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Original article

Energy analysis of solar powered hydrogen production system with CuO/water nanofluids: An experimental investigation

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ABSTRACT

Electrolysis is the process used to produce hydrogen using external electrical energy. Because of less initial and operating cost, less maintenance required, and simple construction, hydrogen production via water electrolysis has gained more attention among users globally. In this current attempt, a novel solar-powered hydrogen generation system was established and tested in different operating circumstances. Throughout the study, nanofluids with concentrations of 0.05%, 0.1%, and 0.2% were utilized, and their effect on electrical performance and hydrogen production rate was examined. Compared to conventional solar panels, the usage of nanofluids resulted in a significant improvement in electrical power productivity and hydrogen output rate. The highest electrical efficiency is with a 0.2% volume fraction of CuO/water nanofluids at 13.5% at Noon. During the same period, the lowest and highest hydrogen yield rates are found for the conventional PV module and 0.2% volume fraction CuO/water nanofluids-based system as 7.9 ml/min and 18.2 ml/min, respectively.

1. Introduction

Over the past few decades, our society has mainly depended on fossil fuels for energy production. As per the data, fossil fuels satisfy around 81% of energy demand. However, energy demand is increasing every day due to the increase in vehicle population and the modernization of industries. However, the rate at which fossil fuels are being depleted and emissions of greenhouse gases are rising dramatically (Muradov and Veziroğlu, 2008; Jacobson, 2009). Many developed and developing countries have accelerated using renewable energy sources in different applications to overcome these issues. As a result, researchers have started looking at hydrogen's potential as an additional fuel source (Karagöz et al., 2019; Demirci et al., 2018; Wang et al., 2009; Vancoillie et al., 2012; Ji et al., 2013).

Generally, many technologies have been adopted to produce hydrogen over the past decades (Soliman and Zakaria, 2021; Abashar, 2018; Abbas et al. 2022). Among them, hydrogen generation through water splitting technique is easy, inexpensive, and extensively used. In this process, the water is electrolyzed using a separate power source. The necessary electrical energy may be generated from either renewable sources or non-renewable sources. The usage of non-renewable energy sources has decreased throughout time because of the issues they cause in various contexts. Because of the clean and huge available, solar-powered electrolysis method gained more attention among researchers (Calderón et al., 2011; Akyuz et al., 2012; Abanades and Flamant, 2006; Pregger et al., 2009). PV modules store surplus heat during energy conversion. This leads to degrade the PV cell material and decrease its efficiency. The previous study results indicates that, 0.258% of electrical efficiency is decreased per degree Celsius temperature rise (Dwivedi et al., 2020; Almuwailhi and Zeitoun, 2023). To resolve this, the cooling system linked to the PV module circulates heat transfer fluid to lower its temperature. Naturally, Solids transport heat better than typical heat transfer fluids (Senthilraja et al., 2010). Traditional heat transfer fluids include micro- and nanometer-sized particles to increase heat transmission. While using fluids with micro-sized particles, many issues, such as clogging, erosion, and additional pumping power required are faced by many researchers. To solve this, SUS Choi suspended metal parti-

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Nomenclature

A_C	thermal collector area (m^2)
A_P	Solar panel area (m^2)
C_P	The specific heat capacity of the fluid (J/kg K)
eR	Experimental error
F	Faraday's constant (96485 °C/mol)
G	Solar radiation (W/m^2)
I_{el}	Electrolyzer input current (Amps)
I_{SC}	Short circuit current (Amps)
m	Mass (kg)
$\dot{m}$	Mass flow rate (kg/s)
P	Atmosphere pressure (1.01325×10^5 N/m^2)
Q	Volume flow rate (ml/min)
R	Gas constant (8.314 J/mol·K)
t	The time duration for which the current is supplied to the electrolyzer (min)
T_a	Atmosphere temperature (K)
T_{in}	Inlet fluid temperature (°C)
T_{out}	Outlet fluid temperature (°C)
V_{OC}	Open circuit voltage (Volts)
$\dot{V}$	Hydrogen volume (ml)
Z	Excess electrons (2)

Greek letters

ϕ	Volume fraction
η_{elel}	Electrical efficiency
η_{the}	Thermal efficiency
η_{total}	Total efficiency
ρ	Density (kg/m^3)

