Thermal and Electrical Performance Evaluation and Design Optimization of Hybrid PV/T Systems

Moustafa Al-Damook [1✉,2]
Email: mustafa.adil@uoanbar.edu.iq

Mansour Al Qubeissi [~~3~~2]

Zinedine Khatir [~~1~~3]

Darron Dixon-Hardy [4]

Peter J. Heggs [4]

[1] Renewable Energy Research Center, University of Anbar, Ramadi, Iraq

[2] Faculty of Engineering, Environment and Computing, Coventry University, Coventry, CV1 2JH, United Kingdom

[3] School of Engineering and the Built Environment, Birmingham City University, Birmingham City University, B4 7XG, United Kingdom

[4] School of Chemical and Process Engineering, University of Leeds, Leeds, LS2 9JT, United Kingdom

Abstract

This study aims to evaluate the performance and cooling effectiveness of both photovoltaic (PV) and hybrid PV/thermal systems under various ambient conditions. Two models, namely standard PV module subject to ambient conditions without active cooling and a single-pass hybrid PV/T air collector, have been designed and simulated using the CFD software of COMSOL Multiphysics V5.3a. The PV material used in our analysis is monocrystalline silicon with a power temperature coefficient of 0.41% $^{\circ}C^{-1}$. The thermal and electrical performances of both systems are evaluated numerically and compared to experimental data for validation. The results predicted for cooling effects show noticeable enhancements in both the electrical and thermal efficiencies of the systems, with up to 44% compared to the PV module without active cooling. The electrical PV/T arrangement has increased the performance of air cooling in a laminar flow regime with up to 4%. A numerical-based design optimization is carried out to enhance the system performance.

Keywords

Conjugate heat transfer
Cooling enhancement
Design optimization
Hybrid efficiency
Hybrid PV/T
Photovoltaic

1. Introduction

Photovoltaic (PV) systems have witnessed exceptional development in the last two decades where it has been shown that a PV panel can absorb more than 75% of the insolation. Only a limited percentage of light waves, however, can be transformed into electricity (10–18%), with the rest wasted as heat into the cells, thus increasing the PV temperature dramatically. As a result, the cell efficiency is predicted to drop by 0.4–0.65% for each 1 °C, when the temperature is above standard conditions (25 °C and 1000 W m^{-2}) [1, 2]. Therefore, it is important to establish a mechanism to address these issues. A hybrid solar energy system known as photovoltaic/thermal (PV/T) utilizes the features of thermal and solar means to produce thermal and electrical energies simultaneously. The exploitation of the hybrid photovoltaic/thermal (PV/T) technology aims to tackle this problem by keeping the PV cell temperature in its optimal range, which in turn improves the efficiency and produces heat and electricity simultaneously.

AQ1

In order to improve efficiency of PV/T air collector, several attempts have been made to examine the effects of extended surfaces on improving the overall (hybrid) efficiency of a PV/T air system. Extended surfaces can be classified into three main categories: (1) traditional fins [3, 4, 5], (2) interposition of a thin metallic sheet [6, 7, 8, 9] (TMS), and (3) obstacles or ribs [10, 11, 12, 13]. Little attention however has been paid to study the impact of offset strip fins within PV/T air systems using optimization strategy [14, 15, 16]. This study is aimed to evaluate the performance of a PV module, without active cooling (i.e. PV module is subject to ambient conditions) and with active cooling a single-duct single-pass hybrid PV/T air collector.

AQ2

2. Numerical Investigation

Three-dimensional models of single-pass PV/T solar air designs and a PV module have been constructed using the COMSOL Multiphysics V5.3a CFD modelling software. All dimensions of the two systems are listed in Tables 1 and 2, and schematics are provided in Figs. 1 and 2.

Fig. 1

Schematics of the PV/T air collector: in (**a**) 3D of single-duct single-pass (**b**) 2D cross-sectional front view and (**c**) 2D cross-sectional side view (not to scale)

