ADVANCES IN HIGH PERFORMANCE PV/T SOLAR COLLECTORS

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Hybrid photovoltaic thermal (PV/T) is a technology with many variations and designs. The aim of this unit is cooling down PV temperature while producing hot water. In this paper, different PV/T designs are compared in terms of energy, exergy and efficiency. Data from experiments and numerical calculations conducted at Bangi, Malaysia was used for the comparisons. The proposed systems were tested in outdoors conditions. The designs in question are: water-based PV/T, water-based PV/T with PCM tank, nanofluid-based PV/T with nano-PCM tank and conventional PV module. Effect of mass flow rate and solar irradiance are emphasized in this paper. The highest combined efficiency, thermal energy and electrical exergy produced are found for PV/T with nanofluids and nano-PCM with around 72%, 14 kW and 74.52, respectively. All PV/T systems proposed exhibit better performance than the conventional PV module. These findings highlight the utility of PV/T technology and its massive potential to energize and popularize the solar energy field.

Keywords: PV/T; Nanofluids; Nano-PCM; Exergy; Efficiency.

1. Introduction

PV/T hybrid collectors offer advantages such as increased electrical energy yield due to cooling and simultaneous production of thermal yield [1-2]. The use of a thermal absorber in combination with a PV module allows to utilize the wasted heat which is bound to be generated as result of losses in the PV cell itself and heat induced from surrounding environment. Many research studies have been carried out to analyze the exergy efficiency of PV/T collectors with comparison to energy yield [3-5]. Overall performance evaluation criteria are the rise in fluid temperature, thermal and electrical efficiency and exergy. Nanofluids have been recently used as coolants for PV modules and working fluids in PV/T collectors. This is mainly due to their excellent thermal properties such as the higher thermal conductivity and specific heat capacity [6]. Although this topic is quite recent and require longer time for investigation and testing, many researchers have employed nanofluids as part of indirect PV/T systems [7-9]. The use of heat exchanger is important to facilitate the hot nanofluid output from hot water output. The use of nanofluid is kept part of a heat-cooling cycle to avoid wasting this expensive material and ensuring maximum heat transfer is achieved for better cooling of PV and higher fluid outlet temperature [10-11]. Passive cooling of PV modules has been performed using organic Phase Change Material (PCM) [12]. These materials are known for high latent heat and hence can be excellent storage mediums for thermal energy and means for thermal regulation. Hasan et al. [13] performed experimental investigation of a system in United Arab Emirates (UAE) which is know for its high ambient temperatures, relative humidity and solar irradiance; making it classified as a hot climate. The system was compared a reference PV module. Both modules were polycrystalline, while difference PCMs were investigated. The authors of the study concluded that at peak time, the PCM-PV exhibited higher electrical efficiency than reference PV. Hence, PV/T systems with PCM have been studied, as Yang et al. [14] where thermal and electrical efficiencies were improved by 19.69% and 16.91%, respectively when using PCM-based PV/T compared to conventional PV/T system. The authors claim the use of PCM-based PV/T has extended energy savings by 14%. After all, many issues are associated with using PCM in terms of thermal extraction, due to its poor thermal conductivity. This issue is solved using nanomaterial, which are employed in PCM to form ‘Nano-PCMs’ or nano-enhanced Phase Change Material. Karunamurthy et al. [15] performed tests on the thermal conductivity of CuO-Paraffin (nano-PCM) which was mixed using two-step method. The authors justified the experiments as an approach to improve the thermal conductivity PCM for thermal energy storage applications. In this paper, an evaluation of the performance of four configurations of PV/T system is presented for comparison in performance under tropical climate of Malaysia. The proposed system is a nano-PCM and nanofluid based PV/T with nanofluids flowing within it. The purpose of such design is to store thermal energy in the nano-PCM tank and extract it through heat transfer using nanofluids; due to their high thermal conductivity. Energy and exergy are the emphasis of this paper, while justification for using a nanofluid volume fraction of 3% and nano-PCM volume fraction of 0.1% are provided in references [16-17]. The other configurations are used to display the utility of combining the PCM and nanofluid technique and highlight differences between proposed design and typical PV/T systems used in the literature. The fourth considered design is a typical PV module used as a reference.

2. Methodology

The methodology is described in three segments to provide the (i) flow chart for investigation parameters, (ii) theoretical analysis, for calculated parameters, and (iii) experimental setup, for outdoor experiments. The methodology consists of standard testing procedures such as sensor calibration, PV/T system testing and mass flow rate tests.

