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Performance Assessment of Hybrid PV/PVT Collectors Incorporating Natural Water-Cooling Circulation

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Abstract

The present work investigates outdoor recitals and characteristics of hybrid PVT collectors and compares using non-cooled Photo-Voltaic (PV) collectors on a clear day at Khamshet, Pune, India. The hybrid PVT is designed, fabricated, and mounted on the terraces of the institute to ensure maximum radiation will fall on PV and PVT collector. The spiral circular thermal absorber is manufactured and placed at the backside of the photovoltaic to lower the surface temperature by extracting heat through water flowing through the absorber. The experimentation is performed at 0.03 kg/sec of water and natural cooling circulation is adopted for experimental work. The uncertainty analysis is also performed to ensure the accuracy of the results. The investigation observed that the PVT collector is superior to the PV system from electrical and thermal efficiency viewpoints. The cutback in PV module temperature was observed in a variation of 8.7-13.7%, which justifies using the water-cooling technique. The maximum electrical and thermal efficiency of 6.93 % and 52.7% were found for PVT collectors while sole maximum electrical efficiency of 5.62 % was found for PV collectors. This study concludes that the PVT collector has better performance characteristics than the PV collector and can be further enhanced using different fluid and thermal absorber designs.

Keywords: *Electrical-Thermal Performance, PV Temperature, Solar Energy, Water Cooling*

1.0 Introduction

In the current energy scenario, the need for replacing fossil energy is of utmost importance and researchers have taken extensive efforts[1-4]. Researchers have focused on energy derived from alternate fuels, Wind, solar, hydrogen and focus is done on their energy derivation and utilization. Of all Solar energy has proven its importance to the world for many decades as one of the promising energy-sustainable solutions. In India, 60-70 % of power generation is derived from conventional fossil fuels that are imported from different parts of the globe. Fossil fuels create climatic concerns and an additional burden on the Indian economy[5-7]. India already started its initiative to explore solar energy and reached solar power generation to 70.10 GW in mid- 2023[6]. Solar energy is extracted in the form of thermal energy using a solar thermal collector and electrical energy using a solar Photo-Voltaic (PV) collector. The researchers discovered the combined system known as Photo-Voltaic- Thermal (PVT) or co-generation system that can unite the benefits of simultaneous generation

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of thermal and electrical energy. Kern and Russel presented the first PVT system in 1978[7] with an efficiency of 1-2 % since then studies and experimentations have been started. In their work mathematical analysis and expected performance was discussed. Inherent features of generating high-grade and low-grade energy, researchers focused their attention on the advancement of PVT technology thereafter. HA Zondag[8], TT Chaw[9], Adnan Ibrahim *et al.*[10],J Buonomano[11], Kumar *et al.*[12], and Tyagi *et al.*[13] performed the reviews on the progression in PVT technology, A L Abdullah[14] discussed various fluid-based absorber designs. A review based on historical research and case studies revealed the significant escalation of PVT in the forthcoming era. The literature survey also highlights the merits and demerits of each cooling technology, selection criteria, the degree of cooling, the cost involved, and recovered heat deployment. The effects of Malaysian climatic conditions on the characteristics of the PVT system were studied by Sakhr M. Sultan *et al*[15]. The spiral flow thermal absorber was proposed, and sunny and cloudy conditions were studied. They observed maximum combined PVT efficiency of 74.1% and 72.63% on sunny and cloudy days respectively. A similar study was performed by Mohamad Modrek and Ali Al-Ali[16] for the United Arab Emirates climatic conditions to study the feasibility of the PVT system. The PVT system was modelled with transient system simulation software and the result favoured the use of the PVT system over a simple PV system due to higher electrical and thermal yield. The study acknowledged the optimum value of coolant flow, solar angle, storage capacity, and collector orientation for the performance of the PVT system. N. Marc-Alain Mutombo and Freddie Inambao[17] demonstrated behavioural features of the PVT system for Durban, South Africa weather conditions. With a flat-box thermal absorber and single glazing, an overall efficiency of 38.7% was obtained by the PVT system whereas PV efficiency was limited to 14.6%. The phenomenon of heat interaction between PV module-surface coolant fluids is a key parameter in the PVT collector[18]. The major considerations about thermal absorber material and pattern need to be considered during PVT design. A comparative study between sheet and tube-type absorber and enclosure absorber was performed to identify better absorber design by B. Hajji *et al*[18]. The sheet and tube absorber presented 55% of the thermal efficiency result. Ahmad El Mays *et al.,*[19] proposed a thermal absorber made up of a finned plate of aluminium to enhance cooling under natural circulation. In the experimental setup, thermal grease was applied between the PV module and absorber to eradicate the air gap and augment thermal conductance. The result endorsed the use of fins as finned plates of aluminium increased the electrical performance. The comparative study of PVT systems with and without a fin was done by Muhammad Zohri *et al.,*[20] to investigate the effectiveness of the fin. The mathematical model was developed, and analysis was done with the matrix inversion method. It was observed that, with fin configuration overall efficiency of 57% was obtained. Work concluded that fin-PVT provides better PV cooling and improved overall performance than without fin-PVT. Juwel Chandra Mojumder *et al.,*[21] studied a series of aluminium rectangular fins for heat transfer augmentation between fluid and PV wall. The fin of different heights and thicknesses were studied, and performance was compared with the "without fin" condition. It was concluded that a rectangular fin absorbs more heat and leads to higher overall efficiency at a higher solar irradiation value. At 700 W/m^2 radiations, 159.8W of heat was absorbed by four aluminium rectangular fin conditions. The effect of the mass flow rate of water and solar radiation on the tubular solar photovoltaic thermal system was investigated by S. Abdul-Ganiyu *et al.*,[22] for the climatic conditions of Ghana. It was observed that an increase in the mass flow rate of water reduces PV temperature which results in an increment in electrical efficiency. The absorbed heat resulted in additional thermal energy thereby increasing overall performance. The comparative study between the reference PV panel and PVT system was performed in different European climate conditions using Matlab/Simulink[23,24]. It was observed that the PVT system provided enhanced electrical output, especially during the summer season compared to the PV system. The authors claimed that the PVT system is still competitive compared to the PV system in better energy yield. The above literature expressed that tremendous work was performed using numerical, experimental, and theoretical studies across the world by changing ambient conditions, cooling fluid, thermal absorber, shape, flow pattern, material, and end-user applications. It is important to note that the thermal absorber plays a vital significant responsibility in the performance of the PVT