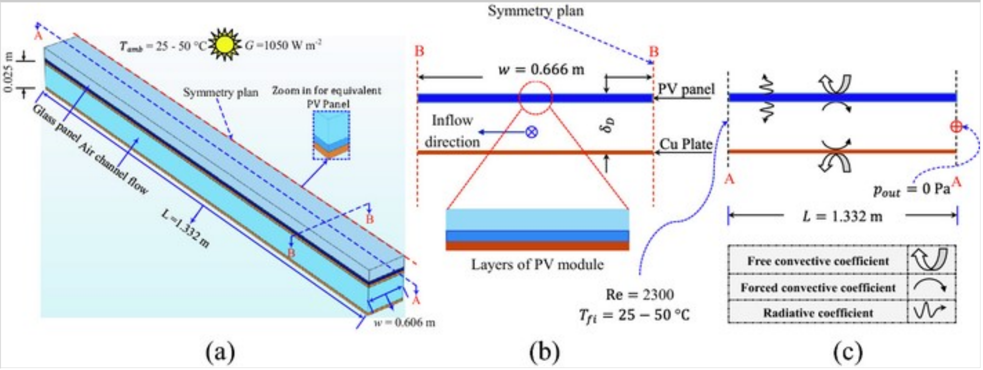


Fig. 2

Description of the main heat transfer modes and components of standard PV module

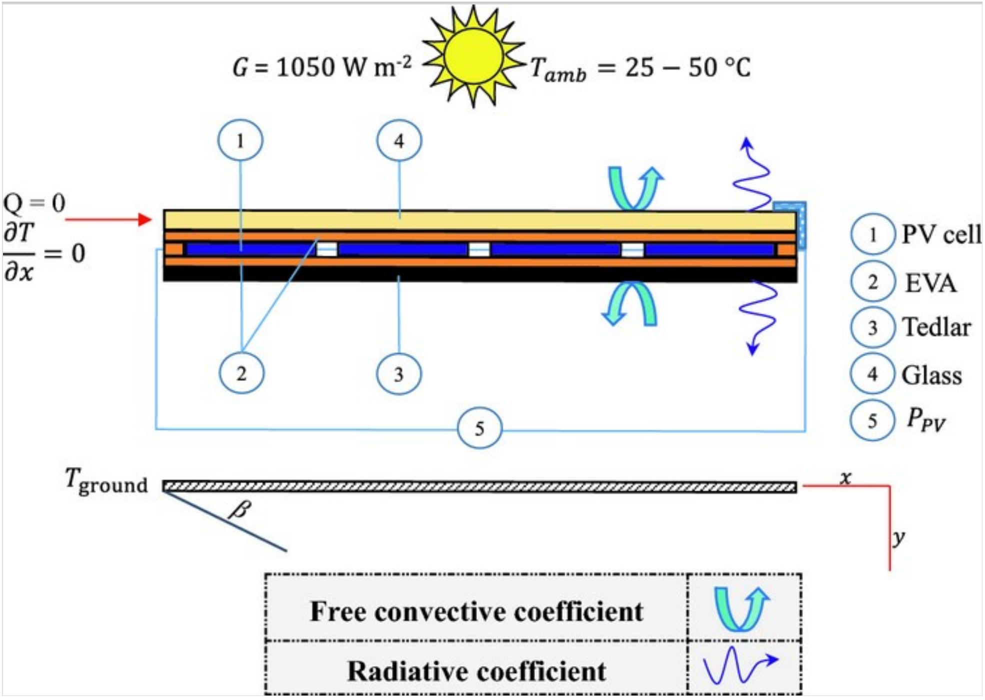


Table 1

Dimension of PV/T air collectors in m

Collector length L (m)	1.332
Collector width w (m)	0.666
Duct depth δ_D (m)	0.025
Bottom absorber plate thickness (m)	0.001

