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Computational fluid dynamics modelling and experimental analysis of a Photovoltaic Thermal system with spiral absorber using hybrid TiO_2 – MWCNT nanofluid

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Abstract.

The temperature increase of the PV panel reduces the electrical efficiency of the module. In order to boost electrical efficiency, the temperature of the PV panel is decreased by working fluids such as water and water based TiO_2 -MWCNT hybrid nanofluid. The pattern of the absorber is spiral. The spiral flow absorber collector is a steady loop. This model was implemented to determine the total heat gain and total combined efficiency of the PV module. The findings show that total thermal performance, optimum thermal output and electrical performance achieved by TiO_2 –MWCNT nanofluid is more compared with water. In the nanofluid coefficient of convective heat transfer is higher than that of the base liquid at the same mass flow rate. For a mass flow rate of 0.01 kg / sec, the maximum thermal efficiency and electrical efficiency obtained are 52.8 per cent and 8.6 per cent, respectively, relative to the simulation results.

Keywords: Photovoltaic Thermal system, TiO_2 -MWCNT, Electrical Efficiency, Thermal efficiency, Nanofluid

1. Introduction

Hybrid photovoltaic-thermal system is a hybrid of both photovoltaic panels and thermal collectors. Hybrid photovoltaic thermal system produces both electricity and thermal simultaneously. Zondag et.al. [1] checked on the PVT collector network with various combinations. Tripanagnostopoulos et.al [2] evaluated that the system performance can be enhanced by using dual media for the heat transfer process. Air and water are used for the heat removal process. Chow et al. [3] studied PVT hybrid solar energy and concluded that more research work has to be carried out including design and manufacture of thermal absorbers,



should be carried out. Dupeyrat et.al.[4] has experimentally studied the efficiency of the collector type as part of the solar thermal system and explained the development and test results of an experimental flat-plate PVT collector.

Keizer,et.al [5] performed experiment on an un insulated PVT collector , collector with insulation and integrated with building steady state analysis has been carried out and typical collector curves are provided. Suhaila et.al [6] developed a thermal model of a PVT system. They use photovoltaic panels with a mix of air-and water-based systems as a single package. Niccolò et.al. [7] experimentally tested and modeled on the PVT collector device with water as a working medium without any glass cover. Lammle et.al. [8] provided a systematic analysis of low-emissivity of PVT collectors with glazing and without it. Al-Waeli, et.al. [9] examined, planned and researched thermal and electrical side-views of PV / T systems. JaharSarkar, et.al.[10] reviewed the use of hybrid nanofluids. The findings indicate that hybrid nanofluids comprising composite nanoparticles have substantial increases in both increase in thermal conductivity and also heat transfer coefficient. Sundar et.al. [11] submitted a review on hybrid nanofluids. The heat transfer properties of nanofluids depend primarily on the thermophysical properties of nanoparticles, the concentration of particle and the rate of mass flow. Yazdanifard, et.al.[12] analyzed the performance of a nanofluid-based photovoltaic thermal system. Babu, et.al.[13] evaluated hybrid nanofluids. Nanofluids play a significant role in the application of heat transfer due to their special characteristics. Several researchers have focused on hybrid nanofluids for various applications. Ali Najah et.al [14] experimentally studied thermal photovoltaic (PVT) flat plate collectors. They are categorized according to the type of fluid used, namely water- PVT collectors, air- PVT collectors and a combination of water and air PVT collectors. Sardarabadi, et.al. [15] experimentally studied the results of using Metal-Oxides / Water Nanofluids on the Photovoltaic Thermal System (PVT). Nanoparticles are known to contain Al_2O_3 , TiO_2 and ZnO distributed in deionized water as a base fluid by 0.2 wt per cent. Thermal conductivity and viscosity of ethylene glycol-based hybrid nanofluid with $\text{TiO}_2\text{--CuO}$ were experimentally tested. Herrando et al. 2019 performed a comparison between 26 PV/Ts with different absorber designs and a reference, commercial sheet-and-tube PV/T collector. A comparison of a combination of PV and ST modules to PV/T in a solar combined cooling, heating and power (CCHP) system was made by Kamel et al 2019. PVT single-sided roll-bond absorber with a refrigerant as the working fluid was used in a tri-generation performance analysis. The absorber with its unique design is theoretically operating at one-quarter of the pressure drop compared to the standard serial absorber. (Zhou et al 2019). Numerical and experimental energy and exergy performance assessments of solar thermal (ST), photovoltaic (PV) and photovoltaic/thermal (PV/T) modules based on roll-bond heat exchangers having three different channel geometries: serial, parallel and bionic was carried out by Poredoš et al. (2020). The thermal efficiency of the system is inversely proportional to the area of the solar absorber and incident solar radiation (Micheal *et al* 2015). Hence by reducing the area of the absorber the overall efficiency could be improved. The flattened tube absorber is selected such that it covers minimal area and optimum thermal contact is established with the PV module. The flattened tube absorber is an alternative to the traditional sheet and tube absorber used mostly in the literature.

2 SYSTEM DESCRIPTION

Solar energy is incident on the PV module consisting of a flattened tube spiral flow arrangement is attached at bottom of the PV module. The layout of the experimental setup is shown in figure 1. Polystyrene is used as insulating material to avoid the heat loss. The tank is used to store the hot water, 304 stainless steel is used to make the storage tank. The polyurethane foam is used as the insulating material of the storage tank.

The (TiO₂- MWCNT) nanofluid is prepared. Volumetric fraction of TiO₂-MWCNT nanofluid has improvement in performance was observed in forced circulation. The (TiO₂- MWCNT) nanofluid is prepared. Volumetric fraction of TiO₂-MWCNT nanofluid has improvement in performance was observed in forced circulation. The thermal performance of the collector was studied. The thermophysical properties of the TiO₂, MWCNT, and TiO₂-MWCNT at 27°C with average particle diameter ($d_p = 40$ nm) are calculated and tabulated below as shown in table 1.

