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INTEGRATED OPTICAL, ELECTRICAL AND THERMAL MODELLING OF A PARABOLIC-TROUGH SPECTRAL-SPLITTING PV-T COLLECTOR

Summary

We develop a coupled optical, electrical, and thermal model of a parabolic-trough spectral-splitting photovoltaic-thermal collector design based on selective-reflection filter. Using the model, we perform simulations of the maximum performance (at zero reduced temperature) of the collector. Results reveal that the primary receiver can achieve a 30% maximum thermal efficiency and a 16% maximum electrical efficiency, while the secondary absorber can reach a 32% maximum thermal efficiency (thus leading to a maximum overall thermal efficiency of 62%) under the following test conditions: primary receiver flow rate of 0.05 kg/s, secondary thermal absorber flow rate of 0.1 kg/s, irradiance at the collector's aperture 1000 W/m^2, inlet and ambient temperatures of 25 °C.

Keywords: Photovoltaic-thermal, spectral splitting, concentrating

1. Introduction

Photovoltaic-thermal (PV-T) collectors are hybrid solar technologies capable of the simultaneous provision of heat and electricity (Acosta-Pazmiño et al., 2024; Pandey et al., 2024). PV-T collectors are compact and have high overall efficiencies compared to PV or solar-thermal technologies (Herrando et al. 2023). However, conventional PV-T collector designs are limited by the direct contact between the photoelectric and thermal absorber components, resulting in a trade-off between the electrical efficiency and the grade of the thermal output (Huang and Markides, 2021). To address this problem, spectral-splitting (SS) PV-T (SSPV-T) collectors utilizing optical filters have emerged as an advanced thermal management approach wherein the visible part of the solar spectrum is directed to solar cells, while the rest of the spectrum is directed to a thermal absorber (Peacock et al., 2022). Volumetric selective-absorption (Chougule et al., 2024) and selective-reflection (Peacock et al., 2022) optical filters are the most commonly explored types of filters for SSPV-T collectors.

Although SSPV-T collectors have been extensively investigated in recent years, the design space remains extensive, and several promising designs remain unexplored. Recent studies dedicated to the exploration of such designs have typically adopted sequential modelling strategies, using separate software environments for ray tracing and solar flux modelling (Chandan et al., 2021), the results from which are then used as inputs to CFD models (Barthwal and Rakshit, 2022). This simplification overlooks potential interactions between optics and heat transfer, thereby decreasing the reliability of the performance predictions of these design tools.

2. Methods

The SSPV-T collector design proposed and investigated in the present work is shown in Fig. 1. The collector employs a parabolic-trough concentrator with an equilateral triangular channel, serving as the primary receiver, located at its focal point. Monocrystalline silicon (c-Si) cells are placed along the length of the two channel faces, and the entire channel is encased by a glass envelope in hard-vacuum conditions.

A parabolic film-based optical filter is interposed between the concentrator and the primary receiver. The filter shape and position were based on the results of 2-D ray-tracing simulations aimed at minimising optical losses (rays reflected outside the collector surface). The optical filter is assumed to have ideal selective-reflection properties for spectral splitting, assuming that the value of heat is negligible compared to that of electricity (Huang et al., 2021), with the transmittivity set to 0 or 1 over the relevant wavelength ranges as defined by the band gap of the cells used in this work. The filter allows 100% of the sunlight over the wavelength range from 500 nm to 1100 nm to be transmitted to the primary receiver, where part of the solar energy is converted to electricity while the rest is extracted by the heat transfer fluid (HTF) as low-temperature heat. Wavelengths outside of this range are reflected onto the secondary thermal absorber, located in the middle of the parabolic-trough concentrator. Key geometric and optical characteristics are given in Tab. 1; the HTF employed is water.

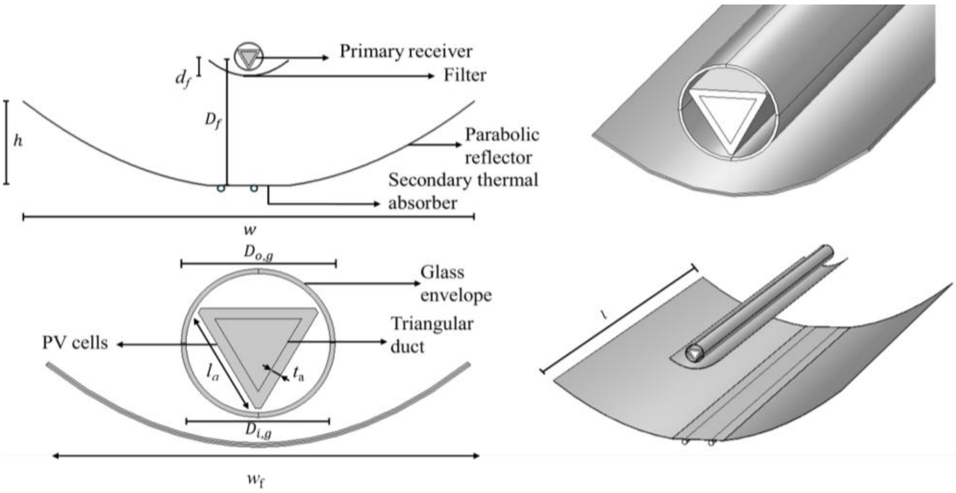

Fig. 1: Schematic and main components of the SSPV-T collector design investigated in the present work

