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Experimental analysis of photovoltaic thermal system assisted with nanofluids for efficient electrical performance and hydrogen production through electrolysis

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HIGHLIGHTS

- Production of hydrogen via electrolysis using PVT were studied.
- Nanofluids mass flow rates such as 0.008 kg/s, 0.010 kg/s, and 0.012 kg/s were analyzed comparatively.
- ZnO at the mass flow rate of 0.012 kg/s reported maximum thermal efficiency and hydrogen production rate.
- Mass flow rate of nanofluids directly affects the cell temperature.

ABSTRACT

In this study the influence of the nanofluid in the photovoltaic thermal system (PVT) has been examined experimentally. The nanoparticles zinc oxide (ZnO) dispersed in the base fluid water at the concentration of 0.25 %wt. A series of experimental tests were conducted between 9:00 A.M. to 16:00 P.M. ZnO nanofluids passed through the PVT panel at various mass flow rates. To increase the thermal efficiency and performance of the PVT, instead of using plain water, nanofluids were introduced. The parameters such as output power, surface temperature, fluid outlet temperature, thermal efficiency, and electrical efficiency were examined at the different mass flowrates such as 0.008 kg/s, 0.010 kg/s, and 0.012 kg/s. Added to above, the proposed photovoltaic thermal system was also assisted in producing hydrogen by electrolysis process. Polymer electrolyte membrane (PEM) has been used to generate the hydrogen via electrolysis. With the use of nanofluids, the electrical efficiency and thermal efficiency were increased owing to the reduction in the cell temperature. Introduction of the nanofluids at the optimal mass flow rate helps the panel to produce higher electrical output. The hydrogen yield rate was also increased by the use of nanofluids. Among the different mass flow rate, 0.012 kg/s reported maximum thermal efficiency of 33.4% with the hydrogen production rate of 17.4 ml/min. Based on the extensive observed results procured, photovoltaic thermal systems can be a promising candidate for the production of hydrogen using PEM electrolyzer.

Keywords: Photovoltaic thermal system**,** Nanofluids**,** Solar energy**,** Hydrogen production**,** Electrolysis

Introduction

Hydrogen is a type of energy carrier that can be used to store, transport, and transmit energy supplied by other sources. All of these above-mentioned things can be viable because of its ability to carry energy. Several different approaches are available for the production of hydrogen fuel. Reforming natural gas with heat is now the most popular method, followed by electrolysis as the most frequent way. Other processes include those that are driven by the sun and biological systems **[1—3]**. The term "steam reformation" refers to a high-temperature process that normally used in thermal processes for the manufacture of hydrogen. In this process, steam combines with a hydrocarbon fuel to generate hydrogen. A wide variety of hydrocarbon fuels, such as natural gas, diesel, renewable liquid fuels, gasified coal, or gasified biomass, may be converted into hydrogen through the process of reformation. In modern times, the steam reformation of natural gas accounts for around 95% of all hydrogen production. An activity known as electrolysis can be used to break water down into its component parts, oxygen and hydrogen **[4—6]**. An electrolyzer is a device that performs electrolytic operations and has a function that is very similar to that of a fuel cell in reverse. Instead of utilizing the energy of a hydrogen molecule, as a fuel cell does, an electrolyzer generates hydrogen from the molecules of water. The creation of hydrogen is accomplished by the use of light in processes that are powered by the sun **[7—10]**. There are a few processes that are driven by the sun, some of which include photobiological, photoelectrochemical, and solar thermochemical reactions **[11]**. Photobiological processes include the production of hydrogen through the use of the natural photosynthetic activity of bacteria and green algae. In photoelectrochemical processes, specific semiconductors are utilized to break down water into its component parts, hydrogen and oxygen. Concentrated solar energy is used to fuel the water-splitting processes that are necessary for the synthesis of solar thermochemical hydrogen **[12,13]**. These reactions frequently involve the participation of additional compounds, such as metal oxides. The production of hydrogen through biological reactions may be accomplished with the help of microorganisms like bacteria and microalgae that are used in biological processes **[14,15]**. In the process known as microbial biomass conversion, microorganisms decompose organic materials such as biomass or wastewater in order to create hydrogen. On the other hand, photobiological processes include bacteria utilizing sunlight as their primary source of energy **[16]**. The creation of hydrogen by photobiology involves using microorganisms and sunlight to convert water and occasionally organic materials into hydrogen. This process is known as photobiology. However, it has the potential to produce sustainable hydrogen with a smaller negative impact on the environment in the long run. Microorganisms in photolytic biological systems, such as green microalgae or cyanobacteria, use sunlight to split water into oxygen and hydrogen ions in order to survive. It is possible for the hydrogen ions to combine by either direct or indirect pathways, resulting in the emission of hydrogen gas **[17—19]**. The low rates of hydrogen generation and the fact that splitting water also creates oxygen are both challenges for this method. Oxygen quickly suppresses the hydrogen synthesis process and can be a safety hazard when coupled with hydrogen in certain amounts **[20,21]**. Researchers are working on developing ways that will allow bacteria to manufacture hydrogen for longer periods of time and at a faster pace. They are also working on developing methods that will allow them to produce hydrogen at a higher rate. Some photosynthetic microorganisms make use of sunlight as the primary catalyst in the decomposition of organic materials, which results in the release of hydrogen. The creation of hydrogen in this manner is referred to as photofermentation. Due to the fact that this route has a very low hydrogen production rate and a low efficiency in converting solar energy into hydrogen, it is currently not an economically feasible route for the manufacture of hydrogen. Researchers are looking at methods to modify the microorganisms' usual biological processes to enhance the amount of hydrogen that they can produce as well as improve the microbes' ability to absorb and use energy, making the microbes themselves more accessible for the production of hydrogen **[22,23]**.