2.1.Investigation parameters

The investigation is conducted to test the difference between three PV/T system configurations and a PV module as a reference. The configurations used were: (i) Water tank with water flowing in pipes, (ii) PCM tank with water flowing in pipes, and (iii) nano-PCM tank with nanofluid flowing in pipes. The methodology is described in terms of assumptions & inputs to the investigation, evaluation parameters, testing, targeted results and comparison criteria. The flowchart of the methodology is provided in figure 1. The comparison criteria were based on equal pumping power, i.e. same mass flow rate & pump power. Also, systems were placed in close proximity for equal input of solar irradiance. The selected design and operating material were made based on criteria of low-cost and high-thermal conductivity. Hence, water, paraffin wax and Silicon carbide were primary mediums for the configurations, all of which are widely used in heat transfer applications [18-20]. Certainly, for fair comparison, the type and size of PV modules were unified for all systems; to avoid discrepancies in comparison due to different material and manufacturing characteristics.

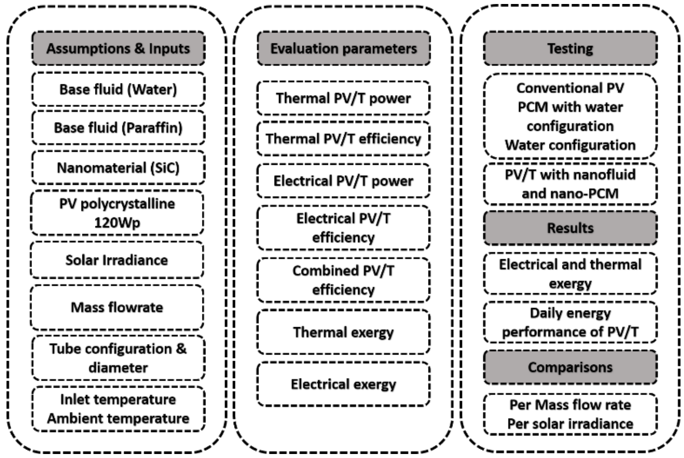


Figure 1: Flowchart of the investigation methodology

As figure 1 shows, the mass flowrate is part of the inputs to the investigation. The solar irradiance on the other hand was considered in the cluster of inputs given that its experiments were targeted for Malaysia weather conditions which are considered tropical. The evaluation of each system is done by measuring parameters such as inlet and outlet temperature of fluid, solar irradiance, voltage and current, and calculations of electrical and thermal power, energy, exergy and efficiency which are provided in the theoretical analysis section. The utility of the reference PV module is to understand the significance of the proposed designs in comparison to the common typical PV systems. Finally, the main target of the experiments is to view the electrical and thermal exergy and daily energy performance in tropical climates such that of Malaysia.

2.2. Theoretical analysis

The parameters used for evaluation which are provided in methodology flow chart, are calculated through equations presented in this sub-section. The electrical and thermal efficiencies and associated parameters are presented in equations (1-4):

The electrical efficiency η_e is [21]:

$$\eta_e = \frac{P_{max}}{G \times A_{PV}}$$

(1)

where P_{max} is the output power from PV module in W, G is the solar irradiance in W/m^2, while area of PV module is A_{PV}, in m^2.

The PV/T electrical power is [22]:

$$P_{max} = V_{mpp} \times I_{mpp}$$

(2)

The PV/T thermal efficiency is [23]:

$$\eta_t = \frac{Q_u}{G \times A_c} \quad (3)$$

Where A_c is the collector area, in m^2, while Q_u is the useful heat gain. Which is denoted in equation 4.

The useful collected heat (W) [22]:

$$Q_u = \dot{m} C_p (T_o - T_i)$$

(4)

Where $\dot{m}$ is the mass flow rate, in kg/s, C_p is the specific heat, in J/kg.K and T_o and T_i are the outlet and inlet fluid temperatures, respectively.

The exergy is a quantity state which is defined on the basis of the ambient conditions. It describes the energy which is available by subtracting unavailable energy out of total energy. Making it equivalent to work that is transformed outside.

The equivalent of electrical exergy is work; given its not affected by ambient conditions. The instantaneous electrical exergy is given by [24]:

$$\grave{E}_{X_{Electrical}} = \eta_e H = \xi_e H$$

(5)

Where $\dot{E}_e$ is the electrical exergy, while ξ_e is the exergy efficiency and H is the irradiance (in this paper denoted G).