collector. In the present study, the copper-based spiral circular thermal absorber is demonstrated to recuperate heat from a flipside PV system that will generate heat and electricity simultaneously. The present work aims to investigate the effect of ambient temperature, solar radiation, and thermal absorber configuration on the thermal and electrical characteristics of PVT systems and perform real-time simultaneous comparisons with PV systems.

2.0 Material and Method

The parameter such as ambient temperature, PV surface temperature, water inlet and outlet temperature, outlet water temperature, PV voltage, PV current, and radiation intensity was measured with various instruments. The ambient air temperature was measured with a mercury-based thermometer. The PV surface temperature and inlet-outlet water temperature were measured with a K-type thermocouple. The thermocouples were placed, temperatures were stored and displayed with a temperature acquisition system. The voltage and current of PV are measured by voltmeter and ammeter respectively. Each set of experiments is recorded after a 30- minute interval, including solar irradiation, water temperature, PV, PVT V-I characteristics, ambient temperature, and surface temperature. The various specifications of the PV and W-PVT collector systems are listed in Table 1. The currently studied PVT and PV collector are mounted on metallic supporting structure with fix face orientation and investigation is performed. The solar tracking can result in better thermal and electrical yield, but it increases installation and maintenance cost and has more moving parts. The solar tracker needs additional electrical energy to run the mechanism that reduce net electrical yield. Hence fix face orientation of PV and PVT collector is preferred in current study.

According to the Mani and Chako study[24] for India, peak radiation values were observed in April or May; hence, experimental work is planned for April. The experimental setup was developed, designed, fabricated, and tested for the outdoor condition in an institutional campus building at SRTTC Faculty of engineering, khamshet, Pune. The location is latitude 18.81465 and longitude 73.54035 in the western part of India. The experiments were conducted on a clear day to ensure maximum radiation. The wind speed varied within 1-1.5 m/s during experimentation. The cumulative results evaluated surface temperature, temperature drop, electrical gain, and thermal gain performance. The electrical efficiency from PV/PVT collector is expressed as equation 1.1,

$$\eta_{el} = \frac{P_{max}}{I_g A_c} \quad (1)$$

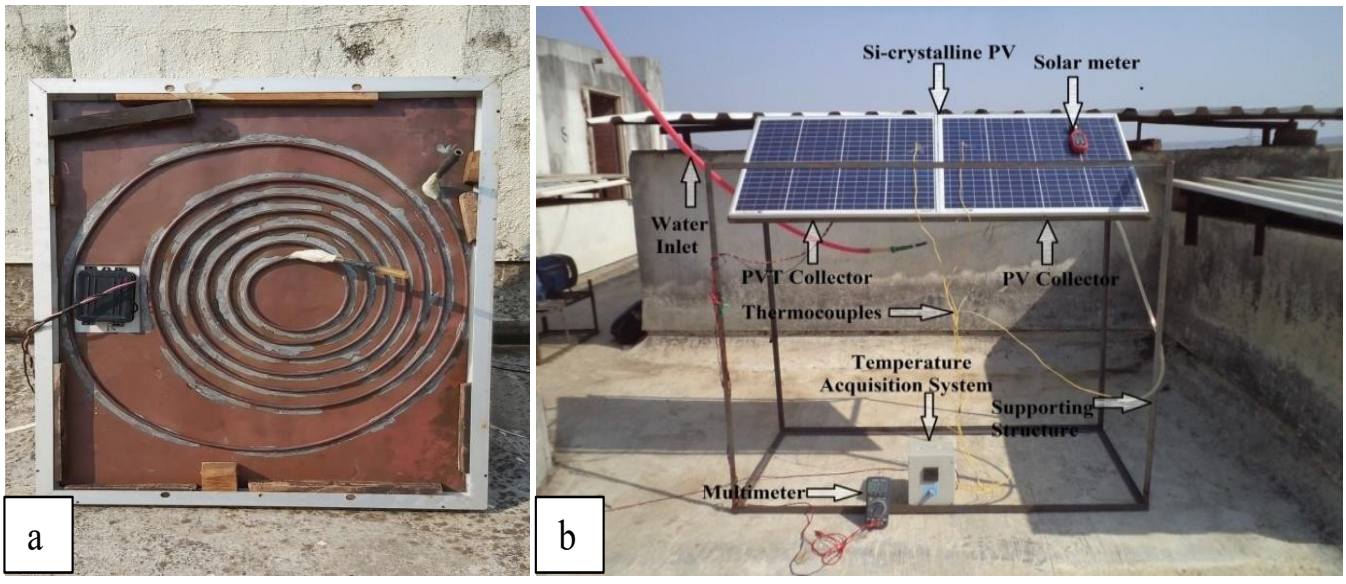


Figure 1. **(a)** Pictorial view of thermal absorber. **(b)** Experimental setup.