Solar energy is one of the most cost-effective types of renewable energy. It has been used a lot in a variety of applications, such as solar stills and the generation of electricity, among other things. Photovoltaic and thermal systems, often known as PVT for short, are among the key solar technologies. These systems not only convert solar energy into electrical power but also generate heat energy. As the temperature of the photovoltaic (PV) panel rises as a result of exposure to solar radiation, the amount of electrical power produced by the panel falls by around 0.2%—0.5% for every degree celsius. The temperature management that is often accomplished via the use of air- or water-cooling systems appears to be important to increase the performance of PV modules as a result **[24,25]**. The excess heat that is taken from PV panels may offer the thermal energy that is necessary for a variety of applications, whether they are industrial or home. PVT the type of system that generates both thermal and electrical energy simultaneously. Several examinations, both experimental and numerical, have been carried out in order to examine the solar units' ability to generate both heat and power simultaneously **[26,27]**. The initial PVT collector that was developed used water in its cooling system. The greater thermal conductivity of nanofluids compared to that of air and water has led to considerable growth in the number of applications of nanofluids in solar energy systems. Utilizing fluids with superior thermal characteristics allows for the performance of the system to be improved without necessitating any alterations to the design of the thermal absorber. Solar energy has the potential to play a significant part in the effort to save our world from the devastating effects of climate change that are being brought on by our continued reliance on fossil fuels to supply our energy needs. Increasing the efficiency of systems that use solar energy is, hence, of the utmost significance. Solar photovoltaics (PV) are demonstrating that they can compete for market share alongside fossil fuels today. The rise in temperature of the solar cells, which reduces the efficiency of the electricity they produce, is one of the most significant obstacles, though **[28,29]**. Consequently, researchers have created a novel technique to remove the surplus heat from these systems to lower their temperatures and enable the electrical efficiency to be increased. This strategy makes use of nanotechnology. The fields of science, engineering, and technology are all brought together at the nanoscale in the discipline of nanotechnology, which is a multidisciplinary field. Nanotechnology has a broad variety of potential applications; for example, it is now being explored in the fields of engineering, biology, and material science. By using nanofluids in place of the traditional working medium, the area of solar energy might benefit significantly from the application of nanotechnology. The use of nanofluid, a novel kind of heat transfer fluid, enables a greater quantity of heat to be extracted from the solar system. The incorporation of nanoparticles into the base fluids is based on the idea that doing so will increase the thermal conductivity of the fluids, which in turn may result in an increased heat transfer coefficient and improved thermal efficiency **[30,31]**. This article focused to generate hydrogen via electrolysis process. Despite the several attempt on the nanofluids on PVT, still the works on hydrogen production were limited. Furthermore, use of the PEM with the PVT systems is not popular. Thereby the current study focused mainly to understand the sustainability of the PEM with PVT system.

