Design and Optical Performance Analysis of a Reflective Type High Concentrating Photovoltaic System

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Abstract: High concentrating photovoltaic system can enhance the commercial deployment of the PV technologies with higher solar energy to electrical conversion efficiency. A high concentrating set-up with 500× concentration ratio has been designed and optical simulation has been carried out for system optimisation. Simulation study results an optical efficiency of 76.7% with a well distributed energy flux at the receiver within the uniformity of ± 13%.

Keywords: HCPV, ray-tracing, optical simulation
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INTRODUCTION

Concentrating photovoltaic (CPV) is the only technology in power generation which aims to achieve over 50% efficiency in coming years. Compared to the commercial flat plat modules CPV can reduce by increasing the overall system efficiency and by reducing the area of expensive solar cell material. The use of high efficiency multijunction solar cell (~43%) in a concentrating system results the higher system efficiency compared to the flat plate PV system [1]. Many high concentrating designs for solar energy applications have been designed and commercialised so far [2,3], however an optimum concentrator design with high optical efficiency is required to increase the overall system efficiency and to reduce the over cost of the unit power output. The refractive (lens based) and reflective type (such as mirror based) system have disadvantages of lower optical efficiencies due to the fuzziness at the receiver and optical losses. The non-uniform distribution of the concentrated light at the receiver is another major challenge for the CPV research community.

Another challenge of the high concentrating CPV system is the cost effective cooling system to maintain low operating temperature of the solar cell. High operating temperature of the solar cell can drastically reduce the power output the solar cell [4]. So a well designed high concentrating system with passive cooling can result in enhancing its system performance.

In this work a CPV system of concentration ratio of 500× has been designed to increase the overall system performance. The designed concentrating system has been optimised for higher optical efficiency and uniform distribution of energy flux.

DESIGN OF THE CPV SYSTEM

The complete CPV system design uses array of specially designed parabolic reflector for each solar cell with a secondary reflector. The dimension of each solar cell is 10mm × 10mm. The schematic design concept of the concentrating system with a primary concentrator and secondary reflector is shown in figure.1. The primary concentrator is a parabolic dish with a square shape aperture opening to create a square shaped image of the sun. This design in expected to reduce the optical losses by concentrating all the incoming solar irradiance on the solar cell. A secondary reflector is used to guide the concentrated light to the solar cell on the base plate and to attain homogeneous distribution of light at the receiver. The reason to opt this design with the secondary reflector is to use a novel passive cooling system with micro- and nano-fin structure at the bottom plate with a large area heat-dissipation.

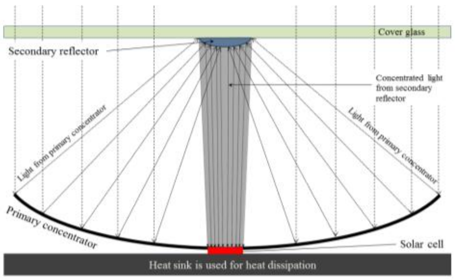
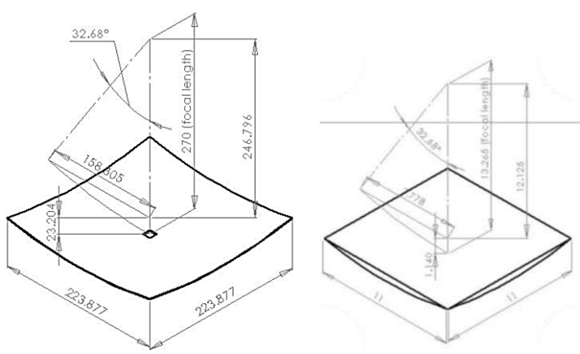


FIGURE 1. A schematic diagram of the CPV system with primary concentrator and secondary reflector.

The design parameters of the primary concentrator have been chosen considering the required concentration ratio, rim angle and the size of secondary concentrator (figure.2 (a)). The receiver area of the system (for one solar cell, located at the centre of the primary) is considered as 11mm × 11mm, to fit the solar cell of dimension 10mm × 10mm. In this study the dimension of the solar cell is termed as active receiver area and all the analysis has been carried out for active receiver area.



(a) (b)

FIGURE 2. Dimension and design specifications of (a) primary concentrator (b) secondary reflector.

For the secondary reflector design a study has been carried out with different designs and based on the design parameters an inverse parabolic secondary reflector has been designed. The initial study for the optimization of the design parameter of the primary concentrator and the secondary reflector has been carried out considering the total energy collected at the receiver, which is represented by the average irradiance in the figure 3.