Abbreviations

CuO	Copper Oxide
EDX	Energy Dispersive X-ray Analysis
LPH	Litre Per Hour
MWCNT	Multi Wall Carbon Nano Tube
PCM	Phase change Material
PEM	Proton Exchange Membrane
PVT	Photovoltaic-Thermal Collector
TEM	Transmission Electron Microscopy

cles with average diameter of 10^{-9} m in base heat transfer fluid in 1995 (Choi and Eastman,1995). This special fluid is named "Nanofluids". After that, many researchers used different techniques to prepare nanofluids and studied their thermal and physical properties. Shah et al. (Shah et al., 2019) developed surfactant-free and surfactant-containing Water + EG based nanofluid. The findings of the research demonstrate that the thermal conductivity improved noticeably when surfactant was added and the volume concentration was raised. Sohel et al. (Sohel et al., 2013) examined thermophysical characteristics and heat transmission ability of different nanofluids. This research found that CuO-water nanofluids improve heat flow by 13.15% than pure water. However, the values dropped to 6.8% for Al_2O_3 nanofluids and 6.2% for TiO_2 nanofluids. Das et al. (Das et al., 2003) examined the temperature dependence of the thermal characteristics of CuO-water nanofluids. In that investigation, the highest thermal conductivity variance was about 14–36% observed for 21–51 °C. From the results provided in the previously published, the nanofluids have been identified as promising heat transfer fluids for a wide variety of uses. Hence, the researchers have focused on reducing the PV module's temperature by circulating different nanofluids in a thermal collector. Fayaz et al. (Fayaz et al., 2018) analysed the MWCNT cooled PVT system's energy and exergy. Initially, they developed an experimental set and conducted the tests by varying the velocity of the flow from 30 LPH to 120 LPH. Finally, the experimental results were validated by the numerical results. During this study, about 10.72% and 5.73% electrical efficiency and overall efficiency enhancement are obtained while circulating MWCNT/water nanofluids at a 120L/h flow rate. Nasrin et al. (Nasrin et al., 2018) examined the MWCNT/water-based hybrid solar collector performance numerically and experimentally. The obtained results found that about 0.14% and 3.67% thermal and electrical efficiencies are obtained for PVT with nanofluids, respectively, compared with water. Furthermore, about 4.11% overall efficiency increment was achieved for PVT with MWCNT/s water nanofluids. Abadeh et al. (Abadeh et al., 2018) conducted the test to conduct the socioeconomic analysis of the hybrid collector. According to the findings, the level of energy efficiency attained for a PVT system based on water, TiO_2, ZnO, and Al_2O_3 was determined to be 21, 32, 33, and 24%, respectively. Similarly, the exergetic efficiency is obtained as 5, 6, 7, and 6%, respectively. Many scientists have experimented with using various nanofluids to improve the functionality of PVT systems in a wide range of circumstances. The findings of this study provide conclusive proof that a substantial drop in cell temperature was achieved inside the solar power module. As a result, more solar energy can be converted into electricity. Caliskan et al. (Caliskan et al., 2013) assessed the efficiency of hydrogen generation system powered by solar energy. In this study, hydrogen was produced using electricity generated from solar energy and wind energy. This research shows that solar PV and wind turbines have exergy efficiencies of 9.74% and 71.7%, respectively. Furthermore, overall exergy and energy efficiency are found to be 5.86% and 3.44%, respectively. Ghribi et al. (Ghribi et al., 2013) performed a research at seven sites to investigate the feasibility of a PV-based hydrogen generating system. Based on the findings of this research, it can be inferred that the quantity of electrical energy generated, and the rate of hydrogen generation are primarily impacted by direct sunlight and wind speed. ÖZDEMİR and Gamze (ÖZDEMİR and Gamze, 2022) studied efficiency of renewable energy-based hydrogen generation systems. The research findings indicate that atmosphere temperature and quantity of nanoparticles have significant influence on efficiency. Cohce et al. (Cohce et al., 2011) presented a method to manufacture hydrogen from biomass with energy and exergetic efficiencies of 19% and 22%.