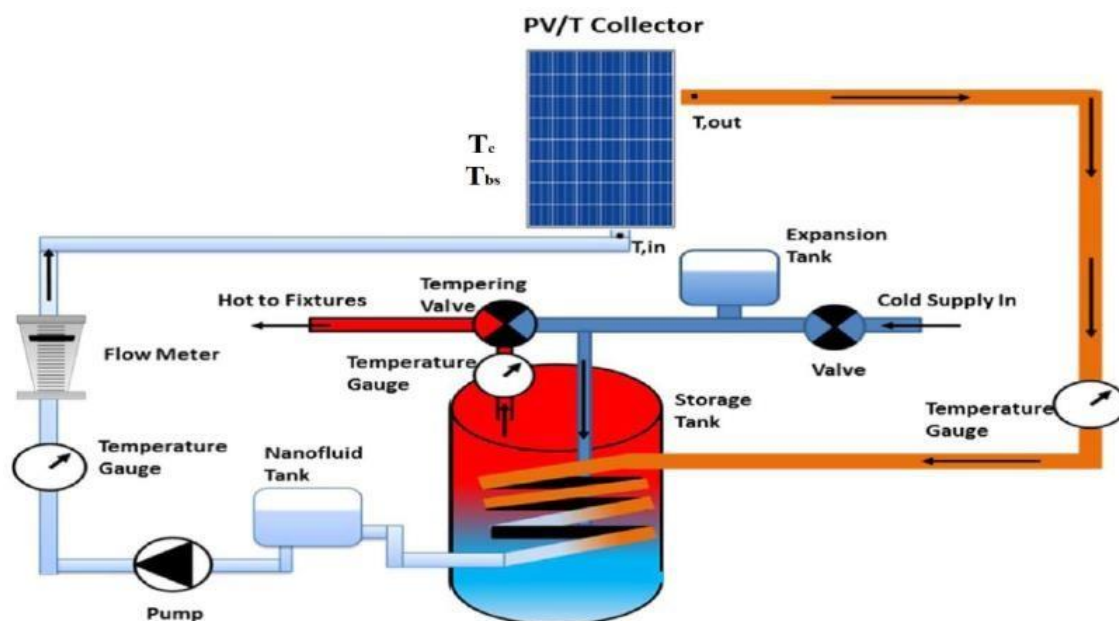


Figure 1 Schematic Diagram of the PVT experimental setup

Properties	Working fluids	
	Water (27°C)	TiO ₂ -MWCNT
Density	998.25 kg/m ³	1010 kg/m ³
Specific heat	4178 J/kgK	3831.25 J/kgK
Thermal conductivity	0.6084 W/mK	1.0540 W/mK
Dynamic viscosity	8.823×10^{-4} Ns/m ²	1.57×10^{-3} Ns/m ²

Table.1. Thermo physical properties of water and TiO₂-MWCNT nanofluids

3 EXPERIMENTAL ANALYSIS

The experiments were conducted by fabricating the absorber and analysing the performance of the absorber using different flow rates.

Fabrication of the Absorber

The area of the collector plays a primary role in determining the efficiency of the collector. As the area of the collector is increased the efficiency of the system gets reduced. The major focus of this work is to increase the efficiency of the collector by reducing the area of the collector, and hence in this work an alternative design of collector is proposed and this replaces the conventional flat plate collector with header and riser arrangement. Flattened tube spiral flow absorber made of copper is used to extract the solar energy. In a solar thermal application, expanding the heat transfer area leads to increase in the outlet temperature. Flattened tube absorber is being considered as it allows more contact area compared to other types of absorbers. Flat tube is light weight and compact design which leads to reduction in design space and is economically viable for fabrication. Considering the geometry of the flattened tube the bottom and top walls are closer to one another and hence the temperature distribution is flat and better compared to other geometrical sections resulting in better heat transfer. The heat transfer coefficient of flat tube is higher than elliptical and circular tubes. The spiral flow configuration enhances the heat transfer to the fluid and hence as a result a higher outlet temperature of water could be obtained. The absorber was fabricated from single copper sheet using welding process. Copper sheet of thickness eighteen gauge is purchased which was then cut and welded to form flattened tube and then bent to form a spiral configuration. The absorber is then black coated and placed in a wooden box surrounded with insulation. Water enters into the absorber and passes through the whole length of the absorber and reaches the outlet. The length of the absorber is measured as 4.5 m. Water entering the flat tube inside gains the heat energy as it passes through the absorber and it is transferred to water that is contained in the storage tank with the spiral tube arrangement.

DESCRIPTION OF THE SYSTEM

The collector is kept at a slope of 23° in an open terrace of the building on a horizontal plane where the experiments are conducted at its Regional Campus of Anna University at Tirunelveli. The latitude and longitude of the test location $8^\circ 73'N$ and $77^\circ 7'E$ respectively. The experimental setup is placed facing south as the test location is situated at the northern hemisphere. The experimental setup consists of flattened tube spiral absorber with storage tank, rotometer, manometer, pump and temperature sensors.

EXPERIMENTAL PROCEDURE

The experiments are conducted in the month of April 2018. The experiment is started at 10.00 AM and ended at 3.30 PM. During the experiment water is filled in storage tank about 50 Litres and the working fluid is also charged inside the closed loop circulation. Then fix the mass flow rate of the working fluid used in system. Solar radiation directly falls on the PVT system and

produce electricity and temperature of the panel get increased. By passing the fluid through the thermal collector the heat is extracted from the panel and temperature of panel get reduced. This process continued over a running period of the system and temperature is maintained. During the period of experiment various temperatures and solar intensity is measured for every half an hours. The same experiment conducted for both water and hybrid nanofluid (TiO_2 -MWCNT) for similar solar intensity data. The experiment is started at morning 10.00 AM and ended at evening 3.30 PM since, solar radiation is effective on 9.00 AM to 4.00 PM. Average hourly global radiation (W/m^2) on horizontal surface, average ambient temperature and wind speed is determined experimentally. The view of the experimental setup is shown in figure 2.

