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Energy and Exergy Analyses of Photovoltaic-Thermal (PV/T) System with TiO₂/Water Nanofluid Flow

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Abstract. Nanofluids are a new generation of heat-transfer fluid with higher thermal conductivity and improved heat-transfer rate compared with conventional fluids. In this study, TiO₂/water (0.5wt% and 1.0wt% TiO₂ in water) nanofluids were used as a coolant to investigate a PV/T system under solar-radiation levels of 700 and 900 W/m² and mass-flow rate ranging from 0.012 kg/s to 0.0255 kg/s. The TiO₂/water nanofluid-based PV/T collector produced PV/T efficiency of approximately 75% to 90% with 9.9% to 10.6% PV efficiency and 65% to 80% thermal efficiency. Meanwhile, the PV/T exergy was between 53 and 73 W with thermal exergy of 6.3 W to 11.9 W and electrical exergy of 46.7 W to 60.1 W.

1. Introduction

A PVT collector combines the functions of PV panel and a flat plate solar collector. In 1978, Kern and Russel introduced the concept of PVT collectors using water or air as a heat removal fluid. These collectors can be classified based on the type of working fluid used: PVT water, PVT air and PVT water/air collectors.

Many experiment studies focused on the size, arrangement, and type of fluid used for cooling in PV/T. However, studies by using nanofluid as a coolant is still at an early stage. As it enhances heat transfer process substantially, the significant increase in thermal conductivity even high when low concentration of nanoparticle added in fluid was concluded by many researchers [1]. Sardarabadi et al. [2] conducted an experiment on the effect of silica/water nanofluid on PV/T and found that the total exergy for 1wt% and 3wt% increased by 22.61% and 23.31% compared with the PV system with no collector.

Yousefi et al. [3] investigated the efficiency of flat plate solar water heater collector by varying the mass-flow rate and volume concentration of alumina nanofluid. The result drew that by increasing mass-flow rate from 1 L/min to 3 L/min, the efficiency of solar collector increased at a constant volume concentration. Xu and Kleinstreuer [4] showed that PV/T concentration by using nanofluid is suitable for silicon solar cell compared with multi-junction solar cells, and the overall energy conversion efficiency of the CPV/T system is higher than that of conventional system.

Exergy analysis has become an essential tool in the system design, analysis, and optimisation of solar energy systems [5]–[12]. However, the main objective of this study is to investigate the efficiency of PVT system by using titania/water nanofluid (TiO₂/water) as the cooling fluid in terms



of energy and exergy analysis. The effect of different mass flow rates on the generation of electrical and thermal energy is also evaluated. The overall energy and exergy outputs are calculated from thermal and electrical energy presented.

2. Performances Analyses of Photovoltaic-Thermal (PV/T) System with TiO₂/Water Nanofluid Flow: an Experimental Study

2.1. Material and Methods

The experiments were carried out in Solar Lab at Level 3 of Physics Building, National University of Malaysia. Figure 1 shows the setup of the PV/T collector during the indoor experiment under a solar simulator which regulated at 700 and 900 W/m². In this experiment, standard PV panel of 1.2 m × 0.5 m with a width of 0.0045 mm at a rate of 80 W power was used. The ambient temperature and other temperatures (inlet, outlet, and PV) were measured using a K-type thermocouple and located at several places around the PV/T collector.

The radiation from simulation lamp was measured by a pyranometer, recorded to the computer linked to the data logger ADAM Data Acquisition System. The conducted study was a closed-loop system which the fluid was circulated through the heat exchanger and pump was used to pumped the coolants into the inlet fluid tank. Both water and titania/water nanofluid (TiO₂/water) has been tested as coolants in this experiment. Apart from that, the properties of the nanofluid used, has been stated as shown in Table 1 below.