The previously mentioned discussion showed that nanofluids have been used to improve the PVT system and its prospective use in hydrogen generation. Only few articles related to hybrid solar collector with nanofluid based hydrogen production system is available in the literature. Therefore, this work primarily aims to experimentally examine the role of nanoparticle quantity on many key parameters, including hybrid system efficiency and hydrogen yield rate. Hydrogen yield rates from PVT-based systems were investigated in this work by varying the volume fraction of CuO/water nanofluids used (ϕ = 0.05%, 0.1%, and 0.2%) at two flow rates (i.e., 20 L/h and 40 L/h), and then comparing the findings to those from water- and air-based systems.

2. Materials and methodology

2.1. Experimental rig description

As shown in Fig. 1, the experimental test setup was made-up with necessary components on the roof at SRM Institute of Science and Technology, Kattankulathur, Chennai, India. Fig. 2 is a visual representation of the spiral flow thermal collector used in this investigation. This system uses 20 W, 21.5 V, and 3.25A photovoltaic modules. A 5-mm copper layer was attached underneath the solar panel to ensure continuous contact with the thermal collector. A copper tube with an inside radius of 5.125 mm and a radius on the outside of 6.3 mm was bent into a spiral form and fastened. The opposite side of the thermal collector has been entirely covered with Rockwool insulating material of thickness 20 mm to stop thermal loss to the atmosphere. The nanofluids were stored in an insulated 10-liter tank, and a centrifugal pump was utilised to pump them into the thermal collector. The floating type of flow meter was attached between the nanofluids tank outlet port and the thermal collector inlet port. Hoffman's electrolyzer was connected to the PV module output and will generate the hydrogen. The volume of hydrogen produced during this process was measured using a hydrogen flow sensor which is attached to the electrolyzer and K-type thermocouples recorded nanofluid and PV module temperatures. To keep the nanofluid at a constant temperature and enable continuous usage, a cooling unit was connected to the thermal collector's output side. All the sensors were connected with the DAC and data were recorded continuously.

2.2. Experimental procedure

Initially, the PV module was tested in an open atmosphere at SRM Institute of Science and Technology, Kattankulathur, Chennai, India. The solar collector was inclined at a 45-degree angle and measures different parameters during the process. For a period of seven days, the same technique was carried out in order to achieve the consistent and steady results, and then the mean values were used for the computations.

2.3. Materials and preparation of CuO/water nanofluids

Owing to the notable thermal properties shown by CuO nanoparticles, particles with 27 nm mean diameter were purchased from Sigma-Aldrich Corporation, India and mixed in distilled water Two broad steps were employed to create a large number of CuO/water nanofluids for this study. Eq. (1) may be used to determine the amount of CuO particles necessary for a certain volume of water to be in addition to distilled water. In order to slow down the sedimentation of particles in a fluid containing a

Fig. 2. Pictorial view of a spiral flow thermal collector.

dispersed particle population, a probe sonicator was used for 4 h. Then, stir it for about one hour. Finally, the prepared nanofluids were placed without disturbance for about seven days. Then it was seen that very few particles were stable at the bottom of the beaker, and the uniform dispersion of particles was also observed. Fig. 3 provides a visual representation of the CuO/water nanofluids that have been prepared.

Images from EDX and TEM examination, which were used to determine the nanoparticles composition, size, and shape. The EDX spectrum shows that the sample contains a significant percentage (i.e, 77.38%) of copper and 23.61% of oxide. The TEM image confirmed that the sample comprises CuO particles with 27 nm and a spherical shape.

$$\%\ \text{Volume concentration}\ (\varphi) = \frac{\frac{m_{CuO}}{\rho_{CuO}}}{\frac{m_{CuO}}{\rho_{CuO}} + \frac{m_{water}}{\rho_{water}}} \times 100 \quad (1)$$

where 'm_{CuO}', 'm_{water}' is the mass of copper oxide nanoparticles and water respectively (kg). 'ρ_{CuO}', 'ρ_{water}' is the density of copper oxide nanoparticles and water respectively (kg/m^3).

2.4. Thermal, electrical, and hydrogen energy generation calculation

Eqs. (2)–(4) can be used to determine the efficiencies of the entire hybrid system. (Lorenzo, 1994; Kumar and Rosen, 2011; Joshi et al. 2009; Vokas et al. 2006).