Methodology

Materials preparation

During the ultrasonication procedure, the chosen nanoparticles were ZnO, and they were dispersed in water. The relative thermophysical characteristics of the ZnO nanoparticles were then determined. **Fig. 1** shows the X-ray diffraction (XRD) patterns for the procured ZnO nanoparticles. The peaks were shown in the figure according to the JCPDS. From the scherrer equation the average crystalline structure is observed to be 43.25 nm. From the diffraction peaks it is clear there are no impurities in the nanoparticles. The peaks such as (100), (002), (101), (102), (110), and (202) observed at 35.1°, 39.2°, 41.8°, 52.5°, 57.6°, and 63.2°. In order to get rid of any trace of moisture that may have been present in the nanoparticles, they were subjected to treatment in the heating surface for at least an hour at a temperature of 210 °C. Following the application of the pre-treatment, the nanoparticles were subjected to gradual and consistent sonication at a frequency of 35 kHz for 120 min. The ultrasonication method was utilized in order to distribute the nanoparticles and incorporate them into the PV/T. At the conclusion of the sonication procedure, a significant colour shift was seen, and there was no indication that any nanoparticles had been deposited. In order to get an excellent uniform suspension, the sonication was carried out nonstop for a period of 7 h at a frequency of 35 kHz **[32,33]**. **Table 1** shows the properties of the nanofluids.

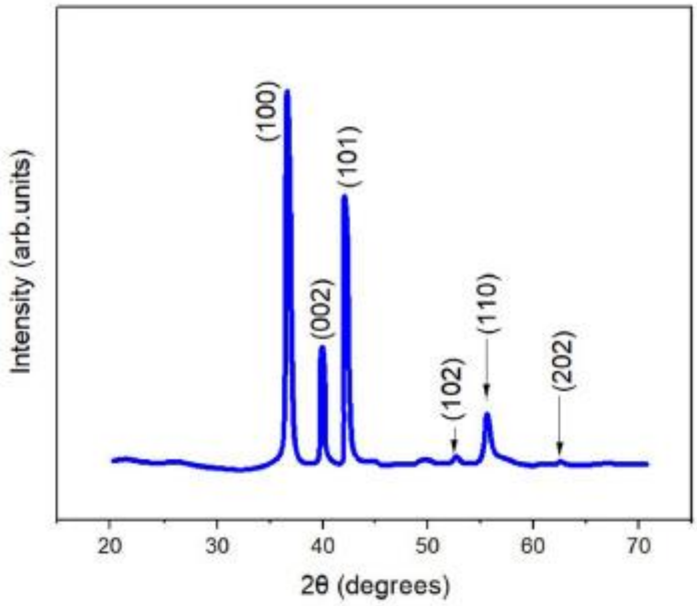
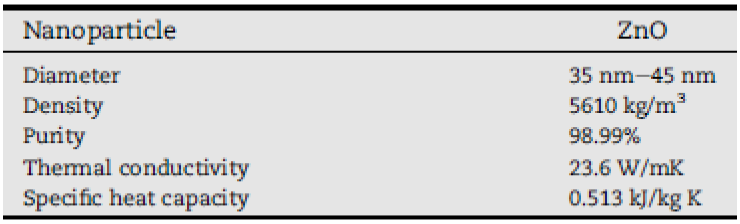


Fig.1 – XRD patterns for ZnO nanoparticles

Experimental setup

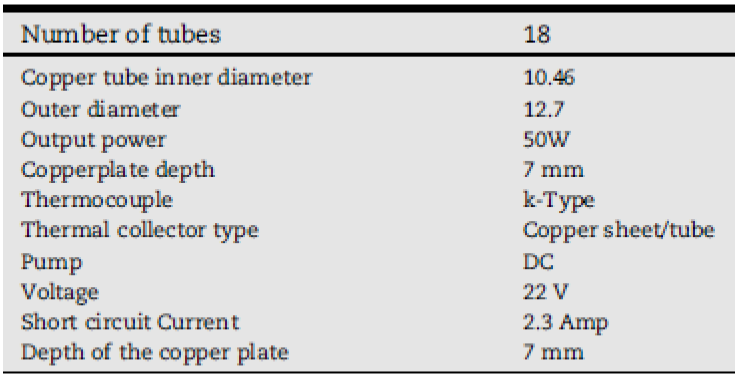
Experiments were carried out in the city of Chennai during the months of April 2022 and June 2022. The examinations were carried out on a daily basis from 8:00 to 16:00 h. Experiments were carried out using a solar module made of monocrystalline silicon measuring 64 mm/130 mm. For the purpose of collecting the working fluid, a separate storage reservoir was utilized. The photovoltaic module that also included the thermal collector was built.

Table 1 – Properties of nanofluid



Nanoparticle	ZnO
Diameter	35 nm–45 nm
Density	5610 kg/m^3
Purity	98.99%
Thermal conductivity	23.6 W/mK
Specific heat capacity	0.513 kJ/kg K

Table 2 – Specification of PVT instrumentation.



