in “Fig. 7”

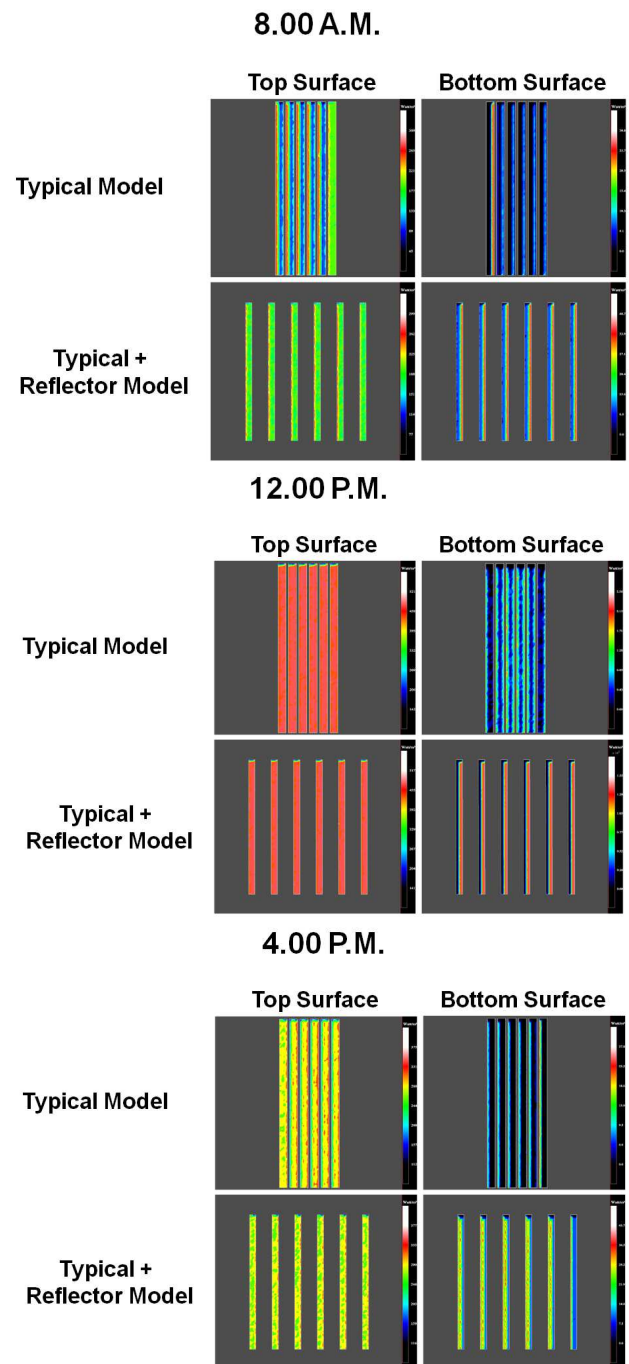


Fig. 5 The compared beam patterns on heat absorber surface for two different configurations of evacuated tube array at 8.00 A.M., 12.00 P.M., and 4.00 P.M.

Table.2 The comparison results of the total power on heat absorber and the total power per installation area for two different configurations of evacuated tube collectors during operating time

	08:00 A.M.		10:00 A.M.		12:00 P.M.		02:00 P.M.		04:00 P.M.	
	P_{Total} (W)	$P_{Total} / A_{Install}$ (W/m ²)	P_{Total} (W)	$P_{Total} / A_{Install}$ (W/m ²)	P_{Total} (W)	$P_{Total} / A_{Install}$ (W/m ²)	P_{Total} (W)	$P_{Total} / A_{Install}$ (W/m ²)	P_{Total} (W)	$P_{Total} / A_{Install}$ (W/m ²)
Typical 6 tubes (Area = 1.19 m ²)	202.1	169.9	435.4	365.8	506.1	425.3	476.9	400.8	311.4	261.7
Typical + Reflector 6 tubes (Area = 3.29 m ²)	248.7	75.5	517.2	157.0	1,350.0	409.8	679.7	206.3	338.1	102.6