Absorber plate thickness (m)	0.001

Table 2

Physical properties of the PV module layers BP 585 [17].*

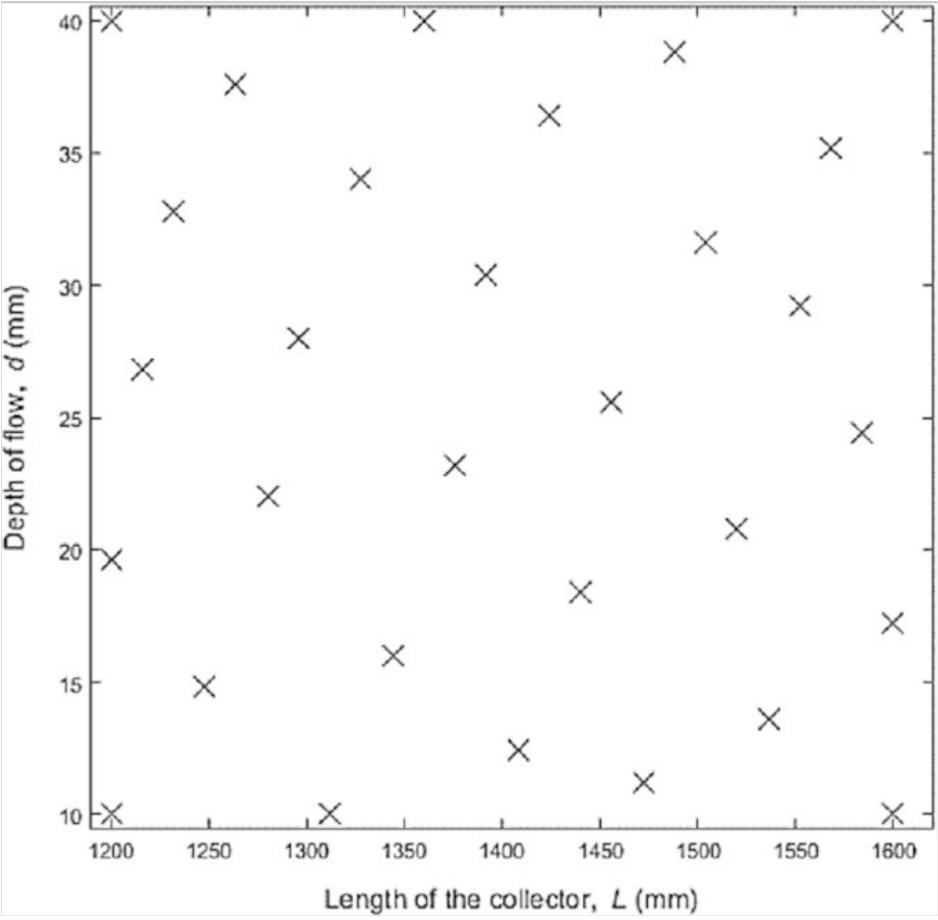
Layer	**t (mm)**	**k (W m^{-1} K^{-1})**	**ρ (kg m^{-3})**	**c (J kg^{-1} C^{-1})**	**ε**
PV glass	3	1.8	3000	500	0.84
EVA	0.5	0.35	960	2090	–
PV cells	0.3	148	2330	677	0.7
Tedlar	0.5	0.2	1200	1250	0.87

*t is the thickness of PV module layers, k is the thermal conductivity of PV module layers, ρ is the density of PV module layers, c is the specific heat capacity of PV module layers, and ε is the emmisivity of PV module layers

The governing equations for the air velocity $\vec{V}(x, y, z) = u, v, w$ and temperature T are based on the conservations of mass, momentum, and energy inferred from [18, 19]. ~~A CFD-based optimization analysis is carried out to minimize both pressure drop and thermal resistance as a function of two design variables: the length of the collector~~A CFD-based analysis is carried out to improve the PV system efficiency by minimising its temperature as a function of two design variables: the length of the collector (L) and the depth of the flow (δ_D). The design of experiment is constructed with 30 points in the two dimensions corresponding to their respective design variable ranges of 1.2 m $\leq L \leq$ 1.6 m and 0.01 mm $\leq \delta_D \leq$ 0.04 m. The uniform distribution of the DoE points is shown in Fig. 3. ~~The resulting Pareto front emphasizing to comprise that needs to be met to minimize both pressure drop and thermal resistance will be laid out.~~

Fig. 3

Design of experiments of single-duct signal-pass PV/T air collector



AQ3

3. Results

Numerical investigations were performed using COMSOL Multiphysics V5.3a to assess the influence of the PV panel temperature on the monocrystalline PV. To ensure the accuracy of the results, two validations with an experimental set-up were conducted by Amori and Abd-AlRaheem [20] and Amori and Al-Najjar [21], and a good agreement was obtained. The first validation between current PV/T model and Amori and Abd-AlRaheem [20] is given in Table 3. The second validation between PV module (subject to ambient conditions), Amori and Abd-AlRaheem [20], and current CFD model is depicted in Fig. 4.

Table 3

Comparison between CFD model and measurement of [20]

Type	Ref. [20]	CFD
T_g	79.49	80.7
T_{pv}	81.22	80.1
T_{Tedlar}	74.51	79.63
T_{fm}	53.64	48.62
T_{fo}	61.51	52.1

Fig. 4

Validation between experimental and current CFD models for standard PV module subject to ambient conditions