Table 1. Fluid properties.

| Fluid | Particle Size (nm) | Density (kg/m ³) | Heat Capacity (J/kgK) | Thermal Conductivity (W/mK) |
|-------------------------|--------------------|------------------------------|-----------------------|-----------------------------|
| TiO ₂ /water | 25 | 3900 | 690 | 8.9 |

The specific heat capacity and density of the prepared nanofluid can be calculated from water and nanoparticle characteristics at the bulk temperature by using the given equations of Xuan and Roetzel [13].

$$C_{p_{nf}} = \frac{\phi(\rho C_p)_{np} + (1-\phi)(\rho C_p)_{bf}}{\rho_{nf}}, \quad (1)$$

and

$$\rho_{nf} = \phi \rho_{np} + (1 - \phi) \rho_{bf}. \quad (2)$$

The efficiency analysis of PV/T system was evaluated from thermal and electrical efficiencies. The rate of heat transfer from the thermal solar collector was based on measuring the temperature of fluid flow in and out. The overall efficiency can be calculated from the total of thermal efficiency and electrical efficiency, known as the PV/T efficiency [14] [15].

$$\eta_{pvt} = \eta_{th} + \eta_{el}. \quad (3)$$

Where

$$\eta_{el} = \eta_r(1 - \beta(T_c - T_r)), \quad (4)$$

where η_r is the reference efficiency of the PV module ($\eta_r=0.12$), β is the temperature coefficient ($\beta = 0.0045 \text{ } ^\circ\text{C}$), T_c is the cell temperature, and T_r is the reference temperature.

The thermal efficiency can be calculated as [16]–[17]

$$\eta_{th} = \frac{Q_u}{IA_c}, \quad (5)$$

where the rate of useful thermal energy can be calculated as follows:

$$Q_u = m_f C_p (T_{f,out} - T_{f,in}), \quad (6)$$

where m_f is the fluid mass flow rate, C_p is the fluid specific heat capacity, and $T_{f,in}$ and $T_{f,out}$ are the fluid inlet and outlet temperatures.

Exergy analysis adopts the conservation of the second law of thermodynamics for the analysis, design and improvement of energy (and other) systems. This method can be used to identify efficient energy use because it determines the location, type and magnitude of wastes and losses. Exergy analysis can indicate whether a design of an energy system is efficient and by how its efficiency could be improved by reducing the inefficiencies in the system. The overall exergy output of the PVT system can be expressed in the form given as follows [14] [15]:

$$\sum Ex_o = \sum Ex_{th} + \sum Ex_{pv}: \quad (7)$$

where

$$Ex_{th} = Q_u \left(1 - \frac{T_a + 273}{T_o + 273} \right), \quad (8)$$

and

$$Ex_{pv} = \eta_c A_c N_c I_{ex}, \quad (9)$$

where

$$I_{ex} = Ex_{in} = IA \left[1 - \frac{4}{3} \left(\frac{T_a}{T_s} \right) + \frac{1}{3} \left(\frac{T_a}{T_s} \right)^4 \right], \quad (10)$$

where I is the solar radiation, T_a is the ambient temperature, and T_s is the sun temperature ($T_s = 5777K$).

3. Results and Discussion

In this study, the effect of mass-flow rate and solar-radiation levels on the performance of PV/T system were obtained. Two types of working fluid were used, namely, distilled water and different concentrations of $\text{TiO}_2/\text{water}$. The radiation changed from 700 W/m^2 to 900 W/m^2 . The experimental results for the variation of temperatures (ambient, inlet, outlet, and PV) under different mass flow rates

and working fluid are shown in Figure 1 to Figure 4. The PV surface temperature reduction was high with increasing mass-flow rate. At 700 W/m^2 , the surface reductions recorded at 0.026 kg/s for $0.5\text{wt}\%$ $\text{TiO}_2/\text{water}$ and $1.0\text{wt}\%$ $\text{TiO}_2/\text{water}$ were 16.05°C and 18.28°C , whereas the surface reductions at 900 W/m^2 for the same condition of working fluid were 11.67°C and 12.3°C .

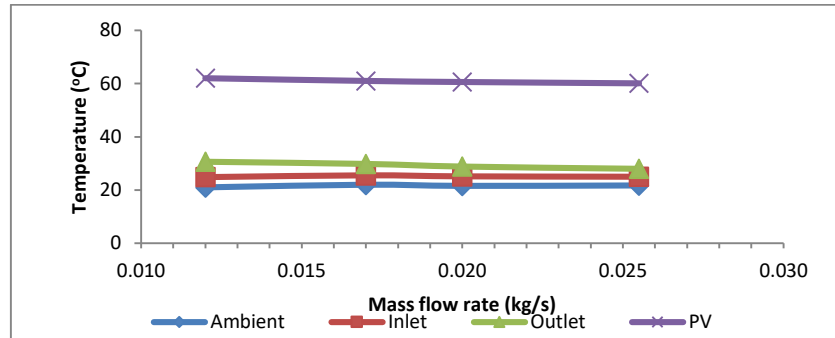


Figure 1. Temperatures (ambient, inlet, outlet, and PV) of $0.5\text{wt}\%$ $\text{TiO}_2/\text{water}$ nanofluid-based PV/T collector at a solar-radiation levels of 700 W/m^2