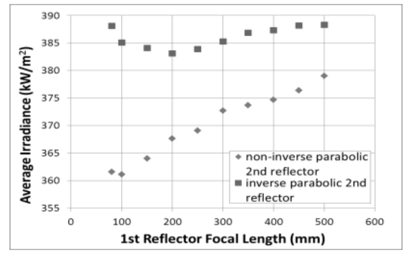


FIGURE 3. Variation of average irradiance (at the receiver) with the focal length of the primary concentrator.

It is observed that the inverse parabola has better properties to collect concentrated light as a secondary reflector compared to the conventional dish type parabolic secondary reflector. In case of inverse parabolic design the average irradiance at the receiver is found to be decreasing initially with the increase in focal length of the primary concentrator. However beyond 200mm, the average irradiance increases for higher focal length of the primary concentrator, until 450mm and stabilises. With this basic initial study the inverse parabolic reflector has been considered for further optical simulation and analysis. The design specification has been optimized with the further analysis on the basis of energy flux distribution at the receiver. The design specifications and dimensions of the primary concentrator and secondary reflector is shown in figure 2 (b).

OPTIAL SIMULATION FOR DESIGN OPTIMISATION

A systematic analysis of the energy flux distribution at the receiver of the concentrating system has been carried out using a ray tracing software 'OptisWorks' for optimization of the system.

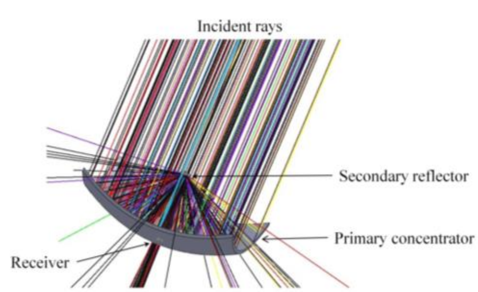


FIGURE 4. A representation ray trace diagram with 100 rays for the CPV system.

The concentrator parameters has been optimised with an detailed optical performance analysis with the variation of the focal length of the primary concentrator and secondary reflector, separation of the primary and secondary reflector and the rim angle of the system. A representation ray trace diagram with 100 incident rays is shown in figure.4.

The 3D optical simulation results show a maximum optical efficiency of 77.4%, considering all the possible losses with the real case scenario and manufacturing errors in the system. The study with the variation of the primary concentrator focal length the optical efficiency varies due to the escaping of light from the system or because of the light concentrating outside the active receiver area. The detail of energy flux distribution at the receiver is discussed in the following section. It is found that the optical efficiency of the system is lowest with the primary reflector of focal length 200mm as shown in figure.5. This drop in optical efficiency is mainly because of the sharp intensity peaks outside the active receiver area. However the variation of optical efficiency is within 77.4% to 76.4% for the change in focal length of the primary concentrator from 75mm to 450mm.

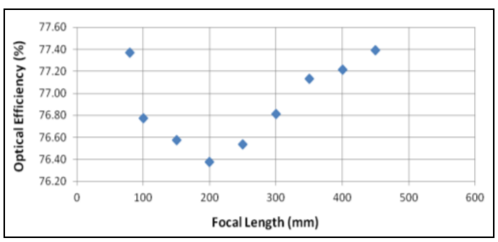


FIGURE 5. Variation of optical efficiency with the focal length of the primary concentrator.

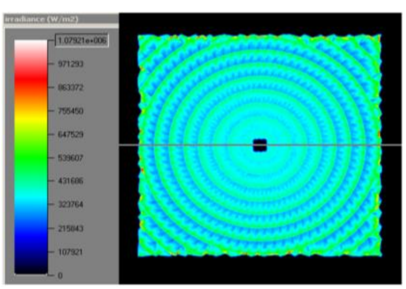


FIGURE 6. Energy flux distribution contour at the receiver of the CPV system for the primary concentrator with foal length 200mm.

The energy flux distribution at the active receiver area has been investigated for optimization of the parameters for primary concentrator and secondary reflector. It is observed that the energy flux at the receiver varies significantly with the change in focal length of the primary concentrator. The study for the energy flux distribution at the active receiver area has been carried out for the range of focal length of the primary concentrator from 75mm to 450mm. It found that, for the primary concentrator of focal length 200mm, the energy flux distribution is within ± 20% excluding the sharp intensity peak at the edges of the receiver. The energy flux distribution at the receiver with 200mm focal length of the primary concentrator is shown in figure.6.