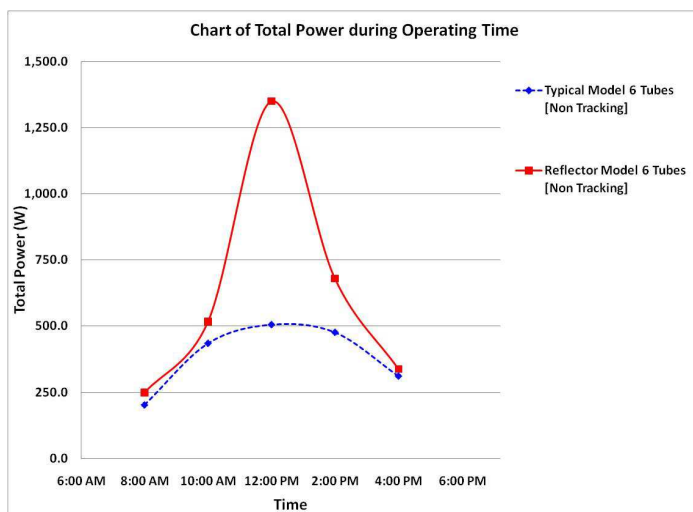


Fig. 6 Chart of Total power during operating time compared between two different configurations of evacuated tube array

In accordance with the analysis results above, at the same solar irradiation, the power on heat absorber increases from 8.00 A.M. to 12.00 P.M. and decreases from 12.00 P.M. until 4.00 P.M. due to the amount of incident and reflected solar rays on heat absorber surfaces as shown in

“Fig. 5”. Besides, Table. 2 presented that, at 12.00 P.M., the maximum power on heat absorber is 1,350 W. for reflector model, while the typical model give only 506 W. However, both types of evacuated tube solar collector give approximately the same power on heat absorber from 8.00 A.M. to 10.00 A.M. and at 4.00 P.M. From chart in “Fig. 6”, due to the additional reflecting solar rays on the bottom surface of heat absorber, the reflector model can effectively increase the radiation power on heat absorber during 10.00 A.M. to 3.00 P.M. (around 5 hours) comparing to the gradual power alteration in typical model.

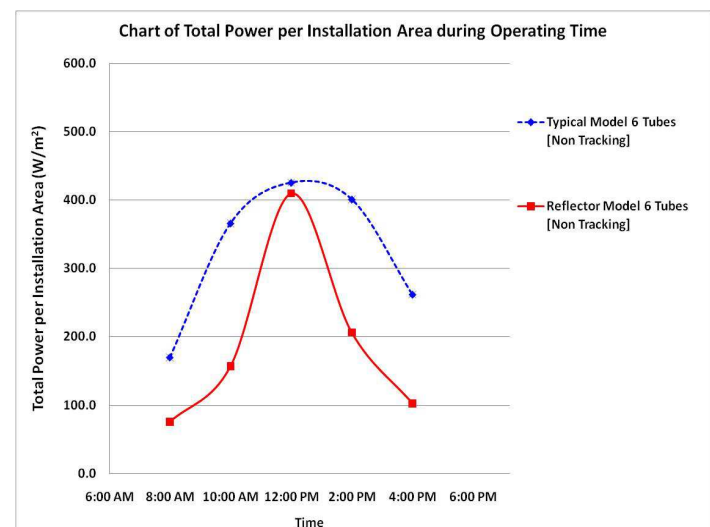


Fig. 7 Chart of Total power per installation area during operating time compared between two different configurations of evacuated tube array

Although, “Fig. 7” shows that the tendency of power per installation area is quite similar to the power on heat absorber. On the other hand, the power per installation area of reflector model is lower than the typical model for all over operating

time due to the excessive area of reflector installation.