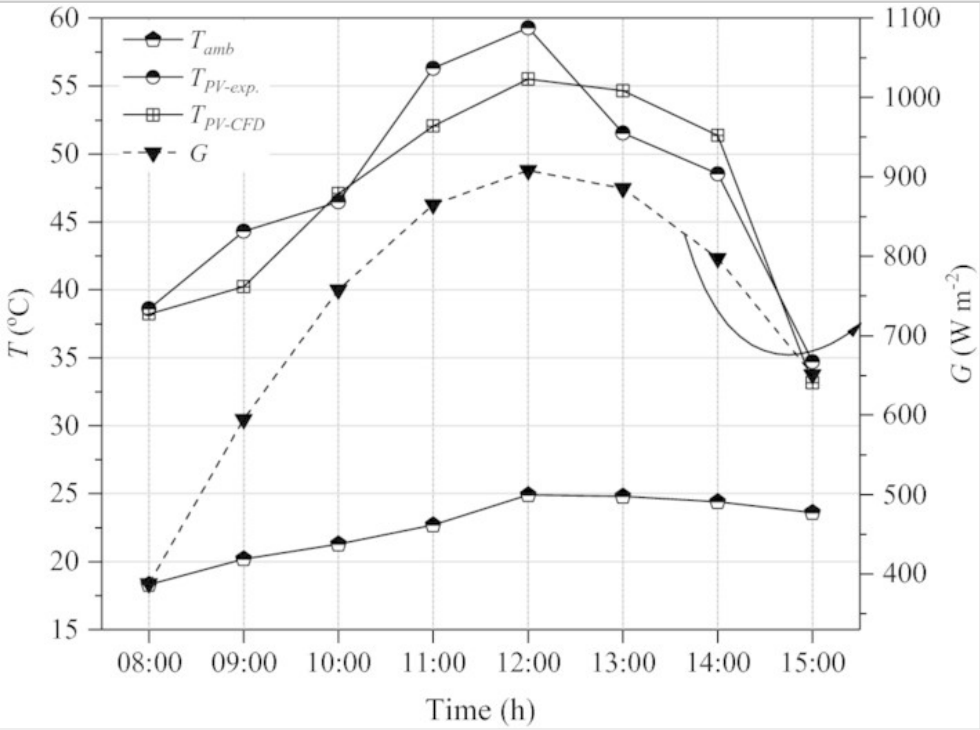


Figure 5 presents the effect of PV temperature on the PV output power under different ambient conditions for standard PV module without active cooling. Predictably, the PV power decreases with increasing PV module temperature. Figure 6 shows the influence of PV temperature on the PV output power under different ambient conditions for PV/T air system. The PV power also decreases with increasing PV module temperature. Figure 7 also reveals the influence of the PV and ambient temperatures (inlet fluid temperatures) on the thermal, electrical, and combined efficiency. It is apparent from this figure that electrical efficiency decreases with increasing PV panel temperature; however, the thermal and combined efficiency increases. Figure 8 presents the temperature gradient across the PV module. It can be seen that the PV cell has the maximum temperature since the electrical power generated in this domain. Figure 9 presents the temperature gradient along the PV/T collector. The temperature in the inlet region is low compared to the rest of the length as this region represents the non-fully developing region, which has a higher heat transfer coefficient. A comparison was made between PV and PV/T air system performances for weather conditions: $G = 1050$ W m^{-2}, T_{amb} 25–50 °C, and Re = 2300, as shown in Fig. 10. The resultant data shows that PV power generation for PV/T air system is better than PV without active cooling even at higher temperature (50 °C), since the PV panel temperature is lower for PV/T air collector.

Fig. 5

Effect of different ambient temperatures under same insolation on power of standard PV module