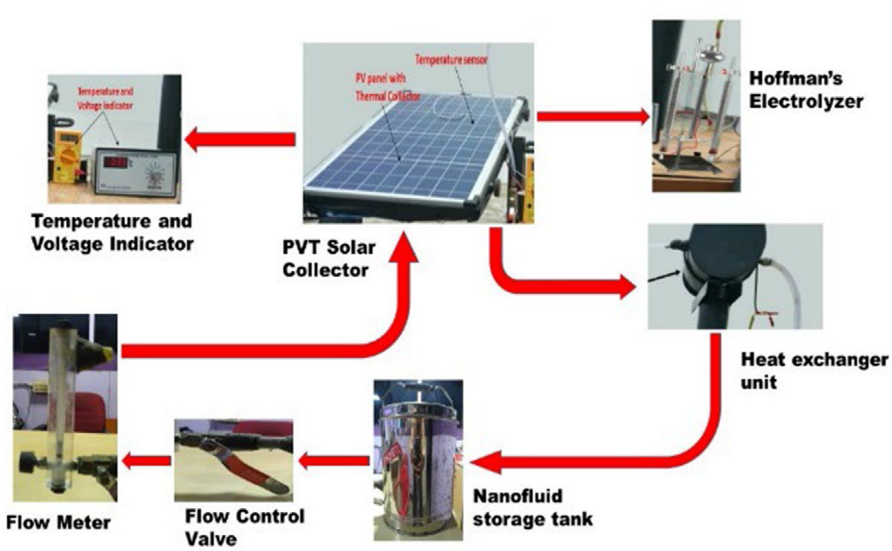

Fig. 1. Diagram of the experimental setup.

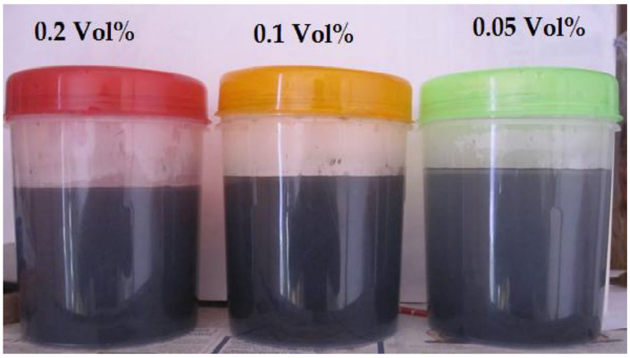

Fig. 3. Pictorial view of prepared CuO/water nanofluids.

$$\eta_{the} = \frac{\mathring{m}\, C_p (T_{out} - T_{in})}{G \times A_c} \tag{2}$$

where ‘m’ is the mass flow rate of nanofluid (kg/s), ‘C_P’ is the specific heat of fluid (J/Kg K), ‘T_{in}’ and ‘T_{out}’ is the temperature of fluid at inlet and outlet side of the thermal collector (°C), ‘G’ is the solar radiation(W/m^2) and ‘A_c’ is the area of thermal collector (m^2)

$$\eta_{ele} = \frac{V_{OC} \times I_{SC}}{G \times A_p} \tag{3}$$

where ‘V_{OC}’ is the open circuit voltage (V), ‘I_{SC}’ is the short circuit current (Amps), ‘G’ is the Solar radiation (W/m^2) and ‘A_P’ is the area of photovoltaic module (m^2)

$$\eta_{total} = \eta_{ele} + \eta_{the} \tag{4}$$

The following formula can be used to calculate the volume flow rate of hydrogen.

$$Q_{H_2} = \frac{V_{H_2}}{t} = \frac{\left(\frac{R \times I_{el} \times T_a \times t}{F \times P \times Z}\right)}{t} = 7.445 I_{el} \left(\frac{\text{ml}}{\text{min}}\right) \tag{5}$$

where ‘V_{H2}’ is the volume of hydrogen (ml), ‘t’ is the time duration for which the current is supplied to the electrolyzer (min), ‘R’ is the Gas constant (8.314 J/mol. K), ‘I_{el}’ is the electrolyzer input current (Amps), ‘T_a’ is the atmosphere temperature (°C), ‘F’ is the Faraday’s constant (96485 °C/mol), ‘P’ is the Atmosphere pressure (1.01325 × 10^5N/m^2) and ‘Z’ is the Excess electrons (2).

