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Research Article

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 100ºC. 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 optics is determined to select the appropriate optics. Then, to compare the energy between non-tracking and tracking solar tube 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 [4]. 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 [5].

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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 [6-7]. 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 flow chart diagram of solar thermal collector analysis is shown in the Fig. 1 below.

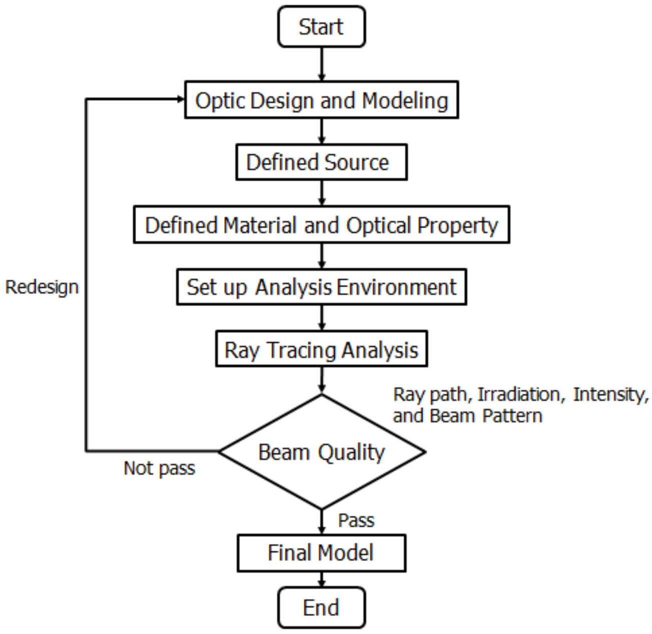

Fig. 1. Flow chart diagram of solar thermal collector analysis.

In this paper, SPEOS was employed to calculate the solar intensity and its beam pattern on the heat absorber to validate the different optics 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. 2, the geometry of all evacuated glass tubes was 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 m^2 double side aluminum planar heat absorber plate is modeled to have aluminum nitride coating with 92% absorption coefficient.

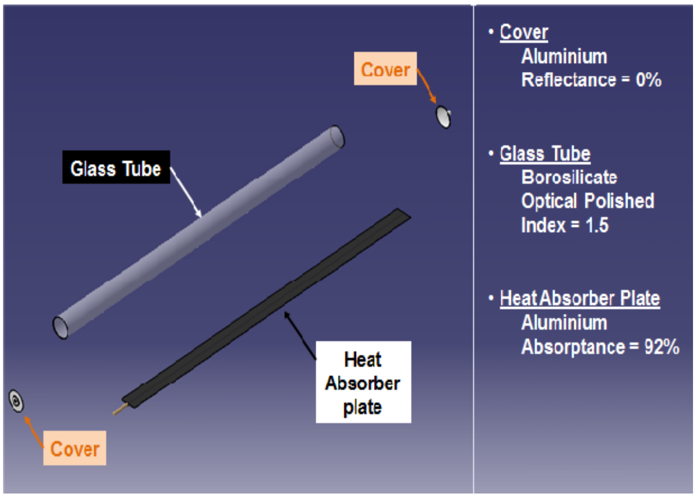

Fig. 2. Ray tracing model and optical properties of evacuated glass tube thermal collector.

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. 3.

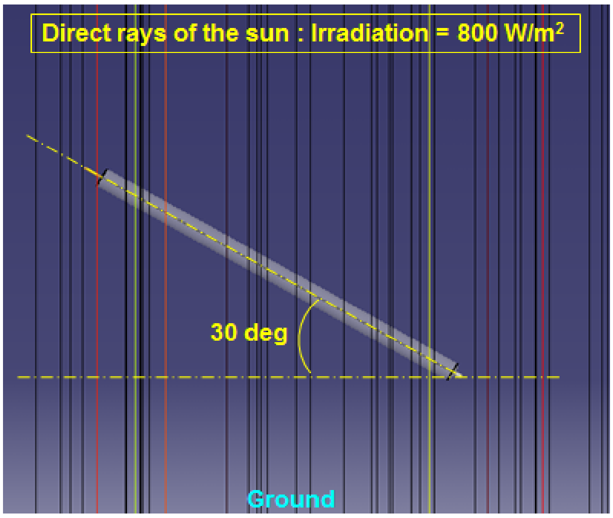

Fig. 3. Evacuated tube solar collector installation for ray tracing simulation.