Table 1. Characteristics of PV/PVT system

Sr No	Parameter	Symbol	Value	Unit
1	Voltage (Open Circuit)	V	22.2	V
2	Current (Short Circuit)	I	2.37	I
3	The power rating	W	40	W
4	Reference efficiency	η_{ref}	0.128	
5	Reference value	β_{ref}	0.005	
6	Diameter of Thermal absorber	D	0.025	m
7	Thickness of the Thermal absorber	T_{abs}	0.001	m
8	Latent heat of water	l	335	kJ/kg
9	Specific heat of water	C_p	4187	J/kgK
10	The slope of the solar panel surface	θ	13	degree

The Pmax is the product of voltage (Vmp) and current (Impp) at the maximum power point, Ig is incident solar radiation, and Ac is PV area,

The remaining solar radiation is transformed into heat and collected by the thermal absorber. The beneficial thermal gain through the W-PVT system is expressed as,

$$Q_u = m_w * C_{pw} * (T_{wo} - T_{wi}) \quad (2)$$

$$\eta th = \frac{Qu}{IsolarAc} \quad (3)$$

The overall efficiency of the PVT system is calculated as

$$\eta_{total} = \eta_{el} + \eta_{th} \quad (4)$$

2.1 Uncertainty Analysis

In the experimental setup, the quantities are measured with physical instruments that have some least count and it is essential to consider these accuracies. All the physical quantities measured to estimate the cooling extent, thermal gain, and electrical gain are subject to certain errors due to inaccuracies in the experimentation. The sandwiched CPC and Fresnel lenses base photovoltaic thermal system was developed by[5,25] and the thermal and electrical efficiencies obtained during experimentation were approximately 50% and 12.9% respectively. The uncertainty analysis was carried out for performed experimental work using the Mean Average Percentage deviation (MAPE) method and found to be ± 0.718% and ± 13.39% uncertainty in electrical and thermal efficiencies respectively. The impulse response and convolution process approach were proposed by[26] to study uncertainty in the transient model to evaluate uncertainty in the solar system for tank temperature. The result illustrates that the proposed approach reduced a number of simulations and tank temperature can differ ±2.2 °C during work. The new method of linear regression uncertainty was demonstrated by J Facao *et al.*,[27] and applied to plate heat-type solar collector. The method has the feature of separating systematic and random variables to calculate correlated uncertainty[26]. Chester Wells[28] explained the ANSI/ASME PTC 19. 1- 1985 standard technique to analyze uncertainty. The work discussed the methodology for PV performance measurements to obtained combine (random and systematic) uncertainty. In the present work, error analysis is carried out by using Kline and McClintock method since the technique describes the uncertainty as a range where the true value lies in. The present error analysis is concerned with the errors pertinent to measurements made during the investigation. The uncertainties associated with measured quantities are as shown below.

Table 2. Instruments with their individual uncertainty

Sr No	Quantity	Instrument	Unit	accuracy
1	Mass Flow rate	Rotameter	Kg/sec	±1%
2	Electrical gain	Multimeter	A, V	±2%
3	Temperature	K-Thermocouple	°C	±1 %
`4	Solar radiation	Pyranometer	W/m^2	±2 %
5	Area	Measuring tape	M	±1 %

Let the overall performance of PVT collector is the function of the independent variable of mass flow rate (m), temperature difference (T_{out}-T_{in}), collector area (A_c), solar radiation (I_g), open circuit voltage (V) of PV and short circuit current (I) obtained and error associated with each observation are w_m, w_{Tout}, w_{Tin}, w_A, w_{Ig}, w_V and w_I respectively.

The total uncertainty can be calculated using general form of Kline and McClintock method

$$w_R = \pm\sqrt{\left(\frac{\partial R}{\partial x_1}w_1\right)^2+\left(\frac{\partial R}{\partial x_2}w_2\right)^2+\ldots+\left(\frac{\partial R}{\partial x_n}w_n\right)^2} \quad (5)$$

Where, R= {m, T_{out}, T_{in}, A_c, I_g, V_{oc}, I_{sc}} are the average value of parameters

Hence, by applying equation to evaluate uncertainty in the thermal and electrical performance as

$$w_{\eta T} = \pm\sqrt{\left(\frac{\partial \eta_T}{\partial m}m\right)^2+\left(\frac{\partial \eta_T}{\partial T_{out}}w_{Tout}\right)^2+\left(\frac{\partial \eta_T}{\partial T_{in}}w_{Tin}\right)^2+\left(\frac{\partial \eta_T}{\partial A_c}w_{Ac}\right)^2+\left(\frac{\partial \eta_T}{\partial I_g}I_g\right)^2} \quad (6)$$

$$w_{\eta E} = \pm\sqrt{\left(\frac{\partial \eta_E}{\partial P}w_P\right)^2+\left(\frac{\partial \eta_E}{\partial V}w_V\right)^2+\left(\frac{\partial \eta_E}{\partial A_c}w_{Ac}\right)^2+\left(\frac{\partial \eta_E}{\partial I_g}w_{Ig}\right)^2} \quad (7)$$

The relative uncertainty needs to be evaluated to understand accuracy of observation and given by equation.

$$U_d = \pm\frac{\delta d}{d} \quad (8)$$

Where δ d the error value and d are the average value obtained during calculation.