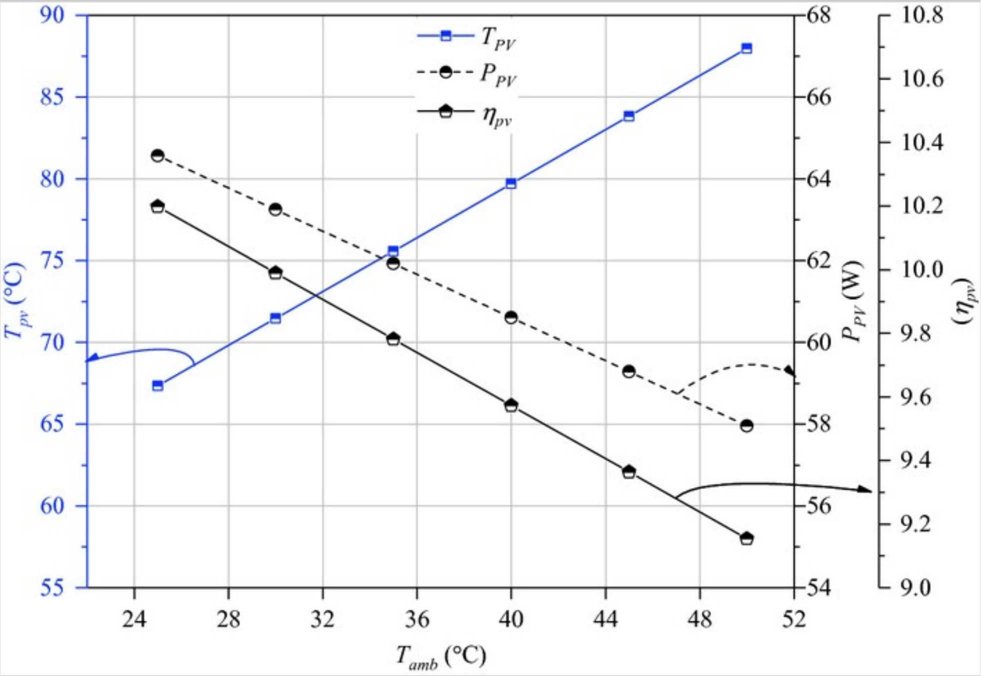


Fig. 6

Effect of different ambient temperatures under same insolation on power of PV/T air system

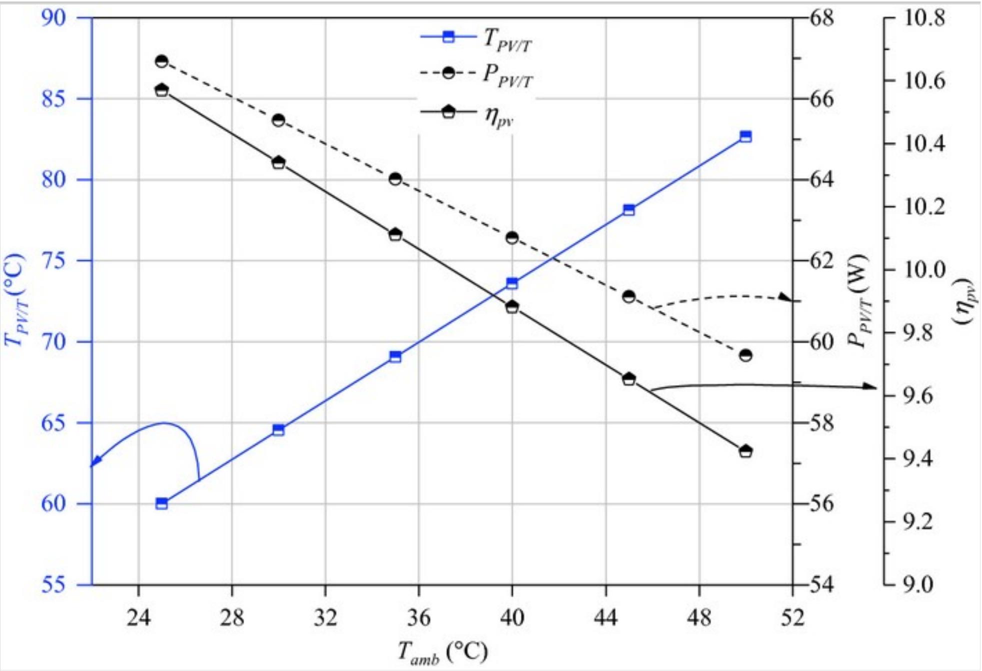


Fig. 7

Influence of PV temperature and inlet fluid temperature on thermal, electrical, and combined efficiency