Tab. 1: Key parameters and characteristics of the collector in Fig. 1

Parameter	Value	Parameter	Value
Concentrator aperture (w)	1088 mm	Glass outer diameter ($D_{o,g}$)	74 mm
Concentrator focal length (D_f)	340 mm	Glass inner diameter ($D_{i,g}$)	70 mm
Concentrator reflectivity (ρ_m)	0.93	Glass envelope transmittance (τ_g)	0.91
Filter aperture (w_f)	192 mm	Triangular channel side (l_a)	52 mm
Filter focal length (d_f)	60 mm	Triangular channel thickness (t_a)	5 mm
Collector length (l)	2 m	Thermal receiver thickness	2 mm

3. Results and Discussion

Results from ray tracing simulations of the collector are presented in Fig. 2, with the flux distribution over the PV cells and the secondary thermal absorber presented in Fig. 2(b) and Fig. 2(c), respectively.

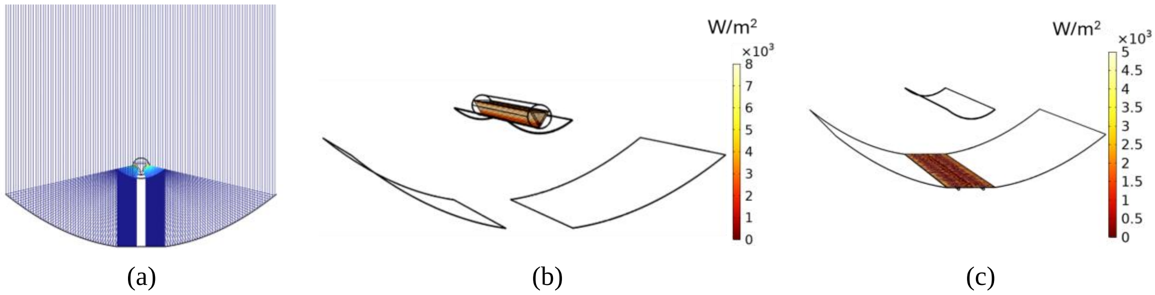

Fig. 2: Results from the collector optical model: (a) ray tracing diagram, (b) solar flux distributions at PV cells, and (c) solar flux distribution on secondary thermal absorber

The optical flux from the ray tracing simulations was then used as a heat source boundary condition in the CFD model using the ray heating option available in COMSOL, thus coupling the optical model with the CFD simulation. For mass flow rates of 0.05 kg/s in the primary receiver and 0.1 kg/s in the secondary receiver, an inlet temperature of 25 °C for the HTF in both channels, an ambient temperature of 25 °C, and an irradiance at the aperture of the collector of 1000 W/m^2, the thermal and electrical efficiency of the primary receiver were estimated to be 30% and 16%, respectively, while the secondary absorber was found to have a 32% thermal efficiency giving an overall thermal efficiency of 62%. These results, which reflect the maximum performance of the proposed collector at a zero reduced temperature, are summarised in Tab. 2.

Tab. 2: Summary of performance predictions for the following conditions: inlet temperature of 25 °C in both channels (i.e., zero reduced temperature), ambient temperature 25 °C, irradiance at the aperture of the collector of 1000 W/m^2

Metric	Value
Maximum thermal efficiency of the primary / secondary receiver	30% & 32%
Maximum overall (total) thermal efficiency	62%
Maximum electrical efficiency	16%

4. Conclusion

In this work, we propose and explore the maximum performance (at zero reduced temperature) of a spectral-splitting parabolic-trough photovoltaic-thermal collector design based on selective-reflection filter. We develop and employ a coupled optical, electrical, and thermal model for the proposed collector. For the optical simulation, the COMSOL ray tracing module was employed while the electrical model was solved in MATLAB. The optical and electrical results were then used as inputs to the CFD module of COMSOL to estimate the collector's thermal performance. For the optical simulation, an ideal filter, fully transparent between 500-1100 nm was selected as it closely matches the spectral response of c-Si cells. The transmitted rays are directed to the primary receiver, while the rays outside this range are entirely reflected to a secondary thermal absorber for high-grade thermal energy generation. Simulation results reveal that under the investigated test conditions (primary flow rate of 0.05 kg/s, secondary flow rate of 0.1 kg/s, inlet and ambient temperatures of 25 °C, irradiance at the aperture of the collector of 1000 W/m^2) the primary receiver can achieve 30% thermal and 16% electrical efficiencies, while the secondary thermal absorber can reach a 32% efficiency, leading to a 62% overall thermal efficiency.

5. References

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