3.0 Results

3.1 Variation in Solar Radiation and Ambient Temperature

The half-hourly average deviation of global radiations and ambient temperature between 10:30 hrs to 15:30 hrs are plotted in Figure 1. Solar radiations always start rising in the morning, reach maximum value in the noon, and start plummeting in the afternoon. An analogous observation was observed in the literature study done by Sukhatme *et al*[26]. An ambient temperature trend is found proportional to solar radiation and increases with solar radiation till 12:30 hrs and then reduces afterwards.

It was observed that global radiations follow dome shape profile where maximum global irradiation value was 895 W/m^2 at 13:00 hrs and reached the minimum value of 462 W/m^2 at 15:30 hrs. Similarly, the maximum ambient temperature of 30.4°C was observed at 13:00 hrs while the minimum of 25.1 °C at 15:30 hrs. The diffuse radiation was observed to vary in 100- 140 W/m^2.

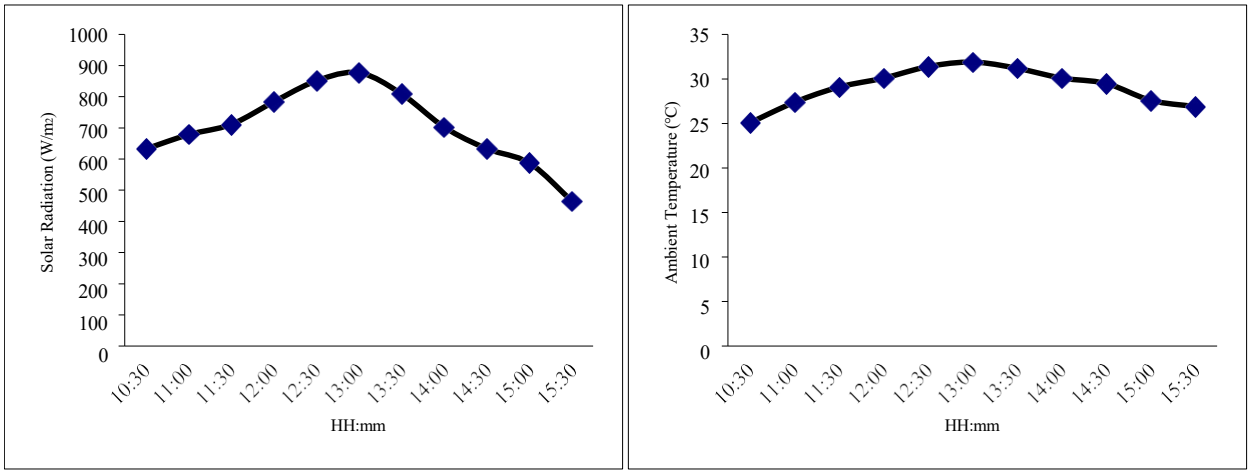


Figure 2. Variation in solar radiation and ambient temperature w r t Time of Day (TOD).

3.2 Effect on Surface Temperature of PVT and PV Collector

Figure 2 demonstrated variations in surface temperature of a) PVT and b) PV collector w r t Time of Day (TOD). It was observed that maximum PV surface temperatures were between 11:00 and 13:00 hrs for all mass flow rates. This can be attributed to solar radiation values, wind speed and ambient temperature. As shown in Figure 2, the PVT surface temperature was turn down by an average of 12.18% with a water-cooling method. The lower surface temperature was observed in PVT system at 0.03 kg/sec during morning and afternoon time. The observed values of PV and PVT surface temperature, atmospheric temperature and water temperature during real time testing at 0.03 kg/sec mass flow rate were put into a table shown in Table 3.

It is also noticed that the surface temperature of conventional PV system temperature was high throughout the day compared to W-PVT surface temperature[29,30]. This low temperature is due to the water circulation through the thermal absorber. The inlet water enters at the entry of the thermal absorber and travels spirally along the entire flipside PV surface. However, conductive, convective and radiative losses increase with a surface temperature limiting heat recovery. During the investigation, it was observed that average PV surface temperature dropped from 58.2°C to 50.2°C with water circulation. This is due to