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, according to Solar Radiation Map from Satellite Data for Thailand [8]. 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 beam performance of three geometrical optics configurations [9] for evacuated solar tube thermal collector, which are a semi parabolic reflector with 87% reflectance, a concentrating convex PMMA lens with index of refraction 1.49 and a combined lens and reflector system. For ray tracing analysis, a solar thermal collector optical model in Fig. 3 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 optics design 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 optics 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/m^2 to 625.3 W/m^2 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 convex PMMA lens can enhance the concentration to intensify the irradiation from 173.6 W/m^2 to 339.7 W/m^2 on the top surface of heat absorber. Besides, by combining the previous two optics configurations, the irradiation on heat absorber is increased from 173.6 W/m^2 to 792.7 W/m^2. Although, the ray tracing results suggest that all three optics 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) seems to be the most 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

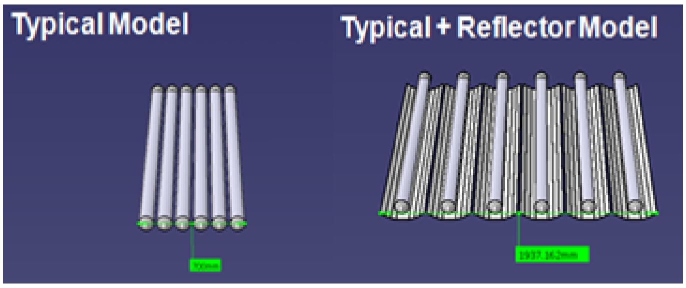

Fig. 4. The typical evacuated tube solar collector array and the one with semi parabolic reflectors.

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 were investigated as shown in Fig. 4.

To calculate and compare the power and power per installation area, various positions 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. 5. 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.

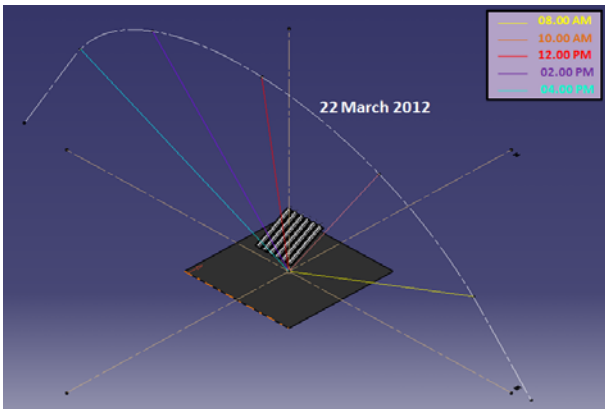

Fig. 5. The sun position during operating hours on March 22nd, 2012 and the installation of evacuated tube solar collector array for simulation.

With the configuration as shown in Fig. 5, the beam patterns on heat absorber's surface for typical tubes and tubes with reflectors were predicted and compared during the different periods of the day as shown in Fig. 6 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. 7, and the chart of total power per installation area was presented in Fig. 8.