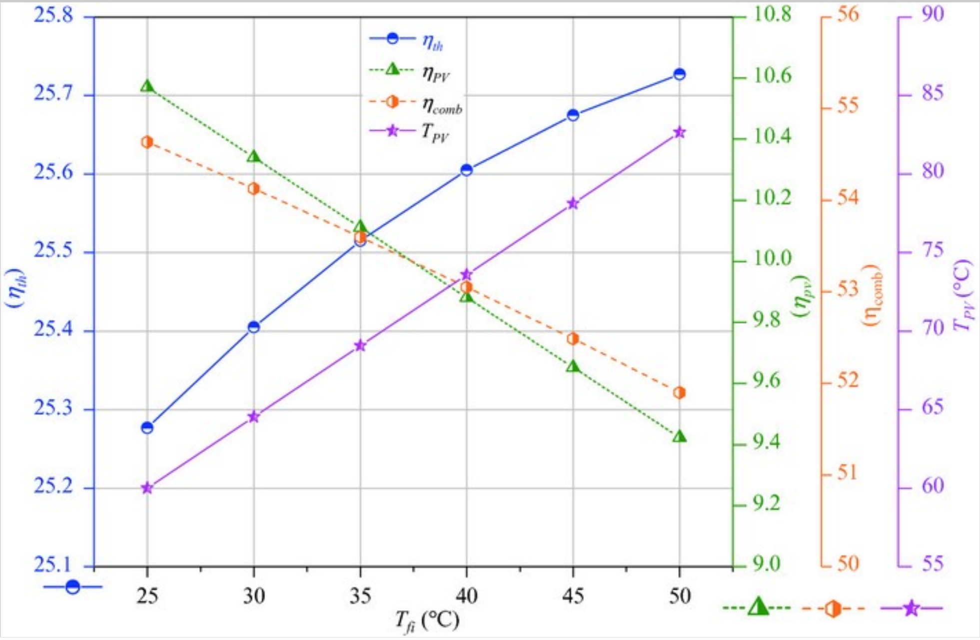


Fig. 8

Temperature surface gradient of standard PV module (section side view) at the ambient conditions of T_{amb} = 50 °C, Re = 2300, G = 1050 W.m^{-2}

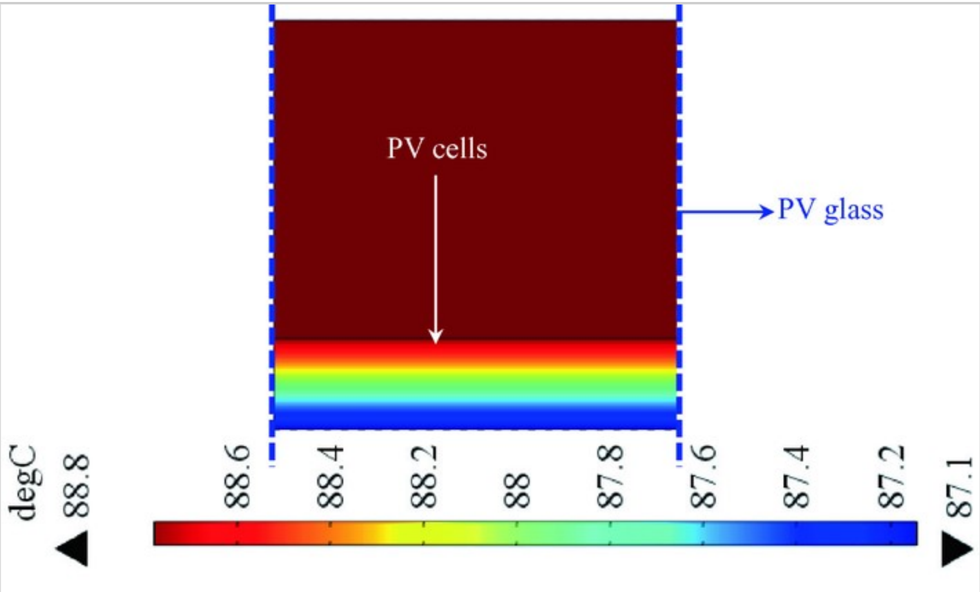


Fig. 9

Temperature surface gradient of isometric 3D view of the PV/T system, for the same ambient conditions as Fig. 8