3. Results and discussions

In this study, a new approach was developed to produce hydrogen via the utilisation of PVT and the impact of fluid flow rate and nanoparticle concentration on the rate of hydrogen output was examined. This study was conducted at three levels. The initial step was the preparation of nanofluids with varying concentrations, followed by an examination of their thermal and physical characteristics. The functionality of the hybrid solar system was evaluated using a variety of fluids during the second part of the study. In the third phase, observations were made about the effect of nanofluids on the amount of hydrogen produced. The results obtained in all these phases are discussed in this section.

Fig. 4 illustrates the relationship between the quantity of nanoparticles, the flow rate of fluid, and the resultant power output. Due to the peak solar radiation at Noon, the heat generation in the PV module increased rapidly. Furthermore, a larger quantity of heat is extracted by the nanofluids compared with other heat transfer fluids. This reduces the cell temperature and reasonably enhances the power output while using the nanofluids. After noon, the PV module is receives a reduced amount of solar energy. Therefore, the generation and accumulation are less in the PV module. As a result, less sunlight is transformed into usable energy. Because of this, the power output will be lowered between the hours of 2.00 noon to 16.00. The findings of this research also make it abundantly evident that the amount of solar radiation, fluid thermal properties, and the flow rate primarily determines the power output of PV modules.

The hybrid system’s thermal power output against nanofluid volume fraction and flow rate is shown graphically in Fig. 5. This graph illustrates that air-based PVT with 20LPH flow rate always has poor thermal efficiency. Similarly, at 40LPH, PVT with 0.2 vol % nanofluid also achieves its greatest values. At 12.00, the hybrid system’s thermal efficiencies are observed to be 26.1% and 30.3% for 20LPH and 32.4% and 33.8%, respectively, for 40LPH operation with air and water. Adding 0.05%, 0.1%, and 0.2 vol% nanoparticles, improved the thermal efficiency to 54.3%, 60.8%, and 66.2% for 20LPH and 58.8%, 69.6%, and 76.3% for 40LPH, respectively.

When the fluid has a high concentration of nanoparticles and there is less fluid in the spiral flow collector and the fluid’s distance from the PV module’s surface is greatly reduced. At low vol%, fewer particle chains are formed in the base fluid. Because of these reasons, less heat transfers the PV surface to the fluid. This leads to increased thermal efficiency with increasing flow rate and volume fraction. Kumar et al. (Kumar et al., 2016) also observed a similar kind of result in their research.

Fig. 6 Depicts the correlation between the electrical outputs produced by the PV module cooled with different fluids. It can be realized to form this figure; the peak electrical output is achieved at 12.00 local time, then it gradually decreases till the day end. A similar trend of results is obtained for all fluids at all times. The obtained electrical output was found least on an air-cooled PV system at 20LPH and highest on a 0.2% volume fraction nanofluids-cooled PV system at 40 LPH at all times. At 12.00 and 20LPH, the electrical energy of the air and water-cooled PV systems is 7.1% and 7.2%, respectively. While the PV modules efficiency cooled with 0.05%, 0.1%, and 0.2% nanofluids were 9.1%, 11.1%, and 11.9%, respectively. The nanofluids of 40LPH, the values are drastically increased to 10.1%, 12%, and 13.5% for air, water and 0.05%, 0.1%, and 0.2% nanofluids respectively.

Fig. 7 illustrates the relationship between nanofluid volume % and total efficiency. As expected from the previous Figs. 5 and 6, the absolute peak efficiency of the PVT unit cooled with 0.2 vol% nanofluids was observed at 89.5% at 12.00, and the corresponding flow rate was 40LPH. At a flow rate of 40LPH, the concentrations of nanofluids with the best overall efficiency were determined to be