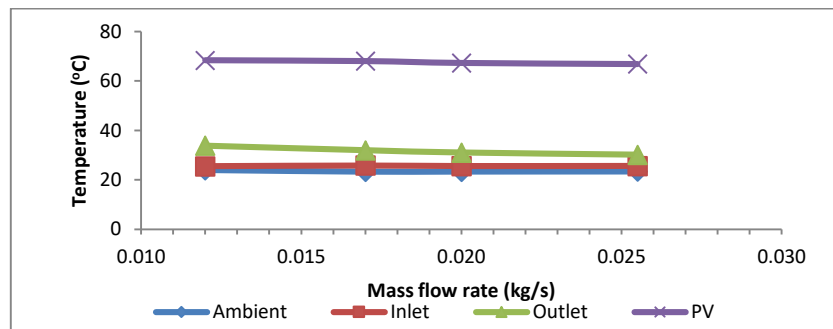


Figure 2. Temperatures (ambient, inlet, outlet, and PV) of $1.0\text{wt}\%$ $\text{TiO}_2/\text{water}$ nanofluid-based PV/T collector for a solar-radiation levels of 700 W/m^2

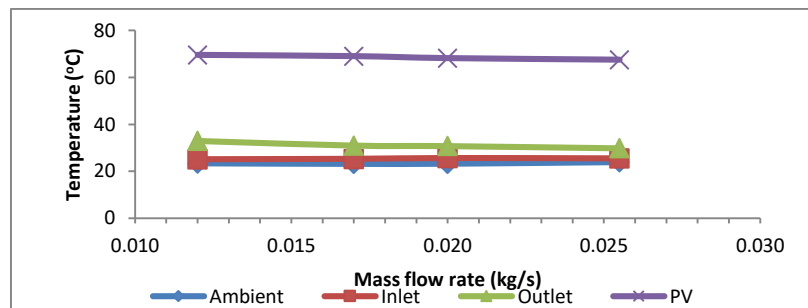


Figure 3. Temperatures (ambient, inlet, outlet, and PV) of $0.5\text{wt}\%$ $\text{TiO}_2/\text{water}$ nanofluid-based PV/T collector for a solar-radiation levels of 900 W/m^2

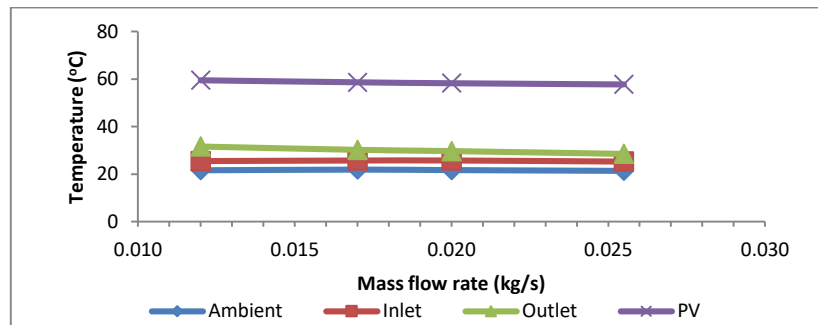


Figure 4. Temperatures (ambient, inlet, outlet, and PV) of 1.0wt% TiO₂/water nanofluid-based PV/T collector for a solar-radiation levels of 900 W/m²

Tables 1 and 2 show the thermal, electrical, and PVT efficiencies calculated at solar radiations of 700 and 900 W/m² under mass-flow rate ranging from 0.012 kg/s to 0.0255 kg/s. The thermal and PVT efficiency was produced from approximately 65% to 76% and 75% to 86% at 700 W/m², respectively. For 900 W/m², the thermal and PVT efficiencies were produced from approximately 65% to 80% and 75% to 90%, respectively. This result indicated that mass-flow rate increased the heat-transfer rate from the fluid to the surface of PV module. The thermal efficiency increased by 3.27% and 4.16% from 700 W/m² to 900 W/m² solar-radiation levels for 0.5wt% TiO₂/water and 1.0wt% TiO₂/water.