With the increase in focal length of the primary concentrator the energy flux distribution changes significantly, resulting the distribution within ± 13% for the focal length 270mm. This also excludes some high peaks on the solar cell which is ~630kW/m^2. The energy flux distribution at the receiver of the CPV system with the primary concentrator of focal length 270mm is shown in figure.7.

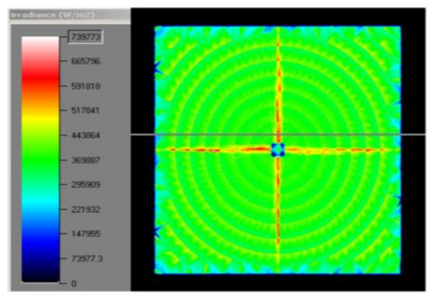


FIGURE 7. Energy flux distribution contour at the receiver of the CPV system for the primary concentrator with foal length 270mm and

Onsidering the optical efficiency and energy fux distribution at the active receier areas of the system, the primary conentrator with the focal length 270mm is found to be the optimum for this system. However during the optmisation study the parameters of the secondary reflector needed to be changed and the optimum focal length for the seondary reflector is found to be 13.27mm.

ASSOCIATED UNCERTAINITY AND TOLERANCE

There are uncertianities associated with the performance of the CPV system effected by the other parameters. Such unceertainities includes the tracking error and the dirversion of the solar irradiance. Proper analysis of the effect of these parameters will help in better desiging of the CPV system to achieve higher optical efficiency.

Effect of Diversion of Solar Irradiance

Although the optimum design has been found for incoming parallel light, natural sunlight has a divergence of ±0.27°. By changing the lambertian light source to have a half limit angle of 0.27° instead of 0° which was used to produce parallel light, irradiance results were obtained for naturally diverging light. This effect dropped the optical efficiency of the significantly to 4%. A further optimisation of the design parameters has been carried out to achieve an optical efficiency higher than 80% with the non-uniformity of energy flux distribution within ± 15%. The optimization study with the similar process mentioned above has been carried out by varying dimension of the secondary reflector and the focal length. This also results in increase in the dimension of the primary concentrator. The assembly of modified primary concentrator and secondary reflector and their specifications is shown in figure.8. The modified optimum assembly achieves an optical efficiency of 86.02% with an insignificant compromise in energy flux distribution at the receiver.

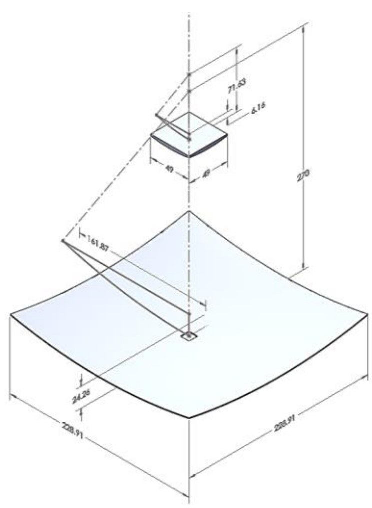


FIGURE 8. Assembly specifications and dimensions of the primary concentrator and secondary reflector after modification for uncertainties.

Effect of Tracking Error

In a efficient high concentrating system the tracking error should be limited to ± 0.1° [5]. This enables to deliver approximately 90% of the rated power output. Optical efficiency study shows that the with the designed CPV system, ± 0.1° error in tracking can lead to 26.7% drop in optical efficiency (figure.9). A further design modification is needed to deal with the tracking error of higher degrees.

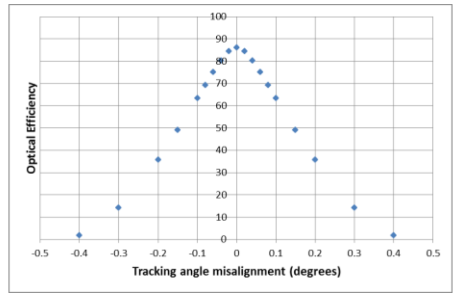


FIGURE 9. Variation of optical efficiency with tracking error.

CONCLUSION

A high concentrating reflective type CPV system has been designed and optical performance has been carried out for design optimisation. Simulation study results a maximum optical efficiency of 77.4% with the initial design considerations. However, optimum design with ideal case scenario results 76.7% with a well distributed energy flux at the receiver within the uniformity of ± 13%. Uncertainty with the real case scenario leads to further modification design parameters, which result in increase in optical efficiency to 86.02% with a compromise in energy flux distribution at the receiver.

ACKNOWLEDGMENTS

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