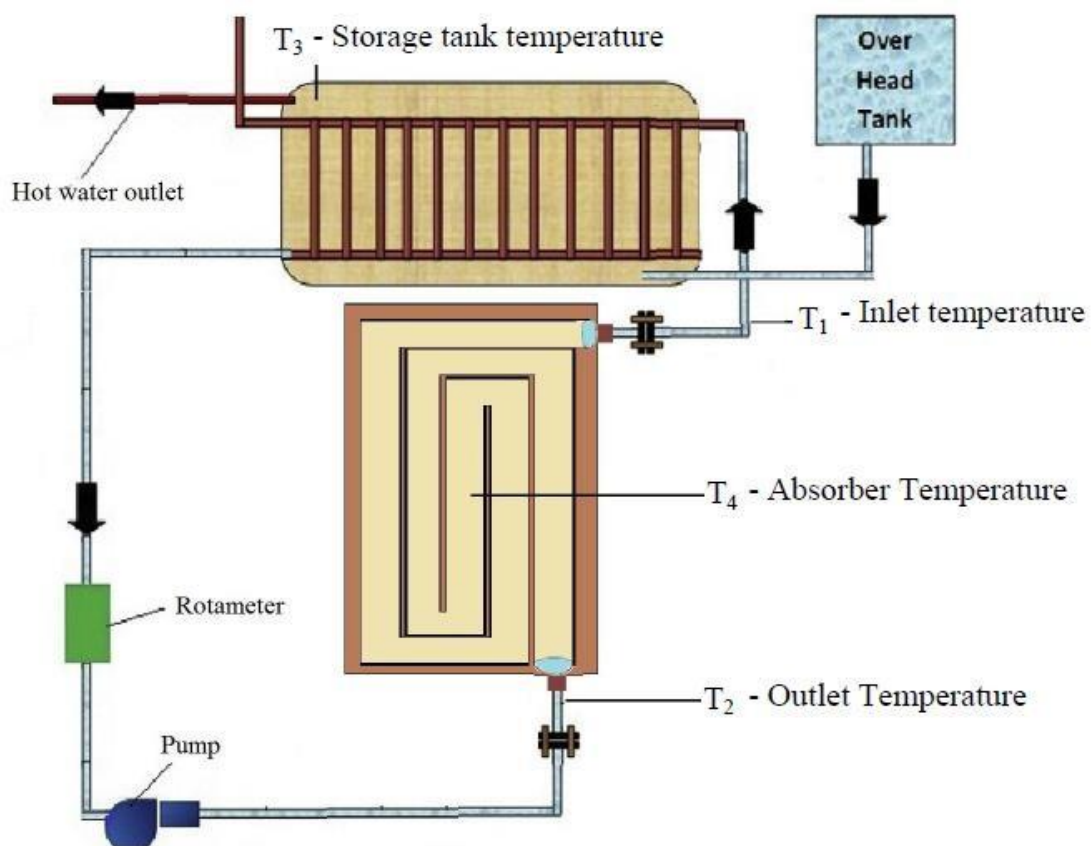


Figure 2 Photograph of experimental setup

PREPARATION OF TiO_2 -MWCNT NANOFLUID

Nanofluid is a colloidal solution in which the nanoparticles are dispersed in the base fluid. Since focus of this work is to study the heat transfer properties nanoparticles available commercially from Alpha Acer Ltd is purchased. Titanium oxide nanoparticle is chosen because of its lesser cost and easy availability and easy dispersion in the base fluid and MWCNT is chosen for its good thermophysical properties. Appropriate scattering of nanoparticle in base fluid is a basic factor in the preparation of nanofluid.

Even after proper mixing with the base fluids the nanoparticles are tend to agglomerate after a particular time period due to the high surface energy of the particle. Ultrasonication is a process that is mostly adopted for the preparation of nanofluid. Amount of working fluid required for circulation is found to be 7 litres. The amount of TiO_2 -MWCNT required for preparation of required quantity nanofluid for 0.1% volume concentration. The following procedure to prepare TiO_2 -MWCNT nanofluid is first CNT is functionalized by treating with HNO_3 - H_2SO_4 at 1:3 v/v for 3 hours at 700C to transform the CNT's from hydrophobic to hydrophilic. 1 ml of TiO_2 is also added by drop wise and continued sonication.

4. RESULTS AND DISCUSSION

VARIATION OF SOLAR INTENSITY AND AMBIENT TEMPERATURE WITH RESPECT TO TIME

The variation of solar intensity and ambient temperature with time is shown in figure 3. The solar intensity at 10:00 am is 660 W/m^2 , the atmospheric temperature and solar intensity reaches the maximum in between 11:00 am to 1:00 pm because solar radiation falls directly on horizontal PV panel.