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

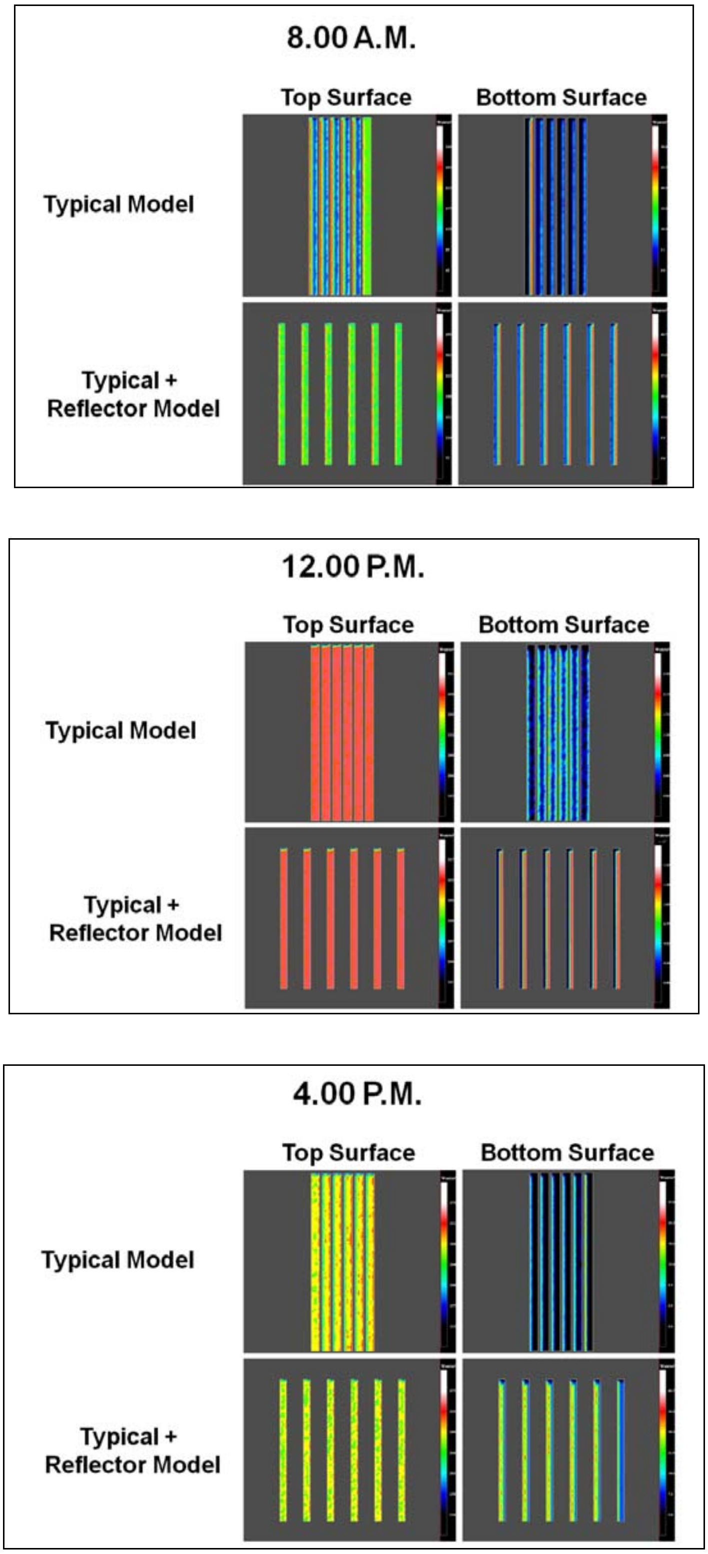

Fig. 6. Beam patterns' comparison on heat absorber surface for two different configurations of evacuated tube array at 8.00 A.M., 12.00 P.M., and 4.00 P.M.

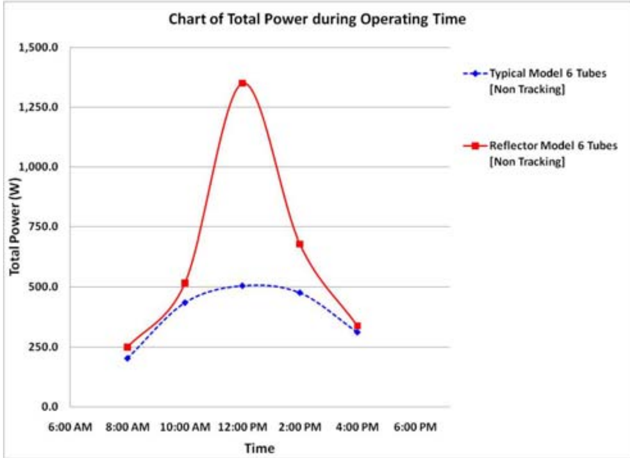

Fig. 7. Chart of total power during operating time compared between two different configurations of evacuated tube array.