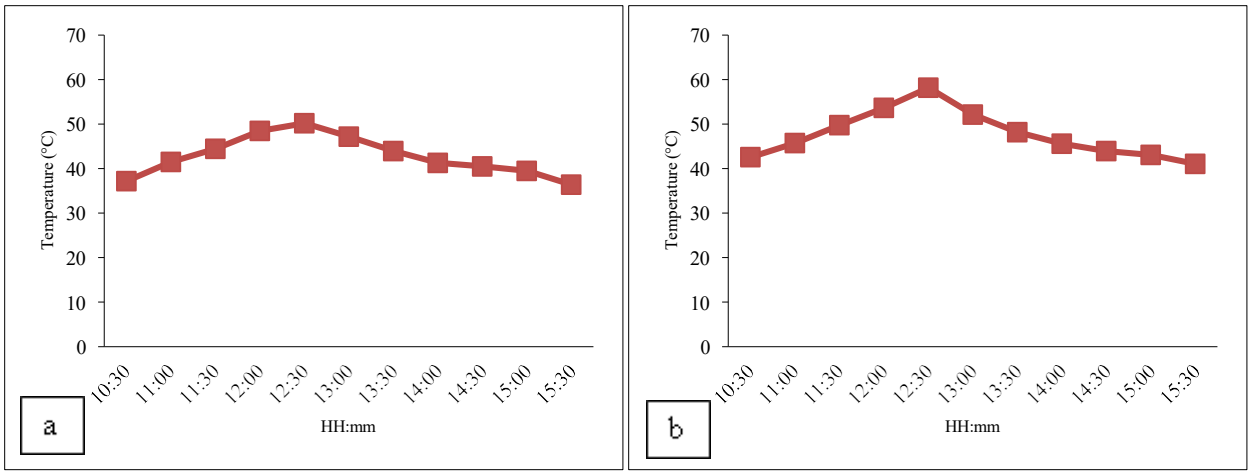


Figure 3. Variation in surface temperature of **(a)** PVT and**(b)** PV collector w r t Time of Day (TOD).

Table 3. Real time observation during testing of PV and PVT

Time	10:30	11:00	11:30	12:00	12:30	13:00	13:30	14:00	14:30	15:00	15:30
Radiation	633	679	711	784	851	878	809	703	634	588	465
Tatm, °C	30.8	31.4	32.7	34	35.2	34.6	33.1	32.5	31.2	30.7	30.4
PV, °C	42.6	45.8	49.8	53.7	58.2	52.2	48.2	45.6	44	43.1	41.1
PVT, °C	37.2	41.5	44.5	48.5	50.2	47.2	44	41.3	40.5	39.5	36.4
Vair, m/s	0.3	0.6	0.78	0.6	0.6	0.9	0.7	0.7	0.8	0.9	0.9
Tdif, °C	0.7	0.9	1.1	1.3	1.35	1.1	0.8	0.6	0.45	0.3	0.2

the fact that surface temperature is directly proportional to incident solar radiation. In case of PVT collector, this rise of surface temperature was comparatively lower as compared to PV system due to cooling of PV from backside through spiral circular thermal absorber[31,32].

3.3 Effect on Electrical Efficiency of PVT and PV Collector

Figure 3 shows variation in electrical efficiency of PV a) PVT and b) PV collector w r t Time of Day (TOD). As shown in Figure 3(a), PV system demonstrated the lower electrical yield while the highest electrical yield of 9.88 % is recorded for the W-PVT system. It is due to water circulation that lowers the surface temperature and results in better electricity generation. Alternatively, the conventional PV system generates a lower electrical yield of 5.62%. This justifies using a thermal absorber and water cooling to increase electrical power output. The PVT collector demonstrated 4.26% higher electrical efficiency due to superior cooling of PV. This is main attribute of PVT collector over PV system. In the literature, researchers also justified use of PV cooling to increase life span of PV.

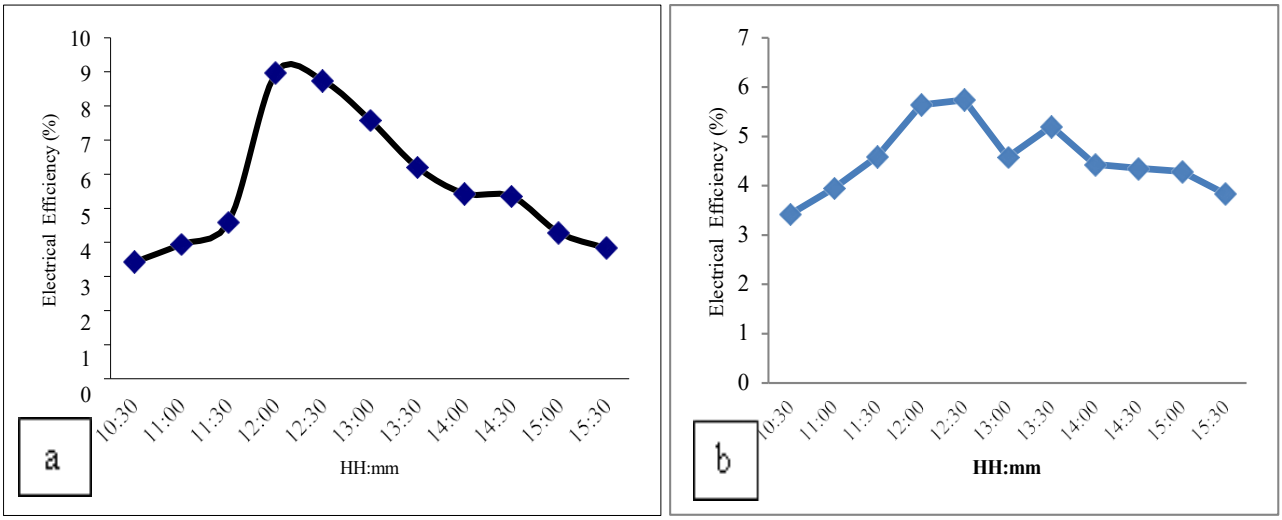


Figure 4. Variation in electrical efficiency of PV **(a)** PVT and **(b)** PV collector w r t Time of Day (TOD).