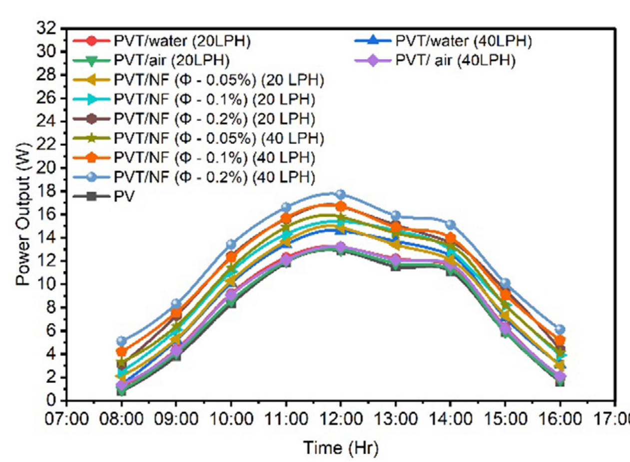

Fig. 4. Hourly power output variation for the PVT system with different heat transfer fluids.

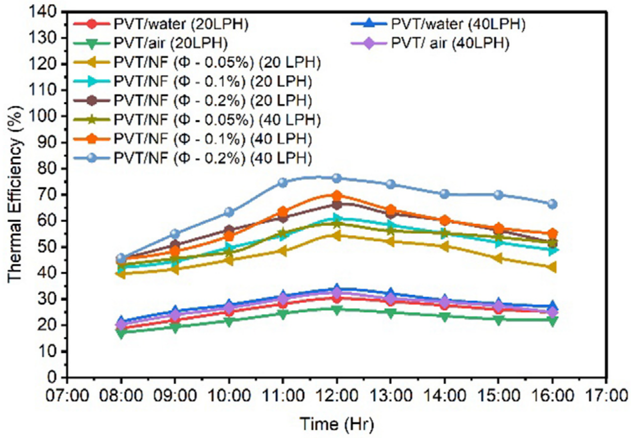

Fig. 5. Hourly thermal efficiency variation for a PVT system with different heat transfer fluids.

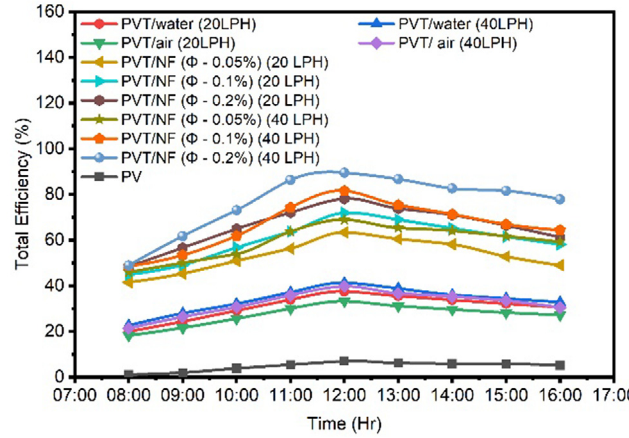

Fig. 7. Hourly Total efficiency variation for a PVT system with air, water and nanofluids.

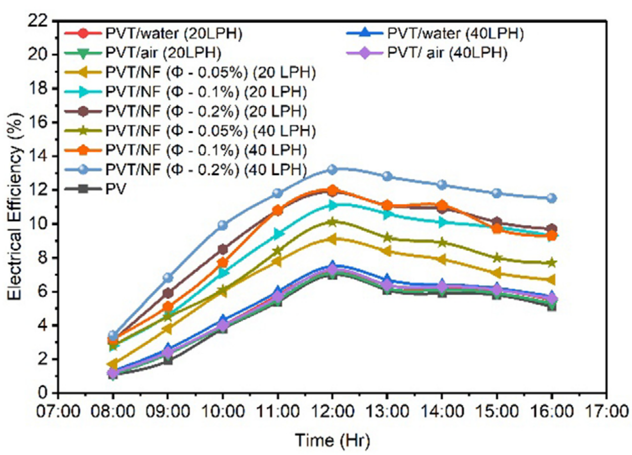

Fig. 6. Hourly electrical efficiency variation for a PVT unit with water and nanofluids.