5. Non Tracking and Tracking Mode

To further investigate the performance of reflector model, the power and power per installation area during the daytime for non-tracking and tracking mode have been analyzed and compared. The simulation model was setup so that the evacuated tube solar collector model orients toward the solar surface light source 600 W/m^2 for all operating hours on March 22nd, 2012 as shown in “Fig. 8”

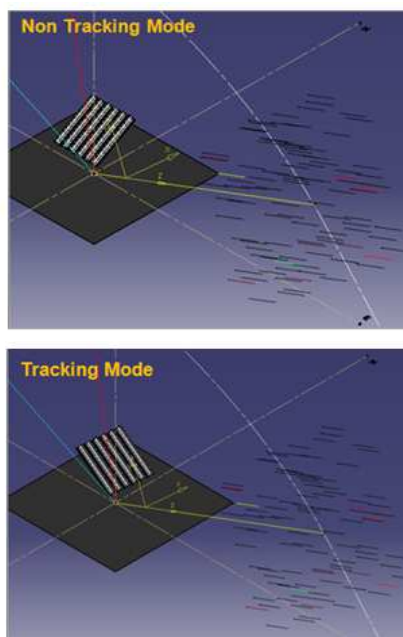


Fig. 8 The orientation of evacuated tube solar collector array for non-tracking and tracking mode simulation during operating hours on March 22nd, 2012

“Fig. 9” presents the beam pattern on heat absorber surfaces of evacuated solar thermal collector array with reflectors comparing between

non-tracking and tracking mode. The simulation results show that, in the tracking mode, the heat absorber receives more solar incident and reflected solar rays on both top and bottom surface comparing to the one with non-tracking mode.

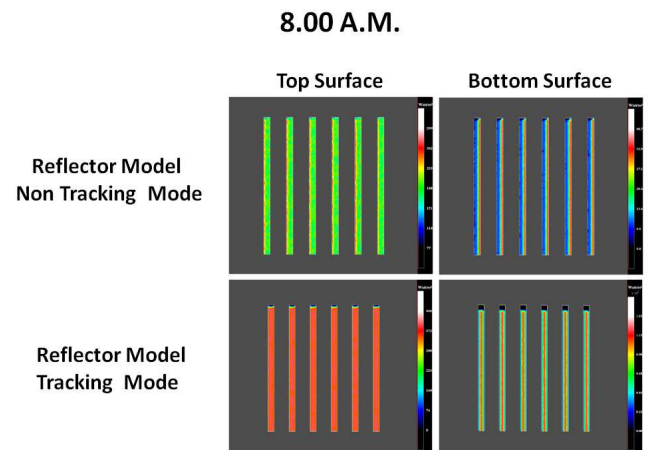


Fig. 9 The compared beam patterns on heat absorber surface of reflector model for non-tracking and tracking mode at 8.00 A.M

Table.3 The comparison results of the total power on heat absorber and the total power per installation area of typical and reflector model for non-tracking and tracking mode during operating time

	Typical [Non Tracking] (Area = 1.19 m^2)		Typical + Reflector [Non Tracking] (Area = 3.29 m^2)		Typical + Reflector [Tracking] (Area = 3.29 m^2)	
	Total Power on Heat Pipe (W)	Total Power / Install Area (W/m^2)	Total Power on Heat Pipe (W)	Total Power / Install Area (W/m^2)	Total Power on Heat Pipe (W)	Total Power / Install Area (W/m^2)
8.00 A.M.	202.1	169.9	248.7	75.5	1159.7	352.0
12.00 P.M.	506.1	425.3	1,350.0	409.8	1,443.6	438.2
4.00 P.M.	311.4	261.7	338.1	102.6	1,341.2	407.1