3.4 Effect on Thermal Efficiency of PVT and PV Collector

The thermal efficiency was assessed derived from the water flow rate, augmentation of the water temperature, the thermo physical properties of water, PV panel area and solar radiation. The overall efficiency is the total thermo-electric performance.

The Figure 4 shows variation in a) thermal and b) overall efficiency of PVT system w r t Time of Day (TOD). It was found that the electrical, thermal and overall efficiency swells with the rise in incident irradiation[33,34]. Since thermal absorbers extracted more heat, which generated better thermal energy and lower PV surface temperature enhanced electrical efficiency. The maximum 9.88% electrical, 47.82% thermal and 57.69 % overall efficiency of found for PVT system respectively, while a minimum of 7.21%, electrical efficiency was found for PV system. The comparative results of literature and current study are studied and tabulated in the Table 4. It was observed from comparative study that spiral circular PVT system has potential to improve electro-thermal efficiency of PVT collector. From the uncertainty analysis,

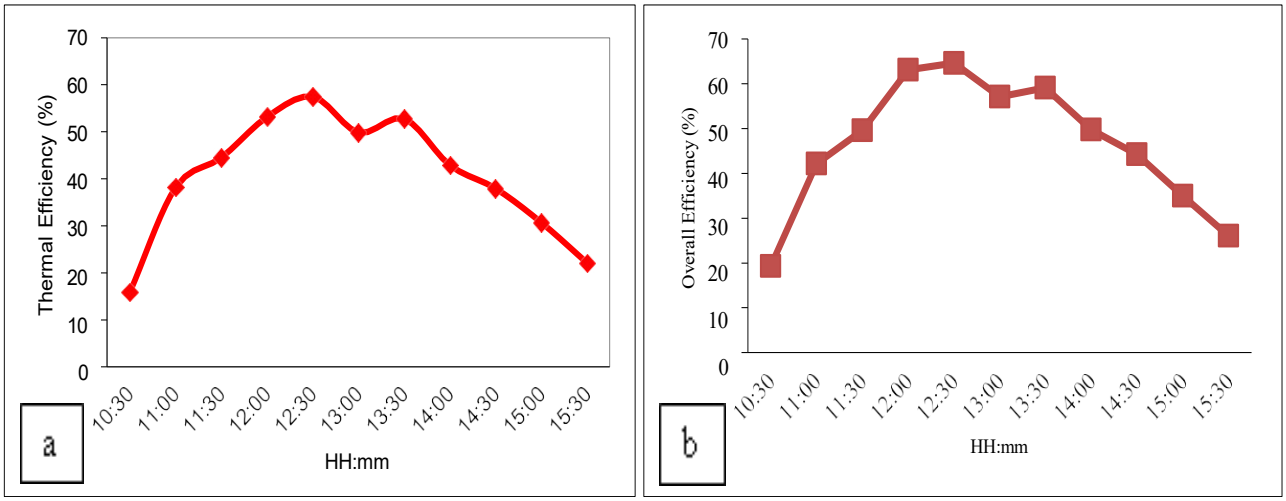


Figure 5. Variation in **(a)** thermal and **(b)** overall efficiency of PVT system w r t Time of Day (TOD).

Table 4. Comparative results of literature and current study.

Study	PVT collector	Coolant	Flow rate(kg/s)	Elect (%)	Therm (%)	Ref
Kim and Jun	Fully Wetted Channel PVT	Water	0.02	15.1	45.5	[35]
Buonomano et. al.	Flat Unglazed PVT	Water	-	13	15	[11]
Amira et. al.	Dual Oscillating PVT	Water	0.083	11.5	58.64	[25]
Misha et. al.	Dual Oscillating PVT	Water	0.1	11.71	59.6	[36]
Anandaraj et. al.	Flat Spiral Tube PVT	Water-Nanofluid	0.083	12.75	56.45	[37]
Current study	Spiral Circular PVT	Water	0.03	9.88	47.82	- -

the maximum uncertainties for PVT collector were ±0.37 and ±0.51 for thermal and electrical efficiencies.

From the obtained result, it was very clear that ambient condition, thermal absorber and its configuration played important role in heat recovery and electrical efficiency improvement[29,30]. it was also found that the recovered heat gave additional benefit of thermal energy that improved overall efficiency of the PVT collector[29]. The present assessment endorsed preferring PVT system over conventional PV collector to overall efficiency improvement. In current study PV system was able to be delivered 5.63% of overall efficiency compared to 57.69% in case of PVT collector. It is also important to mention that cooling of PV also increase effective PV life span.

In performance assessment of current PVT collector, it was also concluded that the PVT collector should be designed based on end use application of thermal energy. The currently designed PVT system is best suited for household domestic application where both electrical and thermal powers are utilized. The collector can be scaled up so that power generation will be multiplied and installed in hotels, hostels and in common kitchen facility to complete electricity and hot water required that will additionally reduce Burdon of conventional power.