The exergy analysis, according to the second law of thermodynamics, which accounts for the total exergy inflow, exergy outflow and exergy destructed from the system. Equations (6-11) provide main equations used for exergy analysis [25-26].

$$\sum \grave{E}_{X_{in}} - \sum \grave{E}_{X_{out}} = \sum \grave{E}_{X_{dest}}$$

(6)

$$\sum \grave{E}_{X_{in}} - \sum (\grave{E}_{X_{Thermal}} + \grave{E}_{X_{Electrical}}) = \sum \grave{E}_{X_{dest}}$$

(7)

Where $\grave{E}_{X_{in}}$ is the exergy of irradiance which is calculated using equation 17:

$$Exergy\ of\ irradiance = A_C \times N_C \times G \times \left[1 - \frac{4}{3} \times \left(\frac{T_a}{T_s}\right) + \frac{1}{3} \times \left(\frac{T_a}{T_s}\right)^4\right]$$

(8)

$$Thermal\ Exergy = \grave{E}_{X_{Thermal}} = \mathbf{Q}^{\cdot}{}_u \left[1 - \frac{T_a + 273}{T_{f_o} - 273}\right]$$

(9)

$$Electrical\ Exergy = \grave{E}_{X_{Electrical}} = \eta_c \times A_C \times N_C \times G$$

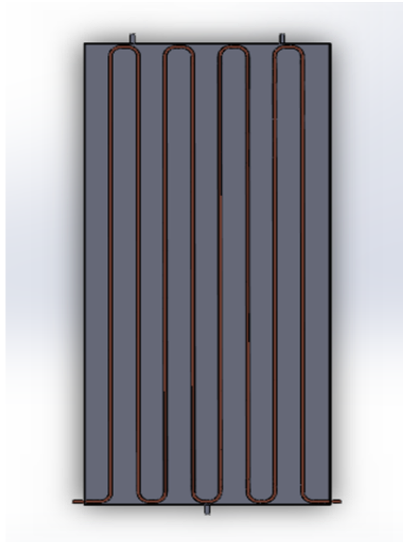
(10)

Where, Ts is the Sun's temperature in Kelvin, Ac is area of cell, Nc is the number of cells. The overall energy is provided in equations (11):

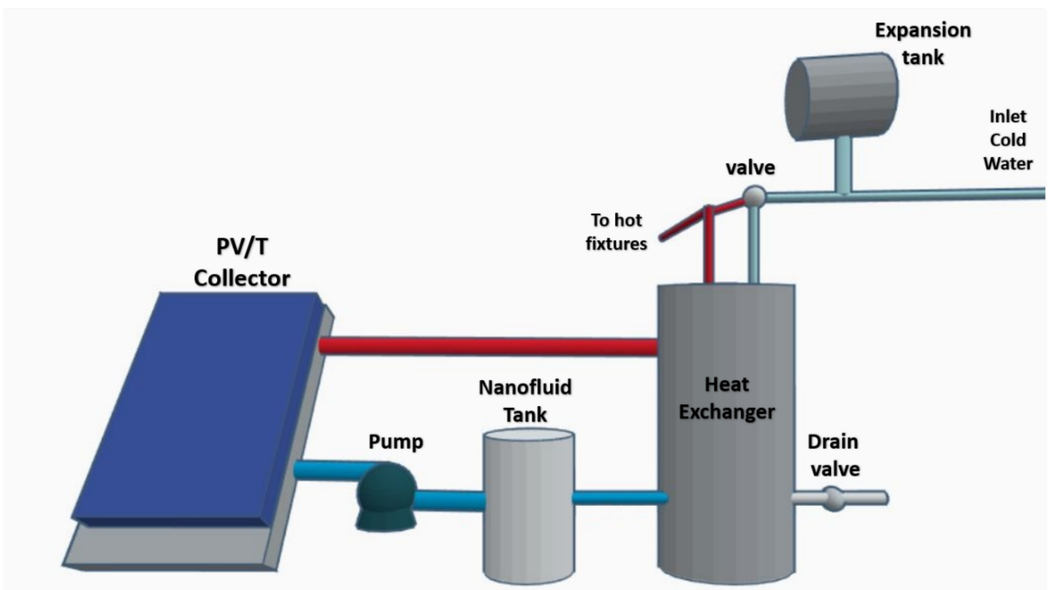
$$Total\ energy = \grave{E}_{X_{Thermal}} + \grave{E}_{X_{Electrical}} \quad (11)$$

2.3.Experimental setup

The systems were setup in the GETIP park of the National University of Malaysia. The site of the experiments is located in the city of Bangi, Selangor (Coordinates 2.9021 N, 101.7830 E) which generally exhibits temperature, humidity and wind speed of 31 °C, 80% and 1 m/s, respectively. In addition, the monthly average hours of sunshine peaks at 210 hours [27]. The PV/T systems contained heat exchangers, shell and tube types, pumps, expansion valves, and for the case of the proposed system, a nanofluid tank was used. Figure 2 (a) shows the conceptual design of the proposed PV/T collectors, while (b) shows a 3D schematic diagram of the proposed system.