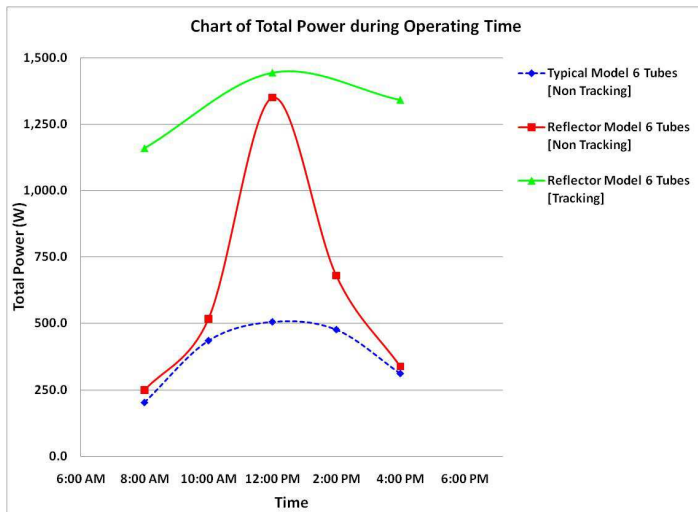


Fig. 10 Chart of total power during operating time of evacuated tube array compared between non-tracking and tracking mode

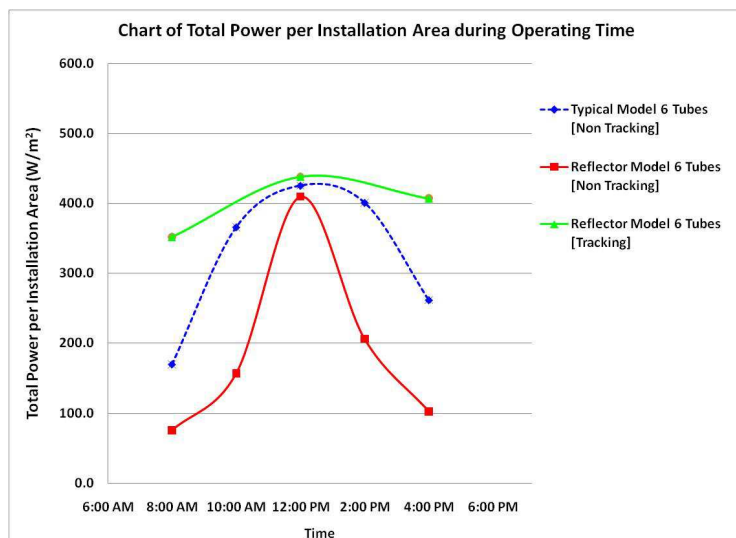


Fig. 11 Chart of total power per installation during operating time of evacuated tube array compared between non-tracking and tracking mode

According to calculation results as shown in “Fig. 10”, in tracking mode, the total power on heat absorber of reflector model is drastically increased comparing to the non-tracking mode

especially in the morning and afternoon, from Table. 3, the power on heat absorber at 8.00 A.M. is increased from 248 W/m^2 to $1,159 \text{ W/m}^2$, and increased from 338 W/m^2 to $1,341 \text{ W/m}^2$ at 4.00 P.M., while the total power at 12.00 P.M. is increased only from $1,350 \text{ W/m}^2$ to $1,443 \text{ W/m}^2$. Furthermore, the chart of total power per installation area in “Fig. 11” shows that the tracking mode can greatly improve the power per installation area of reflector model in the morning and afternoon, while the power per installation area at noon is quite closed for both non-tracking and tracking reflector model.

By comparing with the array of six non-tracking typical evacuated solar tubes, the use of semi parabolic reflector with tracking system can intensively increases the power on heat absorber for all operating times. Moreover, the power per installation area is also improved for operation in the morning and afternoon as shown in “Fig. 11”.

6. Conclusions

In this paper, the semi parabolic reflector was designed and selected by ray tracing analysis for improving the performance of the existing typical evacuated tube solar collector. The performance of typical and reflector model was determined and compared by calculating the power on heat absorber and power per installation area including beam pattern of solar rays during operating hours. Besides, the sun position and tracking mode are taken into account for additional performance investigation. By comparing with typical tube, although the presented tracking evacuated tube solar collector with reflector demands the extra installation area, but it can drastically improved

the solar intensity on heat absorber and power per installation area especially in the morning and evening. Moreover, this model can be used to develop and evaluate the thermal efficiency of the prototype for the proper evacuated tube solar collector for the heating demand application such as solar absorption chiller for instance.

7. Acknowledgements

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8. References

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