4.0 Conclusion

Based on an experimental investigation of solar PVT collector, conclusions are summarized as follows. It was observed that solar radiation, wind speed, clear or sunny day, thermal absorber affects the PV and PVT collector performance. Combining the PV module with the thermal absorber caused the lowering the PV temperature and helped in improved the electrical efficiency. The average improvement in PV electrical efficiency is attained from 5.62% (PV collector) to 6.92 % (PVT collector) at 0.03 kg/sec. The total performance of the PVT collector is much more than the PV collector alone. The average total PVT efficiency obtained was 57.69% at 0.03 kg/sec mass flow rate. The uncertainty analysis using Kline and McClintock method was carried out and relative uncertainties found to be 0.88 % and 3.46% for thermal for electrical efficiency. The research concludes that PVT collector is promising option than PV collector that results in higher energy extraction efficiencies. The present work can be performed scaling up and utilizing other cooling fluid and thermal absorber design to further performance investigation for particular application. The study can be further investigated for Exergy-Environment- Economic concern in commercial perspectives.

5.0 References

1. Campli S, Channapattana SV, Aithal K, et al. Thermodynamic and exhaust emission studies of CI engine powered by neem oil methyl ester blends doped with nickel oxide nano additives. Environ Prog Sustainable Energy. 2024; e14437. https://doi.org/10.1002/ep.14437
2. Campli S, Panshetty S, Madhusudhan, Channapattana SV. Optimization of neem biodiesel blend and injection pressure of CI engine. In Advances in Structures, Systems and Materials: Select Proceedings of ERCAM;. Springer Singapore; 2020. p. 211-225. https://doi.org/10.1007/978-981-15-3254-2_20
3. Campli S, Madhusudhan A, Channapattana SV, Gawali SV, Aithal K. RSM based parameter optimization of CI engine fuelled with nickel oxide dosed Azadirachta indica methyl ester. Energy. 2021; 234:121282. https://doi.org/10.1016/j.energy.2021.121282
4. Campli S, Kshirsagar P, Joshi M, Kulkarni A, Channapattana SV, Madhusudan A, Aithal K, Gawali S. Effect of fuel injection timing on CI engine fuelled with neem biodiesel blends-a comparative study of experimental and numerical simulation. Int J Energy Envir E. 2022: 1-12. https://doi.org/10.1007/s40095-021-00429-6
5. Gajbhiye AM, Sonawane PR, Karle AH, Campli S. Optimization of welding parameters for En8D and SAE1018 materials by Taguchi. Int J Interact Des Manuf. 2023: 1-10 https://doi.org/10.1007/s12008-023-01678-x
6. Reports, National Informatics Centre,by Ministry of New and Renewable Energy, Government of India; 2024
7. Kern Jr EC, Russell MC. Combined photovoltaic and thermal hybrid collector systems. Conference Record of the IEEE Photovoltaic Specialists Conference; 1978.
8. Zondag HA. Flat-plate PV-Thermal collectors and systems: A review. Renewable and Sustainable Energy Reviews. 2008; 12:891-959. https://doi.org/10.1016/j.rser.2005.12.012
9. Chow TT. A review on photovoltaic/thermal hybrid solar technology. Applied Energy. 2010; 87:365-379. https://doi.org/10.1016/j.apenergy.2009.06.037