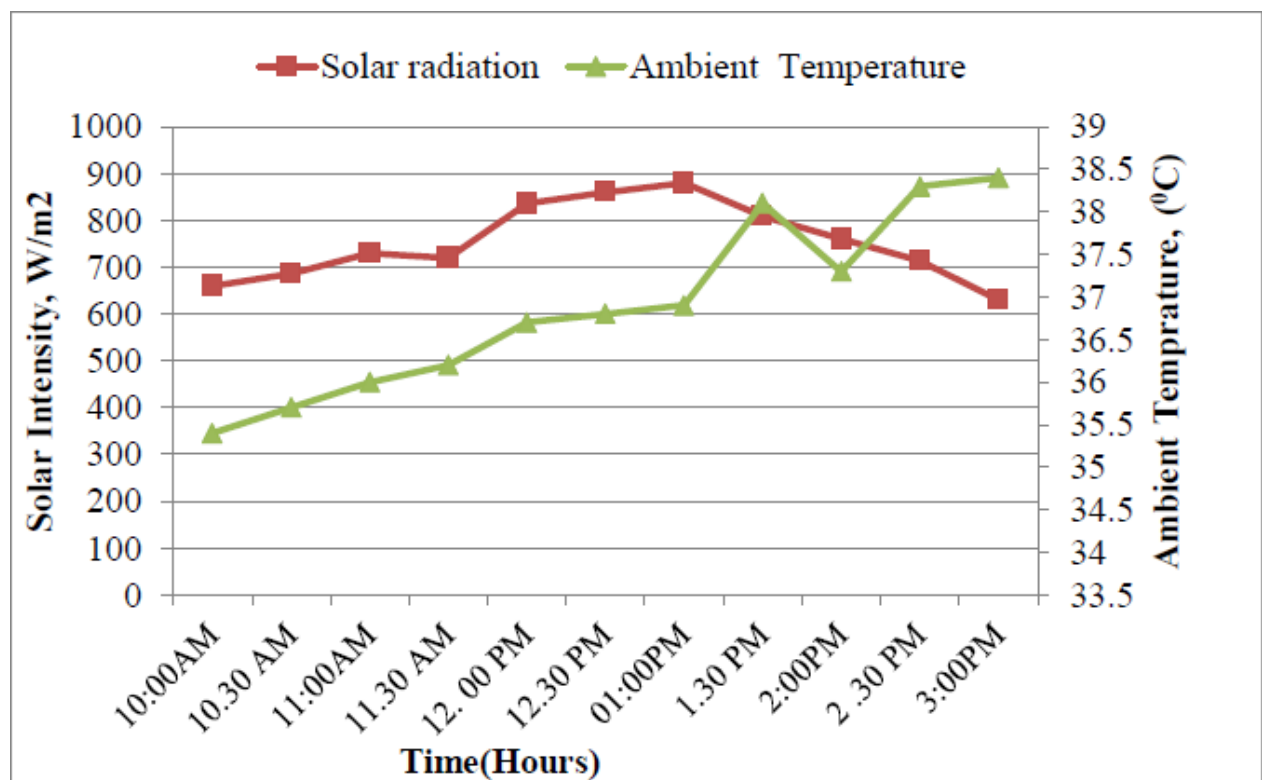


Figure 3 Hourly variation of solar intensity and ambient temperature

CELL TEMPERATURE OF PVT AND PV MODULE WITH RESPECT TO TIME FOR WATER AND TiO₂-MWCNT.

Figure 4 shows the experimental values of the cell temperature for PVT and PV module when water as working fluid. The cell temperature of PV is more than PVT since the fluid flow under the PV panel to reduce the temperature. The maximum temperature for cell reached is 58.11°C for PVT and 60.22°C for PV module. The maximum temperature difference between PVT and PV is about 2.106°C for water used as a working medium.

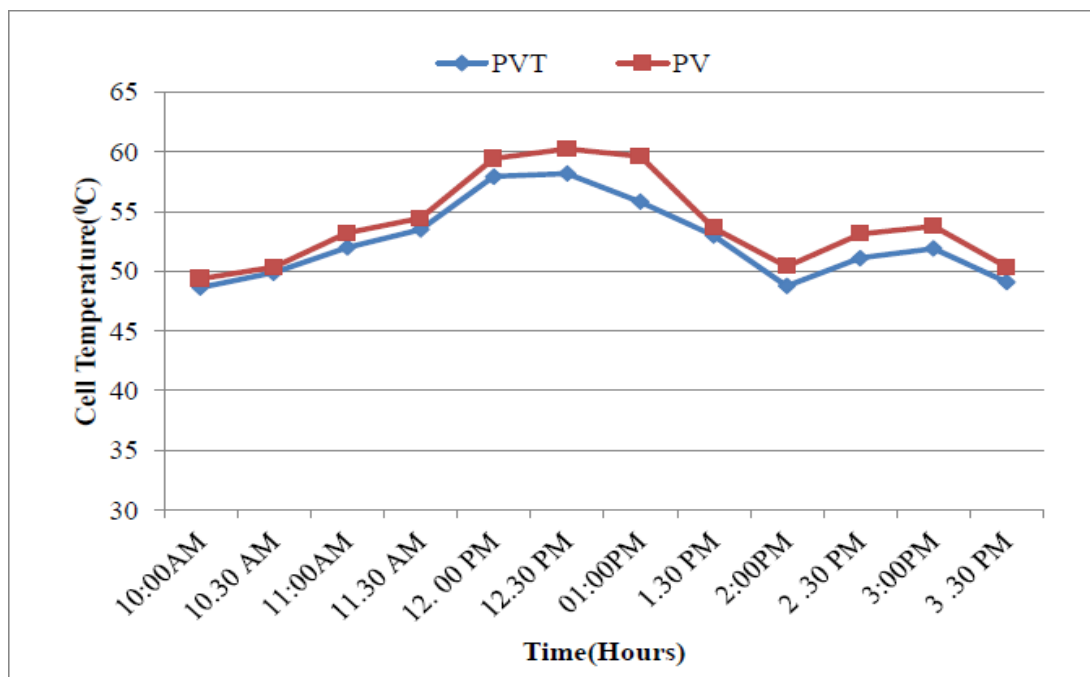


Figure 4 Hourly variation of cell temperature for PVT and PV when water as working medium

Figure 5 shows the experimental values of the cell temperature for PVT and PV module when TiO₂-MWCNT as working fluid. The maximum temperature for cell reached is 57.53°C for PVT and 60.7°C for PV module. The maximum temperature difference between PVT and PV is about 3.17°C.