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. 6. 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. 7, 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.

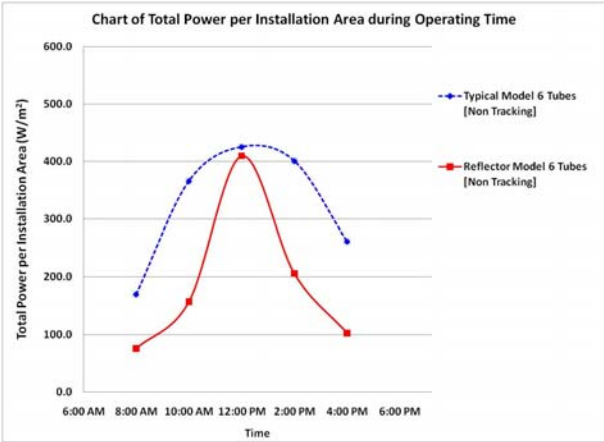

Fig. 8. Chart of total power per installation area during operating time compared between two different configurations of evacuated tube array.

Although, Fig. 8 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. 9.

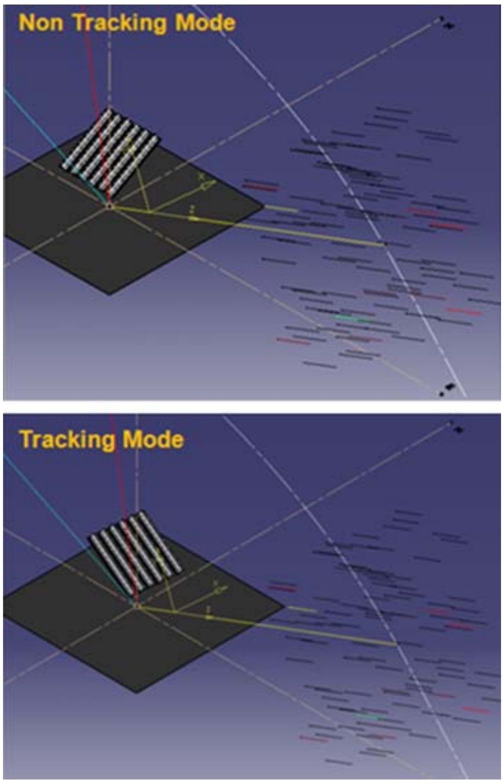

Fig. 9. The orientation of solar collector array for non-tracking and tracking mode simulation during operating hours on March 22nd, 2012.

Fig. 10 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.

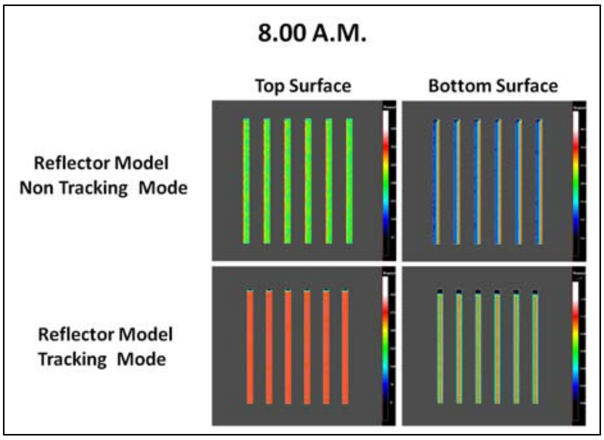

Fig. 10. Beam patterns' comparison on heat absorber surface of reflector model for non-tracking and tracking mode at 8.00 A.M.