(a)



(b)

Figure 2: (a) top view 2D drawing of proposed PV/T collector (SolidWorks) (b) Schematic 3D view of the experimental rig (TinkerCad)

Figure 2(a) shows how the collector is designed in terms of pipe shape and configuration as well as enclosing design. The collector is composed of two parts which are the PV module itself and the nano-PCM tank which encloses copper pipes which carry the nanofluid. Glass wool was used for insulation underneath and around the proposed PV/T collector. In between the PV and nano-PCM tank, a layer of silicon oil was used to eliminate air gaps and increase heat transfer. The installed systems utilized various sensing elements such as temperature and solar irradiance sensors, all of which are illustrated in table 1. Those sensors were connected to a data acquisition system which was linked to a personal computer to store recorded data. While, Table 2 shows the equipment characteristics for critical aspects of the proposed system.

Table 1: Sensor properties and experiment uncertainty

Device	Name	Parameter	Uncertainty	Unit
Weight	Analytical weight	Mass	±0.01	Kg
Multimeter	LIV tester	Voltage	±0.06	V
		Current	±0.06	A
Pyranometer	Apogee meter	Solar irradiance	±1.2	W/m^2
Flowmeter	Rotameter	Mass flow rate	±0.43	Kg/s
Thermocouples	K-type thermocouples	Temperature	±0.3	K
Thermal conductivity tester	KD2 Pro thermal analyser	Thermal conductivity	±0.92	$W.m^{-1}.K^{-1}$
		Thermal capacity	±0.87	J/K
Density tester	DH 300L digital liquid density tester	Density	±0.21	kg/m^3
Viscosity Rheometer	DV3T Touch Screen Rheometer	Kinematic Viscosity	±0.01	m^2/s
Uncertainty percentage	W_R		1.843%	

The uncertainty percentage was calculated using the method of Kline and McClintock [28]:

$$W_R = \left[\left(\frac{\partial R}{\partial x_1} w_1 \right)^2 + \left(\frac{\partial R}{\partial x_2} w_2 \right)^2 + \ldots + \left(\frac{\partial R}{\partial x_n} w_n \right)^2 \right]^{0.5}$$

(12)

Where W_R is the uncertainty of results, R is a function of an independent variable (x_1, x_2…, x_n), and (w_1, w_2, …, w_n) are the independent variables' uncertainties.

Table 2: Characteristics of system material and devices

Silicon Carbide nanoparticles	**Appearance**	**PH value**	**Crystal type**	**Grain size**	**Purity**
	Greyish white	3–7 at 20 °C	Cubic	45-65 nm	99+%
Paraffin Wax	**Melting point temperature**	**Latent heat of fusion**	**Solid state density**	**Liquid state density**	**Thermal conductivity**
	49 °C	196 kJ/kg	930 kg/m^3	830 kg/m^3	0.21 W/m °C
Photovoltaic module	**Type**	**Size**	**V_{OC} at STC**	**I_{SC} at STC**	**Efficiency at STC**
	Polycrystalline	120 Wp	21.5 V	7.63 I	14% ± 3
Data Acquisition device	**Type**	**Channels**	**Power consumption**	**Input type**	**Burn-out Detection**
	ADAM-4019+	8	1 W	T/C, mV, V, mA	4 ~ 20 mA & all T/C
V_{OC} = open circuit voltage, I_{SC} = short circuit current, STC = standard test conditions (Solar irradiance 1000 W/m^2, ambient temperature 25 °C and pressure of 1.5 AM)					

Table 2 shows the material and equipment properties for the nanomaterial, paraffin, PV and Data Acquisition devices, respectively. The experiment was conducted in the months of June and July which are the least rainy months of the year. Clear sky days were selected for performance evaluation of the collectors. Prior to experiments, the system was tested for multiple mass flow rates which ranged between 0.083 kg/s and 0.018 kg/s. When exceeds 0.0175 kg/s the system vibrated due to high value of mass flow rate and hence 0.175 was the highest for the range. Multiple tests were conducted using water and highest temperature reduction for the proposed system were observed for 0.175 kg/s and hence it was selected for all systems.

3. Results and discussions

The results are divided into daily energy performance for the four configurations and the exergy analysis of the proposed PV/T collector. In this section, the proposed system is referred to as PV/T.pcm.n.nf, while PV/T.pcm.w refers to the system with PCM and water as coolant and finally PV/T refers to the water-filled tank with water as coolant.

3.1.Daily energy performance of selected systems

The electrical, thermal and combined efficiency of the PV/T configurations are provided for 1 day in figure 3. The energy change is observable throughout the experiment period, particularly from 12-3:20 PM which is when the solar irradiance peaks and is at highest levels. The electrical efficiency of the proposed system is the highest with an average of 13.1% while PV/T with PCM and Water averages at around 12.5%, followed by 9.1% for the PV/T with water and 8.1% for conventional PV. The thermal behavior for the proposed systems is different. This is due to the latent heat property of the organic paraffin. Hence, the PV/T water cooled system achieves a thermal efficiency of 30% at 12:30 PM, while the PV/T.PCM.W and proposed PV/T achieved 30% thermal efficiency at 12PM and 10:55 PM, respectively. Achieving 30% thermal efficiency by 10:55 PM is an indication that the nano-PCM has excellent thermal conductivity and hence more heat is transferred into the working fluid. The PV/T combined efficiency is the addition of both electrical and thermal efficiencies. The highest combined PV/T efficiency is achieved by the proposed design and is around 86%, followed by 63% and 47% for the PV/T.PCM.W and PV/T, respectively.