Number of tubes	18
Copper tube inner diameter	10.46
Outer diameter	12.7
Output power	50W
Copperplate depth	7 mm
Thermocouple	k-Type
Thermal collector type	Copper sheet/tube
Pump	DC
Voltage	22 V
Short circuit Current	2.3 Amp
Depth of the copper plate	7 mm

The testing apparatus includes a polycrystalline PV module with a power output of 50 W, a spiral flow thermal collector fabricated from a copper tube with an outer diameter of 12.7 mm and an inner diameter of 10.26 mm, a thermocouple of the ‘k' type, a flow metre, a storage tank with a capacity of 15 L, a pump, a compressor, a flow control valve, and an exchanger unit for heat **[33,34]**. The digital environmental metre was utilized in order to ascertain the levels of pressure, temperature, and quality of the air. During the process of producing electricity from the solar panel, the Voltmeter measures the electrical voltage at various points during the process. The metrics, which included output power, cell temperature, outlet fluid temperature, thermal efficiency, electrical efficiency, overall efficiency, and hydrogen flow rate, were calculated after many test runs. A copper plate with a depth of 7 mm is used to make the connection from the thermal collector to the rear of the PV module. A flow control valve is used to adjust the flow rate of the fluid, and a flow meter is used to determine how much fluid is being moved through the system. **Table 2** lists the specification of the PV/T module. A heat transfer unit is used to bring the temperature of the water down so that it may be reused in the system. This allows the water to be recycled. A thermocouple is utilized in order to obtain readings regarding the temperature of the panel's surface as well as the fluid on both the input and output sides. Through the utilization of a data collection system, the real readings are acquired, recorded, and stored in the central processing unit (DAS). In the current study PEM electrolyser has been used to produce the hydrogen. PEM electrolyser consists of aluminium alloy plate, insulated gasket, titanium mesh, microplate, silicon gasket and negative electrode plate. The PEM assembly is arranged in the sequence of aluminium alloy followed by a gasket. Titanium mesh is placed in the order of high, medium, and small dense. Four connectors are used to supply water. In the anode side three outlets are placed for air, oxygen and hydrogen. The Hoffman electrolysis device is put to use in this investigation so that hydrogen gas can be produced. In order to determine the level of purity of the hydrogen gas that was created, a hydrogen purity analyzer was utilized. In the beginning, each of the devices is calibrated by utilizing the typical calibration procedures. The test is then carried out in the open air, and the various parameters, including the temperature of the inlet and outlet water and electrical and thermal efficiencies, also were computed in the hydrogen flow rate that was measured by utilizing the flow sensor. These calculations are done using the values that were acquired in the step before this one. In the last stage, the same procedure was repeated, and the efficiency of the PVT solar collector as well as the rate at which hydrogen is produced are evaluated for the various flow rates of the remaining fluids. **Fig. 2** shows the experimental layout.

Results and discussion

The primary objective of the research is to investigate the rate of production of the solar-assisted hydrogen generation system. To produce hydrogen, this study makes use of the hydrogen production system developed by Hoffman. The use of electrical energy allows for the separation of water into its component gases of hydrogen (H_2) and oxygen (O_2) in this system. During this process, the PVT solar collector is the source of energy that is converted into electrical form. At three different mass flow rates, the different test results were calculated and compared.