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

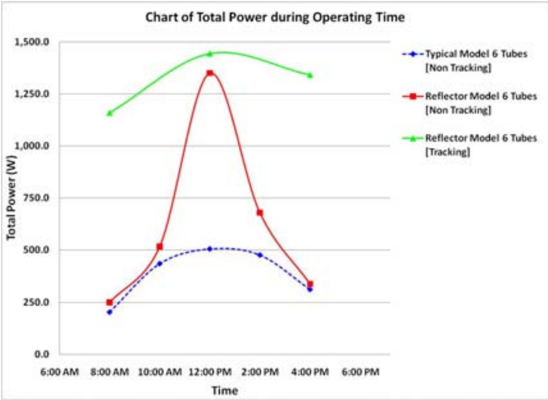

Fig. 11. Chart of total power during operating time of evacuated tube array comparing between non-tracking and tracking mode.

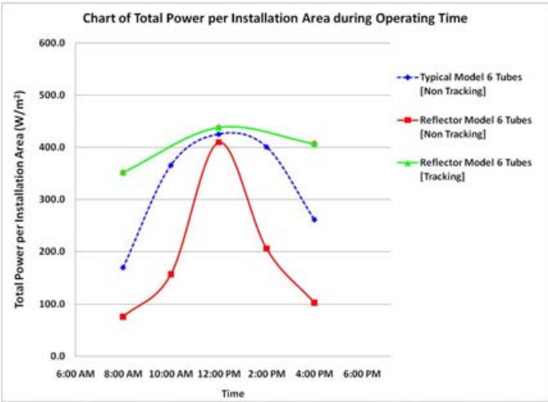

Fig. 12. Chart of total power per installation during operating time of evacuated tube array comparing between non-tracking and tracking mode.

According to calculation results as shown in Fig. 11, 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/m2 to 1,159 W/m2, and increased from 338 W/m2 to 1,341 W/m2 at 4.00 P.M., while the total power at 12.00 P.M. is increased only from 1,350 W/m2 to 1,443 W/m2. Furthermore, the chart of total power per installation area in Fig. 12 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.

6. Discussion

With ray tracing method, the optics components such as lens and reflector can be designed to enhance the solar concentration directly on heat absorber inside an evacuated solar thermal collector. According to the results, the semi parabolic reflector can increase the solar concentration on the bottom surface of heat absorber by 2.6 times higher than typical solar thermal collector, while the use of convex lens can raise the solar concentration on the top surface of heat absorber by 1.95 times greater than the typical solar tube collector.

Although, a semi parabolic reflector can effectively improve the solar irradiation power on the evacuated thermal collector during 10.00 A.M. to 3.00 P.M., but the power per installation area during all operating time is lower than the typical evacuated tube solar collector due to the excessive area of reflector installation. However, 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. Besides, the power per installation area is also significantly improved for operation, especially in the morning and afternoon.

7. 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 improve 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.

8. Acknowledgements

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References

[1] Nkwetta, D.N. and Smyth, M. The potential applications and advantages of powering solar air-conditioning systems using concentrator augmented solar collectors, Applied Energy, Vol. 89, 2012, pp. 380-386.

[2] Duffie, J.A. and Beckman, W.A. Solar engineering of thermal processes, 3rd ed., Hoboken, New Jersey, USA, John Wiley and Sons, Inc., 2006.

[3] Schmid, R., Collins, R.E. and Mannik, E. Performance comparison of flat plate and evacuated tubular collectors used in the Sydney University solar cooling and heating project, University of Sydney, Australia, 2006.

[4] John, A.D. and William, A.B. Solar Engineering of Thermal Processes, Second Edition, Wiley, Canada, 1991.

[5] Shah, L.J. and Furbo, S. Vertical evacuated tubular-collectors utilizing solar radiation from all directions, Applied Energy, Vol. 78, 2004, pp. 371-95.

[6] Soteris, A.K. Solar Energy Engineering Process and Systems, Academic Press, London, 2009.

[7] Garg, H.P. and Prakash, J. Solar Energy Fundamentals and Applications, Seventh Edition, Tata McGraw-Hill, New Delhi, 2006.

[8] Janjai, S. Solar Radiation Map from Satellite Data for Thailand, Solar Energy Research Laboratory, Silpakorn University, Thailand, 2010.

[9] Elmer, W.B. The Optical Design of Reflectors, NY: John Wiley & Sons, New York, 1980.