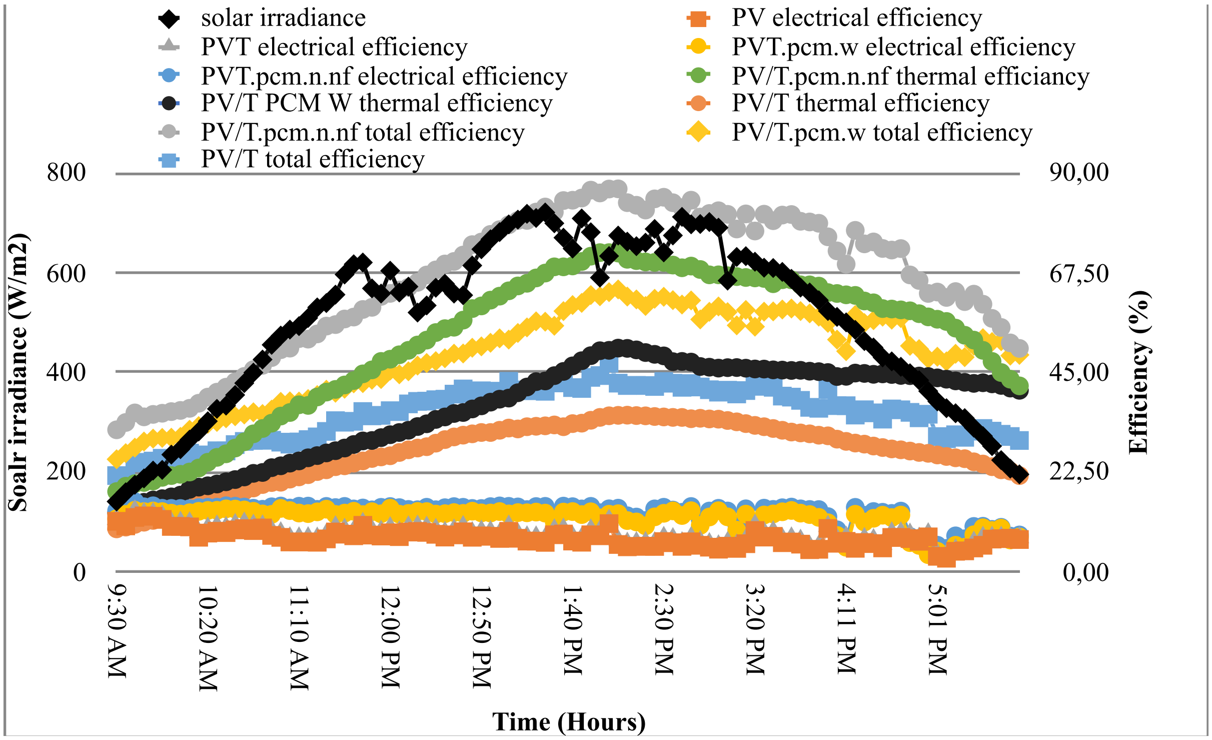


Figure 3: Electrical, thermal and combined efficiency for the four tested systems

Figure 4 shows the electrical power for the four configurations across testing period. The highest power is found to approach 120Wp (full rated value) by the proposed configuration, while the lowest PV has peaked at around 70Wp. The waveform of the electric power was closely similar in shape to that of solar irradiance; however, difference occur due to increase of cell temperature which causes a drop in the voltage of the cell and efficiency. Minor peaks and values occur to variations in the input and cell temperature which is also a product of ambient temperature influence and wind speed. The energy performance of the proposed system, according to figures 3 and 4, has outperformed its counterpart. It is notable to mention that the PV/T using water tank and water as base fluid is different from conventional tube and sheet water-based PV/T which will have different behavior under the same conditions. The thermal efficiency remains even after drops in the solar irradiance and even increases; the stored heat in the PCM and nano-PCM is now being released and hence more output, fluid temperature, for lesser input, solar irradiance, is achieved.