10. Ibrahim A, Othman MY, Ruslan MH, Mat S, Sopian K. Recent advances in flat plate Photovoltaic/Thermal (PV/T) solar collectors. Renew Sustain Energy Rev. 2011; 15(1):352-365. https://doi.org/10.1016/j.rser.2010.09.024
11. Buonomano AJ, Calise F, Vicidomini M. Design, simulation and experimental investigation of a solar system based on PV Panels and PVT Collectors. Energies. 2016; 9:497. https://doi.org/10.3390/en9070497
12. Kumar A, Baredar P, Qureshi U. Historical and recent development of Photovoltaic Thermal (PVT) technologies. Renew Sustain Energy Rev. 2015; 42(C):1428-1436. https://doi.org/10.1016/j.rser.2014.11.044
13. Tyagi VV, Kaushik SC, Tyagi SK. Advancement in solar Photovoltaic/Thermal (PV/T) hybrid collector technology. Renew Sustain Energy Rev. 2012; 16(3):1383-1398. https://doi.org/10.1016/j.rser.2011.12.013
14. Abdullah AL, Misha S, Tamaldin N, Rosli NAM, Sachit FA. Photovoltaic Thermal /Solar (PVT) collector (PVT) system based on fluid absorber design: A review. J Adv Res Fluid Mech Therm Sci. 2018; 48(2):196-208.
15. Sultan SM, Fadhel MI, Alkaff SA. Performance analysis of the Photovoltaic/ThermalCollector (PV/T) system for different malaysian climatic conditions. Applied Mechanics and Materials. 2014; 467:522-527. https://doi.org/10.4028/www.scientific.net/AMM.467.522
16. Modrek M, Al-Alili A. Thermal and electrical performance of a flat platephotovoltaic/thermal collector. Proceedings of the ASME 2017 11th International Conference on Energy Sustainability ES2017, June 26-30, 2017. Charlotte, North Carolina, USA; 2017. https://doi.org/10.1115/ES2017-3462
17. Marc-Alain NM, Inambao F. Performance analysis of thermosyphon hybridphotovoltaic thermal collector. J Energy South Afr. 2016; 27(1):28-38. https://doi.org/10.17159/2413-3051/2016/v27i1a1564
18. El Fouas C, Hajji M, Bouali H, Hajji B, Tina GM, Khlifi Y. Absorber designs effect on the performance of PV/T water hybrid collector. ICEERE2018, LNEE 519; 2019. p. 679-689. https://doi.org/10.1007/978-981-13-1405-6_78
19. El Mays A, Ammar R, Hawa M, Akroush MA, Hachem F, Khaled M, Ramadan M. Improving photovoltaic panel using finned plate of Aluminum. Energy Procedia. 2017; 119:812-817. https://doi.org/10.1016/j.egypro.2017.07.103
20. Zohri M, Nurato N, Fudholi A. Photovoltaic Thermal (PVT) system with and without fins collector: Theoretical approach. International Journal of Power Electronics and Drive Systems (IJPEDS). 2017; 8:1756-1763. https://doi.org/10.11591/ijpeds.v8.i4.pp1756-1763
21. Mojumder JC, Ong HC, Chong WT, Leong KY, NimaIzadyar. An empirical analysis on photovoltaic thermal system with fin design by forced air circulation. Journalof Mechanical Science and Technology. 2017; 31(5):2549-2557.https://doi.org/10.1007/s12206-017-0453-1
22. Abdul-Ganiyu S, Quansah DA, Ramde EW, Seidu R, Adaramola MS. Study effect of flow rate on flat-plate water-based Photovoltaic-Thermal (PVT) system performance by analytical technique. Journal of Cleaner Production. 2021; 321:128985. https://doi.org/10.1016/j.jclepro.2021.128985
23. Kallio S, Siroux M. Energy analysis and exergy optimization of photovoltaic-thermal collector. Energies. 2020; 13(19):5106. https://doi.org/10.3390/en13195106
24. Mani A, Chako O. Solar radiation climate of India. Solar Energy. 1973; 14:139-156. https://doi.org/10.1016/0038-092X(73)90030-3
25. Abdullah AL, Misha S, Tamaldin N, Rosli MAM, Sachit FA. Theoretical study and indoor experimental validation of performance of the new Photovoltaic Thermal solar collector (PVT) based water system. Case Studies in Thermal Engineering. 2020; 18. https://doi.org/10.1016/j.csite.2020.100595
26. Sukhatme SP. Solar Energy, Principles of Thermal Collection and Storage. 6th Edition. , New Delhi: Tata McGraw Hill Publishing Company Limited; 2012.
27. Facao J, Oliveira AC. Experimental uncertainty analysis in solar collectors. Int J Ambient Energy. 2006; 7:59-64. https://doi.org/10.1080/01430750.2006.9675004
28. Wells C. Measurement uncertainty analysis techniques applied to PV performance measurements. Colorado: National Renewable Energy Laboratory Golden; 1992.
29. Singh B, Singh S, Yen CH, Zaidi SH. Kamaruzzaman Sopian, Part II: Enhanced performance of concentrating photovoltaic-thermal air collector with fresnel lens and Compound Parabolic Concentrator (CPC). J Adv Res Fluid Mech Therm Sci. 2018; 47(1):16-24.
30. Cho H, Smith A, Luck R, Mago PJ. Transient uncertainty analysis in solar thermal system modeling. J Uncertain Anal Appl. 2017; 5(1):1-15. https://doi.org/10.1186/s40467-017-0055-6
31. Campli S, Channapattana SV, Aithal K, Sarnobath S, Patil NA, Patel S, Karle A, Mohammed AA. Relative exergy and energy analysis of DI-CI engine fueled with higher

blend of Azadirachta indica biofuel with n-butanol and NiO as fuel additives. Environ Prog Sustain Energy. 2024; 43(3):e14336. https://doi.org/10.1002/ep.14336

32. Zareie Z, Ahmadi R, Asadi M. A comprehensive numerical investigation of a branch- inspired channel in roll-bond type PVT system using design of experiments approach. Energy. 2024; 286:129452. https://doi.org/10.1016/j.energy.2023.129452
33. Satpute J, Rajan AJ. Analysis of energy, exergy, environmental and economics (4E) on PV-Thermal collector system. Thermal Science. 2022. https://doi.org/10.2298/TSCI210905010S
34. Kumar R, Marc AR. A critical review of photovoltaic-thermal solar collectors for air heating. Applied Energy. 2011; 88(11):3603-3614. https://doi.org/10.1016/j.apenergy.2011.04.044
35. Kim J-H, Kim J-T. The experimental performance of an unglazed PVT collector with two different absorber types. Int J Photoenergy. 2012. https://doi.org/10.1155/2012/312168
36. Misha S, Abdullah AL, Tamaldin N, Rosli MAM, Sachit FA. Simulation CFD and experimental investigation of PVT water system under natural Malaysian weather conditions. Energy Reports. 2020; 6(S7):28-44. https://doi.org/10.1016/j.egyr.2019.11.162
37. Anandaraj S, Ayyasamy M, Marquez FPG, et al. Experimental studies of different operating parameters on the photovoltaic thermal system using a flattened geometrical structure. Environ Sci Pollut Res. 2023; 30:1116-1132. https://doi.org/10.1007/s11356-022-22261-z PMid:35913695.