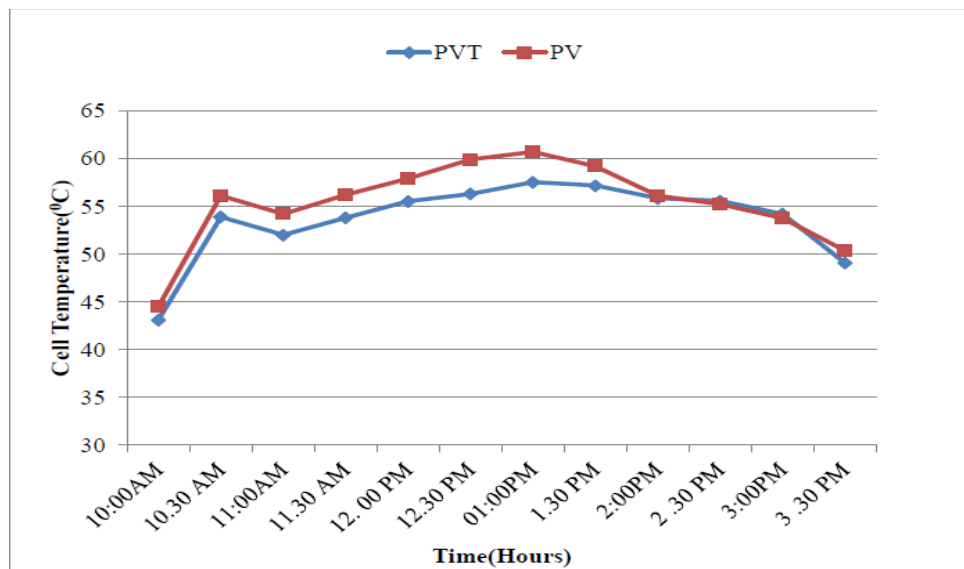


Figure 5 Hourly variation of cell temperature for PVT and PV when TiO_2 -MWCNT as working medium

TEMPERATURE WITH RESPECT TO TIME FOR WATER AND TiO_2 -MWCNT.

The temperature at the PVT module for water and TiO_2 -MWCNT are calculated for mass flow rate of 0.133 kg/sec is shown in figure 4.4 and figure 4.5 respectively. The maximum outlet temperature is obtained for TiO_2 -MWCNT nanofluid. For water the maximum outlet temperature is calculated is 51.31°C and for TiO_2 -MWCNT nanofluid is 53.47°C and the tank temperature is about 50.9°C for water and 53.2°C for hybrid nanofluid TiO_2 -MWCNT which is shown in respective figures 6 and 7.

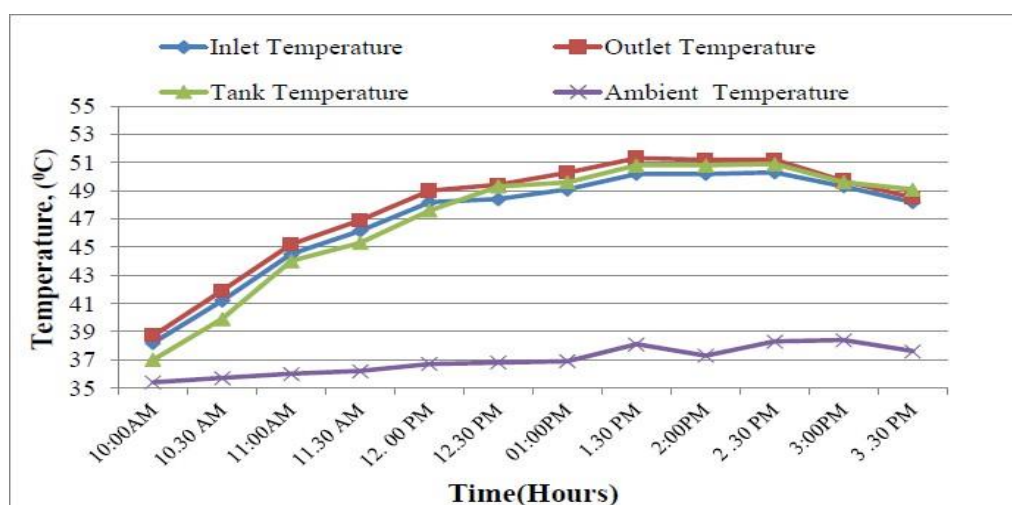


Figure 6 Hourly variation of outlet fluid temperature for water at constant mass flow rate

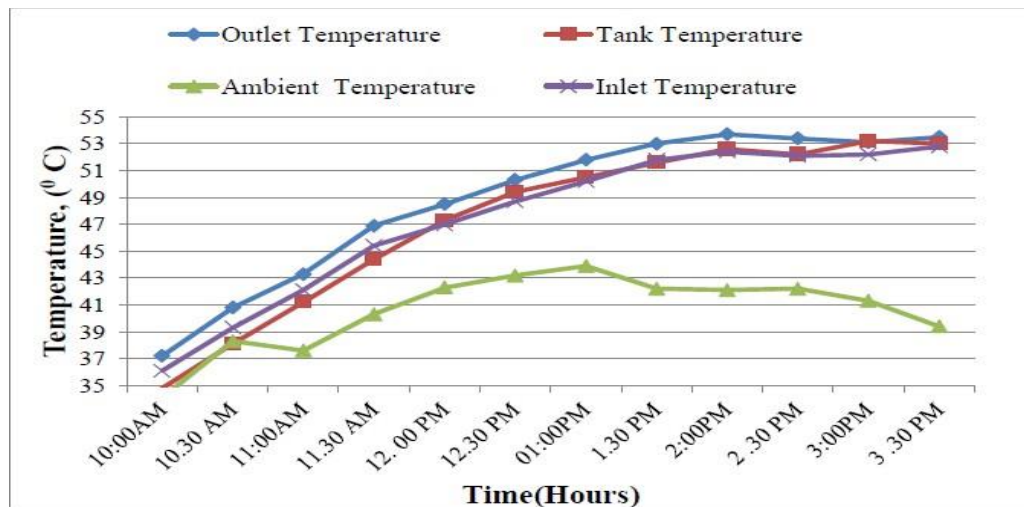


Figure 7 Hourly variation of outlet fluid temperature for TiO₂-MWCNT nanofluids at constant mass flow rate

USEFUL HEAT GAIN WITH RESPECT TO TIME FOR WATER AND TiO₂-MWCNT.