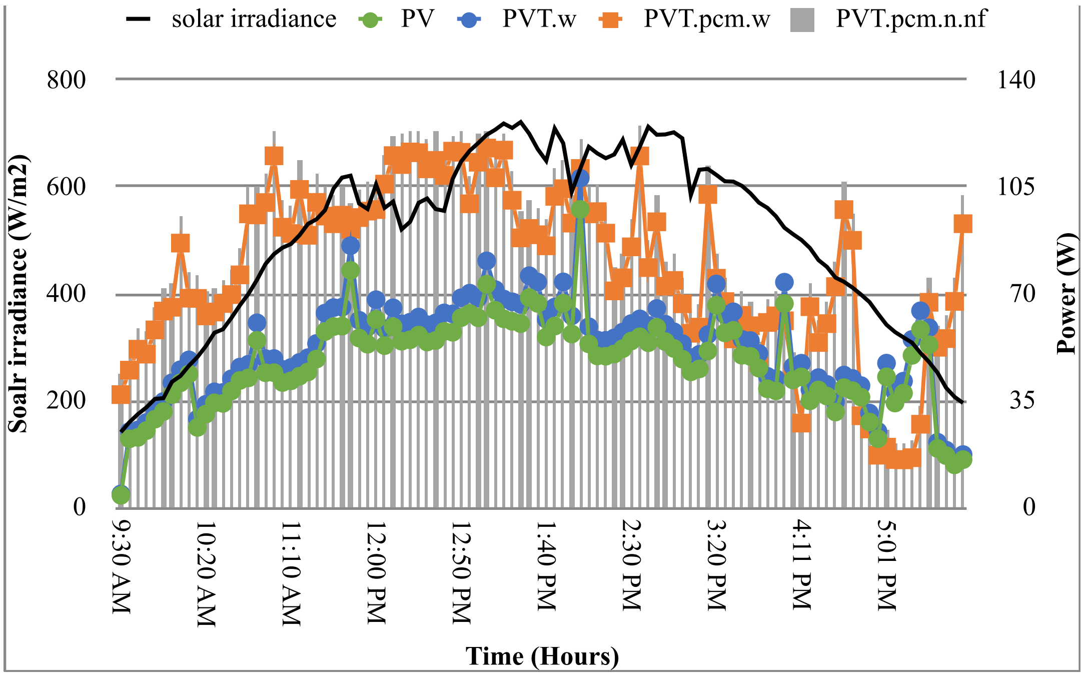


Figure 4: Electrical power for the four tested systems

The need to describe all system urges for showing their behavior with respect to solar irradiance which is the only input to the system. Although factors such as humidity, temperature and wind speed have influence and may cause variations in peaks and valleys. The energy performance is important, however, for more accurate understanding of the system, exergy analysis was conducted for the four tested systems in terms of electrical exergy, while thermal and overall exergy are provided for the proposed system.

3.2.Daily exergy performance of selected systems

The variation of solar irradiance has significant effect on the exergy of PV systems, and is clear from equation (10). Figure 5 shows the increase of the exergy as results of increase in solar irradiance for the tested systems. However, the uncooled -conventional- PV faces some drops and an overall lower peak which sets at 60. Not much difference in exergy is achieved by the PV/T using water tank and water coolant. Higher exergy is found for the PV/T.pcm.n.nf and the PV/T.pcm.w which peaked at 141 and 128, respectively at 900 W/m^2. However, on average the electrical exergy of the four configuration (PV, PV/T, PV/T.pcm.w and PV/T.pcm.n.nf) were around 34.9, 39.5, 71.2 and 78.4, respectively. The steady increase in electrical exergy for the proposed system indicates the quality of thermal regulation. Finally, figure 6 shows the electrical, thermal and overall exergy (in W) of the proposed system which shows a peak total exergy of 132; resultant of electrical and thermal exergy of 109 and 23, respectively.