Table 2. Energy analysis of TiO₂/water nanofluid-based PV/T collector for a solar-radiation levels of 700 W/m²: (a) for 0.5wt% and (b) for 1.0wt%

| (a) | | | | (b) | | | |
|--------|----------------|------------|--------|--------|----------------|------------|--------|
| m | Efficiency (%) | | | m | Efficiency (%) | | |
| (kg/s) | Thermal | Electrical | PVT | (kg/s) | Thermal | Electrical | PVT |
| 0.012 | 64.845 | 10.334 | 75.179 | 0.012 | 68.213 | 10.475 | 78.688 |
| 0.017 | 66.629 | 10.391 | 77.020 | 0.017 | 69.017 | 10.521 | 79.538 |
| 0.020 | 69.233 | 10.414 | 79.647 | 0.020 | 71.496 | 10.542 | 82.038 |
| 0.026 | 73.451 | 10.442 | 83.893 | 0.026 | 75.524 | 10.570 | 86.094 |

Table 3. Energy analysis of TiO₂/water nanofluid-based PV/T collector for a solar-radiation levels of 900 W/m²: (a) for 0.5wt% and (b) for 1.0wt%

| (a) | | | | (b) | | | |
|--------|----------------|------------|--------|--------|----------------|------------|--------|
| m | Efficiency (%) | | | m | Efficiency (%) | | |
| (kg/s) | Thermal | Electrical | PVT | (kg/s) | Thermal | Electrical | PVT |
| 0.012 | 64.786 | 9.914 | 74.700 | 0.012 | 69.030 | 9.978 | 79.008 |
| 0.017 | 66.598 | 9.943 | 76.541 | 0.017 | 72.242 | 9.996 | 82.238 |
| 0.020 | 71.090 | 9.989 | 81.079 | 0.020 | 75.456 | 10.037 | 85.493 |
| 0.026 | 76.726 | 10.026 | 86.752 | 0.026 | 79.682 | 10.061 | 89.743 |

The reference system in this experiment is referred to the PV panel without the cooling system. The result also draws that the working fluid with the best thermal performance is $\text{TiO}_2/\text{water}$ 1.0wt% compared with the others.

The reference PV electrical efficiencies is 9.38% for 900 W/m^2 . The increment in electrical efficiency compared with the reference system for 0.5wt% $\text{TiO}_2/\text{water}$ and $\text{TiO}_2/\text{water}$ 1.0wt% are 6.95% and 7.32%, respectively, at 900 W/m^2 solar radiation. The thermal and electrical outputs are calculated from Eqs. (3) and (6) for both cases of solar radiation. The thermal and electrical outputs were 460.83 and 46.12 W for 0.5wt% $\text{TiO}_2/\text{water}$ and 343.94 W and 47.44 $\text{TiO}_2/\text{water}$ 1.0wt%, respectively

The exergy analysis was conducted using Eqs. (7) to (10) for both cases of solar radiation. The thermal and electrical exergies for 700 W/m^2 radiation were 5.786 and 46.534 W and as for 900 W/m^2 radiation, the thermal and electrical outputs were 8.858 and 58.828 W. The PVT exergies were 52.32 and 67.68 W for 700 and 900 W/m^2 , respectively.

4. Conclusions

Based on the testing performed on the collector, both efficiencies increased when the mass-flow rate increased. Therefore, the total efficiency (PV/T efficiency) increased concurrently when the mass-flow rate increased. Energy and exergy were analysed, and the results showed energy outputs of 521 and 539 W and 362 and 391 W for 0.5wt% $\text{TiO}_2/\text{water}$ and 1.0wt% $\text{TiO}_2/\text{water}$ at solar radiations of 700 and 900 W/m^2 , respectively. Meanwhile, the total exergy output of PV/T systems with distilled water 0.5wt% $\text{TiO}_2/\text{water}$, and 1.0wt% $\text{TiO}_2/\text{water}$ were compared with those of the PV panel without a cooling system. The exergy of the two cases increased by 24.05% and 27.42% for 700 W/m^2 , as well as 26.85% and 28.5% for 900 W/m^2 , respectively.

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