The maximum heat gain (Q_u) obtained for water is 341.08 W for solar intensity of 830 W/m² at 1:00 pm. Figure 8 shows hourly variation of thermal energy/energy gain for water for different solar intensity. The thermal energy gain increases with solar intensity and vice versa. The useful heat gain increases from 142.12 W to 341.08 W and then decreases to 85.27 W for water for constant mass flow rate 0.133 kg/sec.

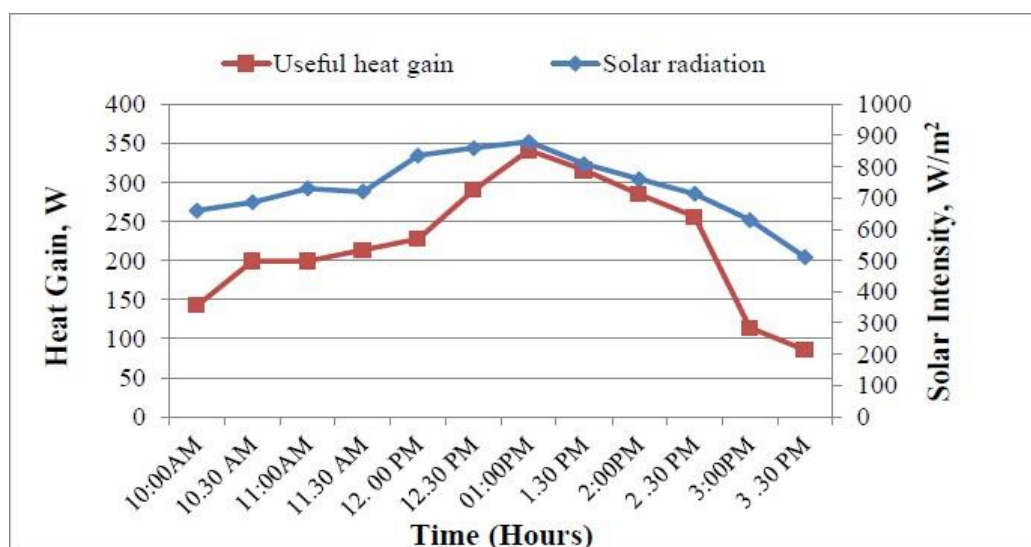


Figure 8 Hourly variation of thermal energy gain for working fluid water

The maximum heat gain (Q_u) obtained for TiO_2 -MWCNT nanofluid is 349.78 W for solar intensity of 830 W/m^2 at 12:30 pm. Figure 9 shows hourly variation of thermal energy/energy gain for different fluids for different solar intensity. The useful heat gain increases from 196.16 W to 349.78 W and then decreases to 198.96 W for TiO_2 -MWCNT nanofluid for constant mass flow rate 0.133 kg/sec. TiO_2 -MWCNT nanofluid has maximum outlet temperature and heat gain is also higher. For higher solar intensity, the difference in heat gain for TiO_2 -MWCNT nanofluid is higher while compare with lower solar intensity.