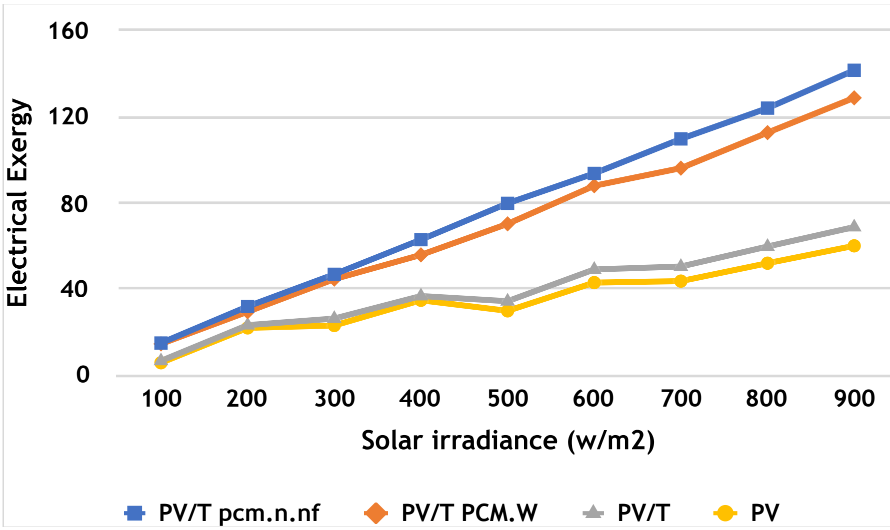


Figure 5: Electrical exergy of the proposed PV/T system across solar irradiance

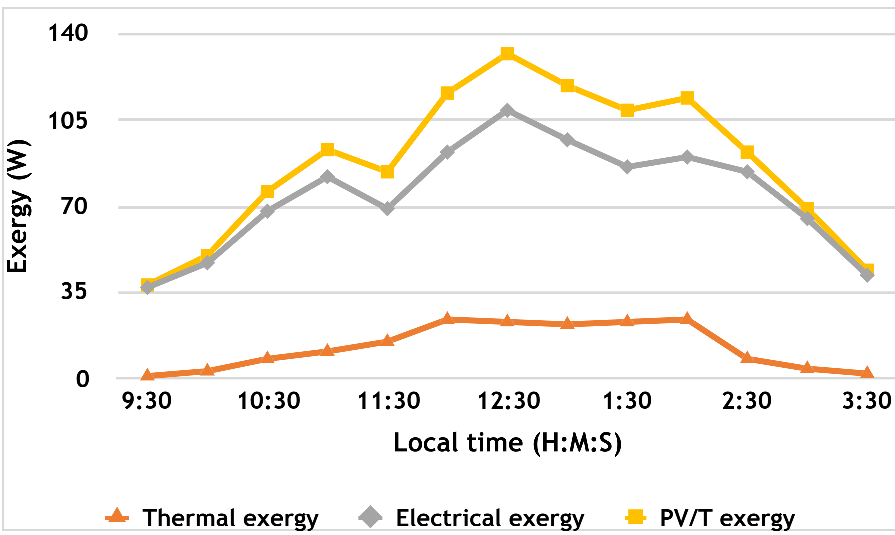


Figure 6: Electrical, Thermal and PV/T exergy of the proposed PV/T system throughout experiment period

The electrical, thermal and PV/T exergy achieved a daily, per 12 hours, average of around 80, 14 and 94, respectively. Optimizing the system design and operating condition can result in higher exergy values under same climate conditions.

4. Conclusions & recommendations

This paper presented an experimental investigation of four different PV configurations; three of which are PV/T combined with (i) water tank and water flowing in pipes, (ii) PCM tank and water flowing in pipes, (iii) nano-PCM tank and nanofluid flowing in pipes. According to the observations of the experiments the highest energy was produced by the proposed PV/T with nano-PCM tank and nanofluid coolant. The system was found to exceed its rivals due to higher overall thermal conductivity and design material. The maximum combined PV/T efficiency achieved was around 86%, for a maximum thermal efficiency of 72%. While the average daily thermal and electrical exergies were around 14 and 80, respectively. Further research into this system is recommended by undertaking the following research ideas:

1) Investigating the number of charging/discharging cycles and opening melting temperature for nano-PCM in the tank.
2) Employing the system directly to the back of the PV module instead of using separate tank for nano-PCM.
3) Examine inorganic PCM material with nano-material for the proposed PV/T system.

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References

[1] Reddy, S. R., Ebadian, M. A., & Lin, C. X. (2015). A review of PV–T systems: Thermal management and efficiency with single phase cooling. International Journal of Heat and Mass Transfer, 91, 861-871.

[2] Chow, T. T. (2010). A review on photovoltaic/thermal hybrid solar technology. Applied energy, 87(2), 365-379.

[3] Sudhakar, K., & Srivastava, T. (2014). Energy and exergy analysis of 36 W solar photovoltaic module. International Journal of Ambient Energy, 35(1), 51-57.

[4] Jahromi, S. N., Vadiee, A., & Yaghoubi, M. (2015). Exergy and economic evaluation of a commercially available PV/T collector for different climates in Iran. Energy Procedia, 75, 444-456.

[5] Tiwari, A., Dubey, S., Sandhu, G. S., Sodha, M. S., & Anwar, S. I. (2009). Exergy analysis of integrated photovoltaic thermal solar water heater under constant flow rate and constant collection temperature modes. Applied Energy, 86(12), 2592-2597.

[6] Vollath, D., & KGaA, W. V. V. G. C. (2008). An introduction to synthesis, properties and application. and Management, 7(6), 865-870.

[7] Taylor, R. A., Otanicar, T., & Rosengarten, G. (2012). Nanofluid-based optical filter optimization for PV/T systems. Light: Science & Applications, 1(10), e34.