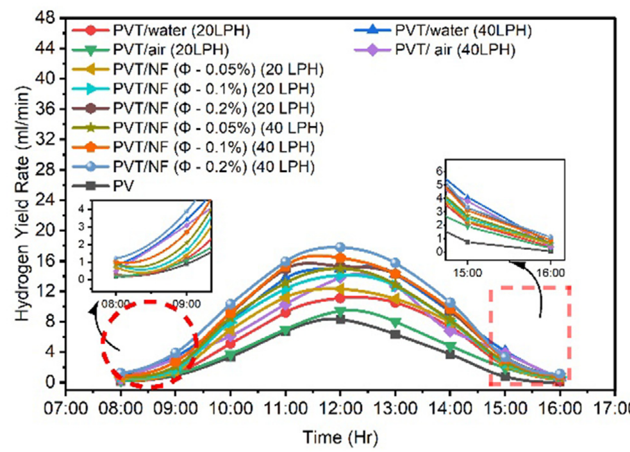

Fig. 8. Hourly hydrogen yield rate variation for the PVT system with air, water and nanofluids.

0.05% and 0.1%, with the maximum total efficiency being 68.9% and 81.4%, respectively. The highest total efficiencies of the air and water-cooled PVT unit are observed as 39.1% and 41.3%, respectively.

Fig. 8 shows the hourly changes in hydrogen generation rate for the hybrid system with water and nanofluids at constant solar radiation. The rate of hydrogen production was found to increase till 12.00 Noon then drop progressively till 16.00. At the same time, the rate of water splitting increased as the system's electrical output increased. Hence, more amount of hydrogen generation was obtained for the hybrid system with 0.2 vol% of nanofluids at 40LPH. The lowest rate of hydrogen production utilizing a solar panel with no a thermal collector was 8.3 ml/min at 12.00. However, the hydrogen generation rate is obtained as 13.9 ml/min and 15.2 ml/min while using air and water in the PVT solar collector at 40 LPH.

Obviously, solar radiation is less at the start of the experiment (i.e. 8.00), but the solar panel absorbs more heat by 12.00, leading to a large increase in electrical production. At the same time, more solar radiation is wasted as heat accumulates in the solar panel. Hence, the PV module efficiency is reduced drastically. However, while circulating fluid with 0.2%-volume CuO nanoparticles at 40LPH, more fluid and solid particle interactions are increased and decreased the PV module temperature noticeably. These are the possible reasons for supplying more electrical power to the electrolyzer and achieving more hydrogen generation rate.

4. Conclusions

In this research, it was proved that there is a potential to improve the overall responsiveness of the PVT used to create hydrogen. This study used the spiral flow thermal collector with different fluids to gather the heat from the solar panel. Before using the nanofluids in the PVT unit, the thermophysical properties were studied, and the critical findings obtained in this research are gathered and given below.

1. All nanofluid volumes exhibited considerable thermal conductivity increase, confirming that CuO/water nanofluids have high promise in all heat transfer applications. Additionally, both volumetric concentration and temperature contribute to a rise in thermal conductivity. The peak thermal conductivity ratio of (K_{nf}/K_f) of 1.044 was obtained for 0.2 vol% nanofluids prepared with 4 hr time.
2. When all nanofluids were compared, it was discovered that nanofluids with 0.05 vol% had the lowest viscosity (nf), which was around 0.75 mPa-S. Also, it is also clear that, as preparation time and temperature for nanofluids increase, the viscosity decreases because of better dispersion.

3. The PVT system with a 0.2% volume fraction of nanofluids showed the best electrical and thermal performance than other PVT systems. It was noted that the PVT system cooled with a 0.2% volume fraction of nanofluids reaching the maximal thermal and electrical efficiencies of around 79% and 13.5%, respectively, compared to other systems. These results were derived from the findings. When the nanofluids with a high flow rate passed through the thermal collector, significant cell reduction was observed.
4. Comparing all, the peak hydrogen yield rate was achieved for the system with 0.2 vol of nanofluids. At the highest solar radiation, about 10.3, 12.1 and 16.5 ml/min, were obtained for air, water and 0.2% volume fraction of nanofluids at 20LPH, respectively. These values increased to 13.9 ml/min, 15.2 ml/min, and 18.8 ml/min for air, water and 0.2% volume fraction of nanofluids at 40LPH respectively.

These findings suggest that nanofluids are better than water in all thermal applications owing to their enhanced thermal property. Such a system produces electricity, hydrogen, and hot water simultaneously and can be used for drying applications. Although this system offers many positive results, the particles are settled down quickly and need more preparation time. Hence, more research must decrease the agglomeration and sedimentation time.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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