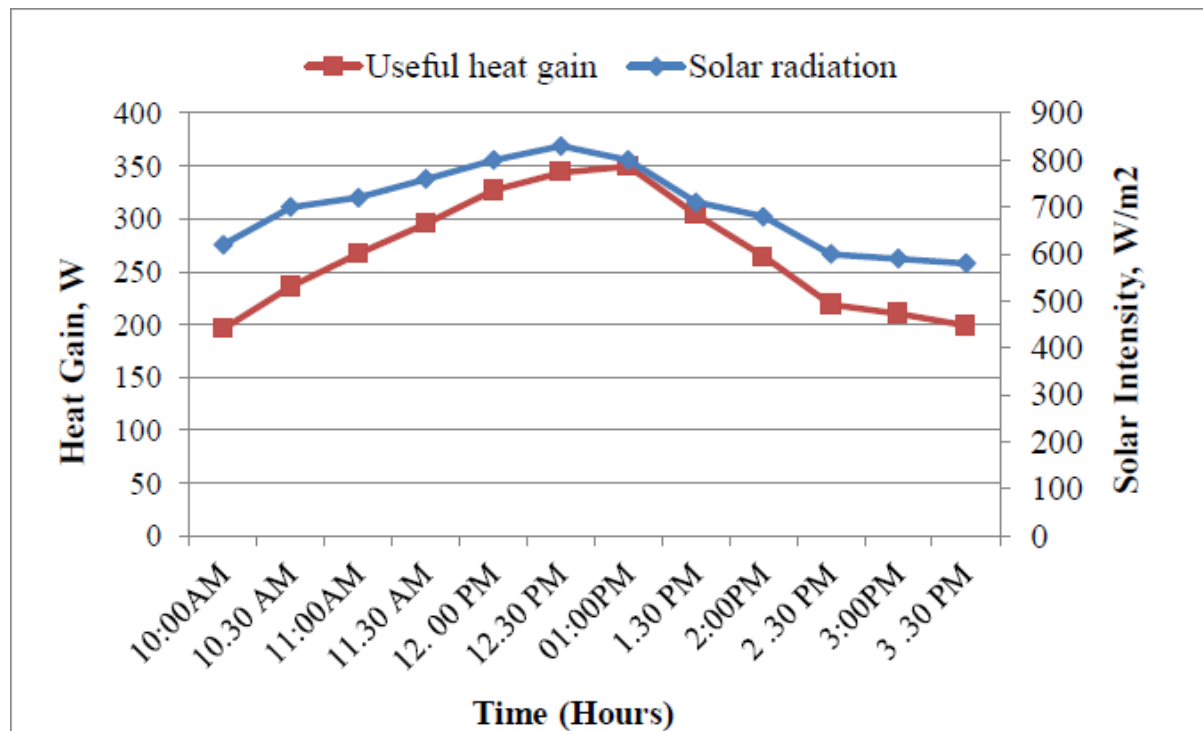


Figure 9 Hourly variation of thermal energy gain for TiO_2 -MWCNT nanofluid

ELECTRICAL EFFICIENCY WITH RESPECT TO TIME

Variations of electrical efficiency with respect to time are shown in following figure 10 and figure 11. At maximum cell temperature, the electrical efficiency is low. The electrical efficiency depends on cell temperature and ambient temperature. At cell temperature of 48.633°C, the electrical efficiency is 12.511% for water. At cell temperature of 43.10°C, the electrical efficiency is 12.859% for TiO_2 -MWCNT nanofluid. This electrical efficiency is only for mass flow rate of 0.133 kg/sec of water. If the heat extraction from PV panel is more, the cell temperature decreases, the electrical efficiency increases

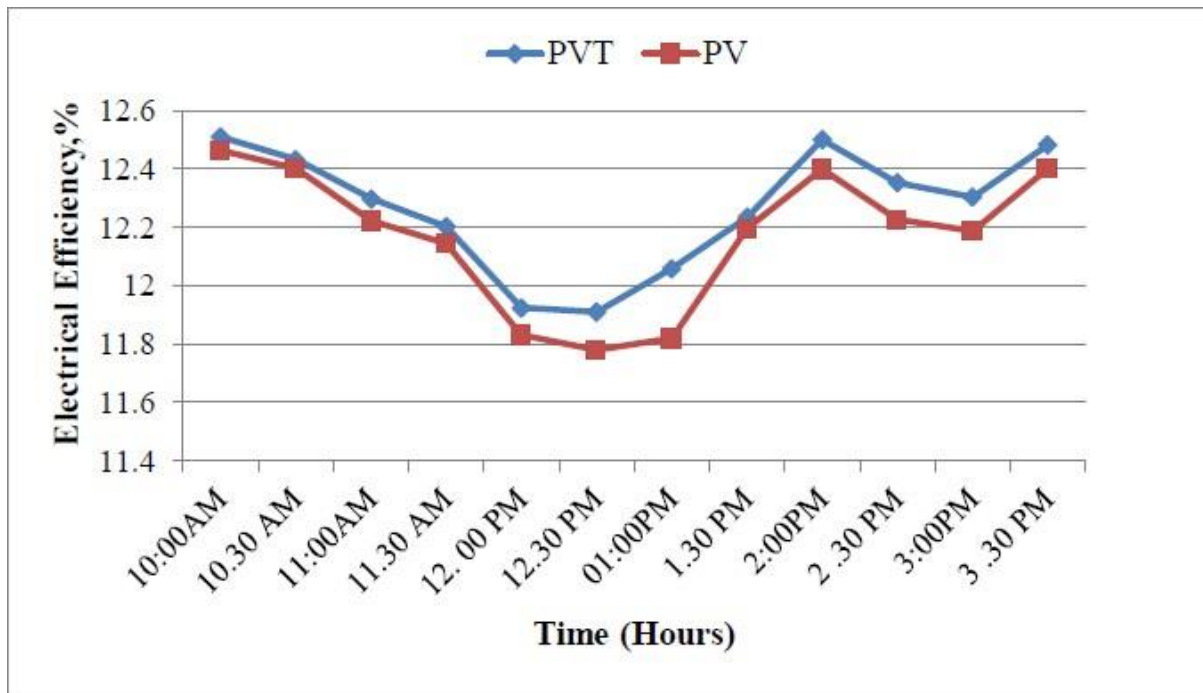


Figure 10 Variation of electrical efficiency with respect to time when water as working fluid