[8] Hjerrild, N. E., Mesgari, S., Crisostomo, F., Scott, J. A., Amal, R., & Taylor, R. A. (2016). Hybrid PV/T enhancement using selectively absorbing Ag–SiO2/carbon nanofluids. Solar Energy Materials and Solar Cells, 147, 281-287.

[9] Crisostomo, F., Hjerrild, N., Mesgari, S., Li, Q., & Taylor, R. A. (2017). A hybrid PV/T collector using spectrally selective absorbing nanofluids. Applied energy, 193, 1-14.

[10] An, W., Li, J., Ni, J., Taylor, R. A., & Zhu, T. (2017). Analysis of a temperature dependent optical window for nanofluid-based spectral splitting in PV/T power generation applications. Energy conversion and management, 151, 23-31.

[11] Chaji, H., Ajabshirchi, Y., Esmaeilzadeh, E., Heris, S. Z., Hedayatizadeh, M., & Kahani, M. (2013). Experimental study on thermal efficiency of flat plate solar collector using TiO2/water nanofluid. Modern Applied Science, 7(10), 60-69.

[12] Regin, A. F., Solanki, S. C., & Saini, J. S. (2008). Heat transfer characteristics of thermal energy storage system using PCM capsules: a review. Renewable and Sustainable Energy Reviews, 12(9), 2438-2458.

[13] Hasan, A., Sarwar, J., Alnoman, H., & Abdelbaqi, S. (2017). Yearly energy performance of a photovoltaic-phase change material (PV-PCM) system in hot climate. Solar Energy, 146, 417-429.

[14] Yang, X., Sun, L., Yuan, Y., Zhao, X., & Cao, X. (2018). Experimental investigation on performance comparison of PV/T-PCM system and PV/T system. Renewable energy, 119, 152-159.

[15] Karunamurthy, K., Murugumohankumar, K., & Suresh, S. (2012). Use of CuO nano-material for the improvement of thermal conductivity and performance of low temperature energy storage system of solar pond. Digest Journal of Nanomaterials and Biostructures, 7(4), 1833-1841.

[16] Al-Waeli, A. H., Sopian, K., Chaichan, M. T., Kazem, H. A., Hasan, H. A., & Al-Shamani, A. N. (2017). An experimental investigation of SiC nanofluid as a base-fluid for a photovoltaic thermal PV/T system. Energy Conversion and Management, 142, 547-558.

[17] Al-Waeli, A. H., Sopian, K., Chaichan, M. T., Kazem, H. A., Ibrahim, A., Mat, S., & Ruslan, M. H. (2017). Evaluation of the nanofluid and nano-PCM based photovoltaic thermal (PVT) system: an experimental study. Energy Conversion and Management, 151, 693-708.

[18] Velraj, R. V. S. R., Seeniraj, R. V., Hafner, B., Faber, C., & Schwarzer, K. (1999). Heat transfer enhancement in a latent heat storage system. Solar energy, 65(3), 171-180.

[19] Kakaç, S., & Pramuanjaroenkij, A. (2009). Review of convective heat transfer enhancement with nanofluids. International journal of heat and mass transfer, 52(13-14), 3187-3196.

[20] Tse, K. K., Chow, T. T., & Su, Y. (2016). Performance evaluation and economic analysis of a full scale water-based photovoltaic/thermal (PV/T) system in an office building. Energy and Buildings, 122, 42-52.

[21] González-Longatt, F. M. (2005). Model of photovoltaic module in Matlab. Ii Cibelec, 2005, 1-5.

[22] Wolf M, Performance analysis of combined heating and photovoltaic power systems for residences. Energy Conversion and Management 1976; 16:79-90.

[23] Kern ECJ, Russell MC, Combined photovoltaic and thermal hybrid collector systems. IEEE Photovoltaic Spec Conf., 1978; 1:1153-7.

[24] Fujisawa, T., & Tani, T. (1997). Annual exergy evaluation on photovoltaic-thermal hybrid collector. Solar energy materials and solar cells, 47(1-4), 135-148.

[25] Ibrahim, A., Fudholi, A., Sopian, K., Othman, M. Y., & Ruslan, M. H. (2014). Efficiencies and improvement potential of building integrated photovoltaic thermal (BIPVT) system. Energy Conversion and Management, 77, 527-534.

[26] Fudholi, A., Zohri, M., Jin, G. L., Ibrahim, A., Yen, C. H., Othman, M. Y., ... & Sopian, K. (2018). Energy and exergy analyses of photovoltaic thermal collector with∇-groove. Solar Energy, 159, 742-750.

[27] World Weather and Climate Information. [Online]. Available: https://weather-and-climate.com/average-monthly-Rainfall-Temperature-Sunshine,bangi-selangor-my,Malaysia (retrieved: 4th August 2019).

[28] Kline, S. J. (1953). Describing uncertainty in single sample experiments. Mech. Engineering, 75, 3-8.