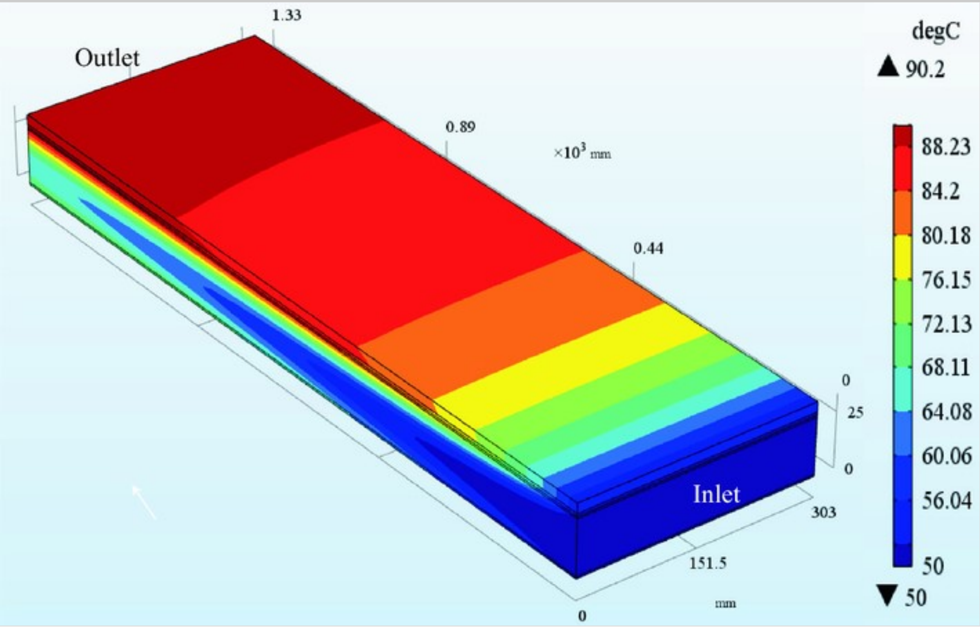
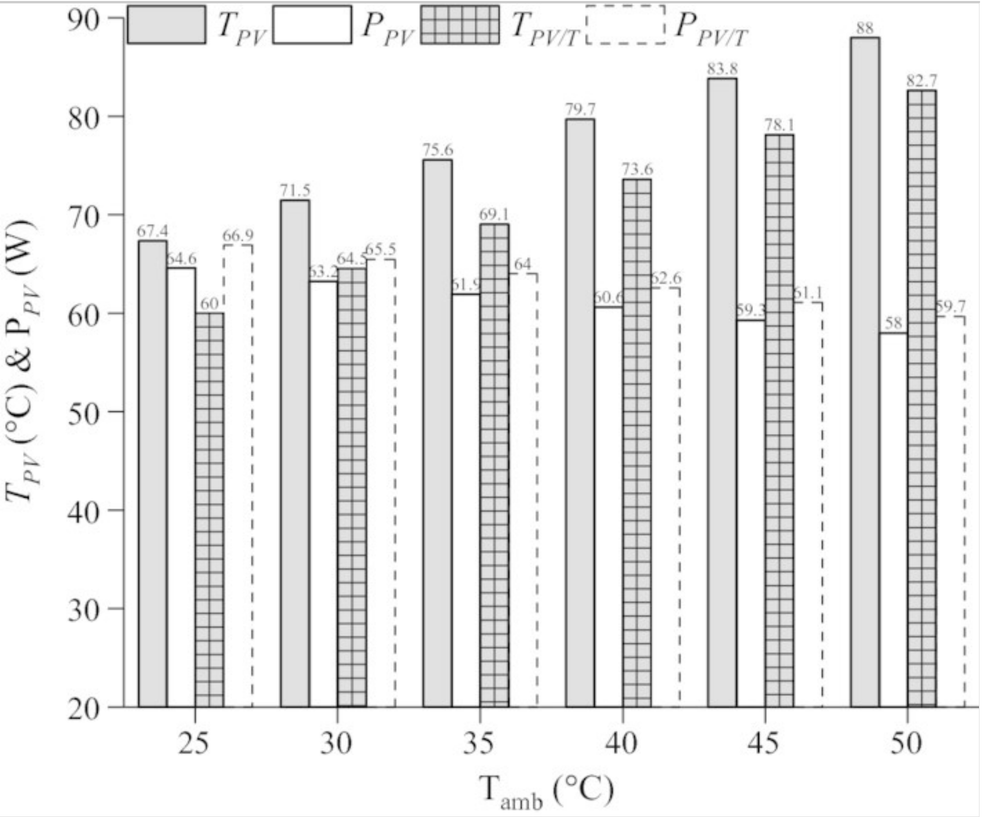


Fig. 10

Comparison between PV and PV/T air system performances for ambient temperature range T_{amb} = 25–50 °C, and the same other conditions as those of Figs. 8 and 9



4. Conclusion

~~Based on the findings, the cooling system can be developed to provide higher performance PV systems. Under the worst case scenario (1050 W m^{-2} and 50 °C) and lower fan consumption (laminar flow condition Re = 2300). The air cooling system is effective in reducing the PV temperature (increase PV efficiency). In addition, the overall collector efficiency increases. Future work will focus on using a novel heat sink design in cooling PV systems, with optimization of the collector dimensions and employing a different channel or flow type.~~The numerical investigation was conducted to evaluate the performance of two PV thermal designs. The first design was a PV module without active cooling (subjected to the ambient conditions) while the second design was a single duct single pass PV/T design with active cooling. The two systems were evaluated under the same conditions (under the worst-case scenario (1050 W m^{-2} and 50 °C) and lower fan consumption (laminar flow condition Re=2300). Based on the findings, the PV/T design can provide higher performance than the PV system. The air cooling system is effective in reducing the PV temperature (increase PV efficiency). Besides, the overall collector efficiency increases.

Acknowledgements

The first author is extremely grateful to the Higher Committee for Education Development (HCED), Iraq, and the Renewable Energy Research Center, University of Anbar, for their support to the project.