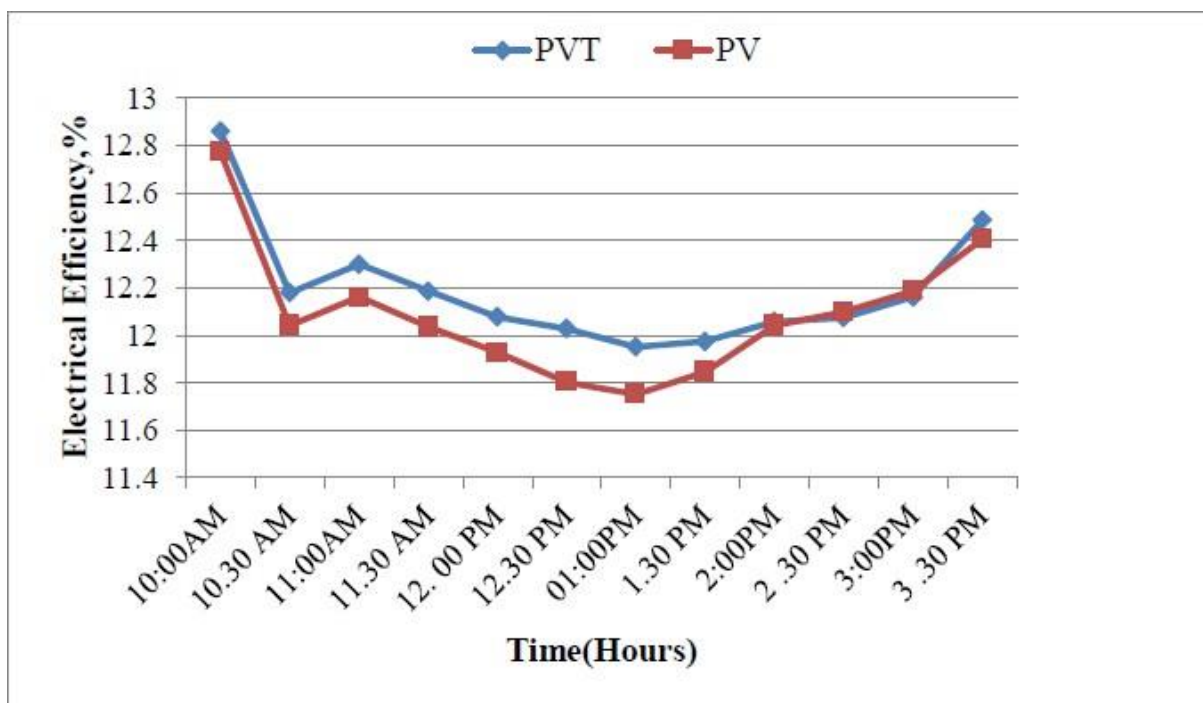


Figure 11 Variation of electrical efficiency with respect to time when TiO₂-MWCNT nanofluid as working fluid

THERMAL EFFICIENCY WITH RESPECT TO TIME

The maximum thermal efficiency is 51.45% for TiO_2 -MWCNT nanofluid and 45.91% for water for a mass flow rate of 0.133 kg/sec is shown in figure 12. The thermal efficiency mainly depends on the packing factor and the collector absorber area. Hence the packing factor nearly one, the thermal factor is low. The thermal efficiency varies from 37.24% to 51.45% for TiO_2 -MWCNT nanofluid and 25.35% to 45.91% for water.

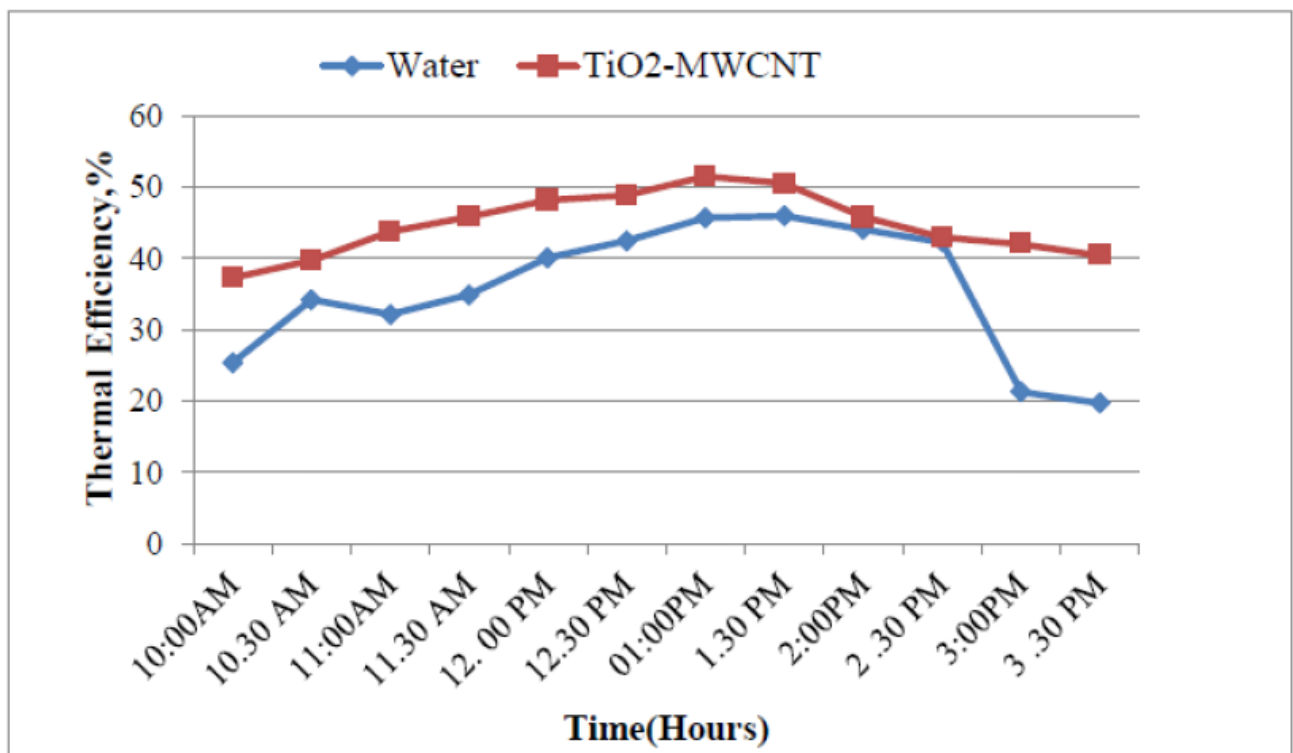


Figure 12 Variation of instantaneous thermal efficiency for water and TiO_2 -MWCNT mass flow rate of 0.133 kg/sec

Conclusion

By changing the design of the flat plate solar collector to spiral flow design with flat tube cross sectional area, the heat removal factor is more due to area covered. Thermal conductivity and heat transfer coefficient is increased due to increase in heat removal factor for nanofluid. Experimental analysis is carried out with water and hybrid (TiO_2 -MWCNT) nanofluid and results are given below. The temperature at the outlet temperature is gradually increased from 1.95% for 10 am to 4.8% for 2.00 pm, when water is compared with TiO_2 -MWCNT nanofluid. And useful heat gain constantly increased about 2.7% when time (hours) increases and thermal efficiency of the PV/T module is also get raised about 10% when compared to water. And electrical efficiency is also increased. Therefore efficiency of PVT module is more for TiO_2 -MWCNT nanofluid while comparing with water. The future work may involve the experimental investigation of the PVT system with the different absorber design. The base fluid of involved in the preparation of nanofluid could be replaced by other base fluids such as ethylene glycol.

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