References

1. E. Radziemska, The effect of temperature on the power drop in crystalline silicon solar cells. Renew. Energy **28**, 1–12 (2003)

2. H.R.T Haisler, Latent heat storage on photo-voltaie, in *A. Sixteen European Photovoltaic Solar Energy Conference. C. UK: Glasgow* (2000)

3. M. Masud, R. Ahamed, M. Mourshed, M. Hossan, M. Hossain, Development and performance test of a low-cost hybrid solar air heater. Int. J. Ambient Energy **40**, 40–48 (2019)

4. M. Al-Damook, D. Dixon-Hardy, P. J. Heggs, M. Al Qubeissi, K. Al-Ghaithi, P. E. Mason, et al. CFD analysis of a one-pass photovoltaic/thermal air system with and without offset strip fins, in *MATEC Web of Conferences* (2018)

5. C. Kalkan, M. A. Ezan, J. Duquette, Ş. Yilmaz Balaman, A. Yilanci, Numerical study on photovoltaic/thermal systems with extended surfaces. Int. J. Energy Res. (2019)

6. A. Shahsavar, M. Ameri, Experimental investigation and modeling of a direct-coupled PV/T air collector. Sol. Energy **84**, 1938–1958 (2010)

7. A. Shahsavar, P.T. Sardari, S. Yasseri, R.B. Mahani, Performance evaluation of a naturally ventilated photovoltaic-thermal (PV/T) solar collector: A case study. Int.. J. Energy Environ. **9**, 455–472 (2018)

8. Y. Tripanagnostopoulos, Aspects and improvements of hybrid photovoltaic/thermal solar energy systems. Sol. Energy **81**, 1117–1131 (2007)

9. J. Tonui, Y. Tripanagnostopoulos, Improved PV/T solar collectors with heat extraction by forced or natural air circulation. Renew. Energy **32**, 623–637 (2007)

10. A. Fudholi, M. Zohri, N.S.B. Rukman, N.S. Nazri, M. Mustapha, C.H. Yen et al., Exergy and sustainability index of photovoltaic thermal (PVT) air collector: A theoretical and experimental study. Renew. Sustain. Energy Rev. **100**, 44–51 (2019)

11. M. Al-Damook, Z. H. Obaid, M. Al Qubeissi, D. Dixon-Hardy, J. Cottom, P.J. Heggs, CFD modelling and performance evaluation of multi-pass solar air heaters, in *Numerical Heat Transfer; Part A: Applications,* (In-press) (2019)

12. S. Şevik, M. Abuşka, Thermal performance of flexible air duct using a new absorber construction in a solar air collector. Appl. Therm. Eng. **146**, 123–134 (2019)

13. A. Abdullah, M.A. Al-sood, Z. Omara, M. Bek, A. Kabeel, Performance evaluation of a new counter flow double pass solar air heater with turbulators. Sol. Energy **173**, 398–406 (2018)

14. W. Fan, G. Kokogiannakis, Z. Ma, A multi-objective design optimisation strategy for hybrid photovoltaic thermal collector (PVT)-solar air heater (SAH) systems with fins. Sol. Energy **163**, 315–328 (2018)

15. M. Yang, X. Yang, X. Li, Z. Wang, P. Wang, Design and optimization of a solar air heater with offset strip fin absorber plate. Appl. Energy **113**, 1349–1362 (2014)

16. I.K. Karathanassis, E. Papanicolaou, V. Belessiotis, G.C. Bergeles, Multi-objective design optimization of a micro heat sink for Concentrating Photovoltaic/Thermal (CPVT) systems using a genetic algorithm. Appl. Therm. Eng. **59**, 733–744 (2013)

17. K. Kant, A. Shukla, A. Sharma, P.H. Biwole, Thermal response of poly-crystalline silicon photovoltaic panels: Numerical simulation and experimental study. Sol. Energy **134**, 147–155 (2016)

18. J. A. Jr, Governing equations of fluid dynamics, in *Computational fluid dynamics*, ed Springer, pp. 15–51 (2009)

19. M. Al Hamdani, M. Al Qubeissi, M. Al-Damook, D. Dixon-Hardy, P. J. Heggs, Thermal Optimisation of Fin

Clusters for Heat Sink Purposes, in *ICTEA: International Conference on Thermal Engineering* (2018)

20. K.E. Amori, M.A. Abd-AlRaheem, Field study of various air based photovoltaic/thermal hybrid solar collectors. Renew. Energy **63**, 402–414 (2014)
21. K.E. Amori, H.M.T. Al-Najjar, Analysis of thermal and electrical performance of a hybrid (PV/T) air based solar collector for Iraq. Appl. Energy **98**, 384–395 (2012)