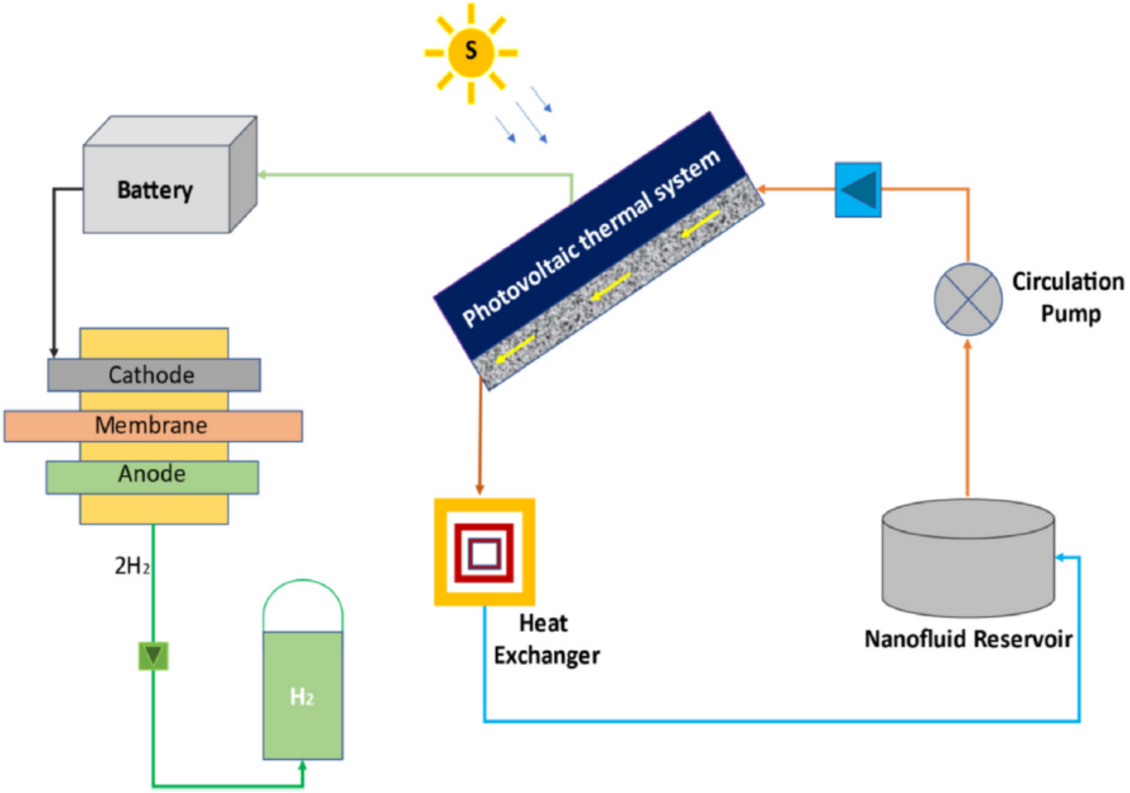


Fig. 2 – Experimental layout.

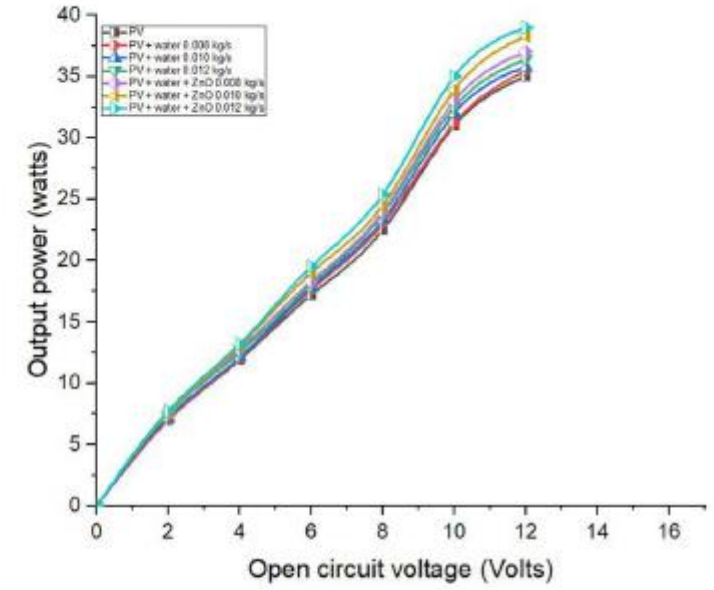


Fig. 3 – Output voltage variation for various specimen.

Output power

Fig. 3 represents the relationship between output power and the open circuit voltage. The power was measured using temperatures of 50 °C within the cell, along with three distinct flow rates of both water and ZnO nanofluid. These results made it abundantly clear that the maximum power output of 48 W is obtained for a nanofluid PVT solar collector with a 0.012 kg/s mass flow rate at 50 °C cell temperature. In most cases, the temperature of the cell is the primary factor that determines the output voltage. To phrase this another way, when the temperature of the cell is lowered, the value of the output power rises. The PV module that does not have a solar collector produces an output voltage that is 13.2 V which is lower than any other configuration. According to the available research, water contains more properties for the transport of heat than air does. Therefore, for any given mass flow rate, water is capable of absorbing a greater amount of heat from the PV module than plain PV. The density, viscosity, and thermal conductivity of a nanofluid all have a crucial impact on the parameters of heat transmission for that nanofluid **[35]**. This is the primary reason for the success of the PVT solar collector with 0.012 kg/s in producing a higher power output.

The surface temperature of the PV panel

Fig. 4 illustrates how the cell temperature varies for different coolants used at different mass flow rates at different times from 8:00 A.M. to 16:00 P.M. The temperature of the surface drops in response to an increase in the mass flow rate of all fluids. In addition, the temperature gradually increases from 8:00 A.M. until 12:00 P.M., after which it begins to drop until 16:00 P.M. Regarding the temperature changes, the findings were observed in all of the coolants that were tested at varying amounts of mass flow. The temperature of the panel shoots up until 12:30 P.M., after which it began to gradually go back down. With a mass flow rate of 0.012 kg/s, the nanofluid-based PVT reached their maximum cell temperature of 53.2 °C and meanwhile the water-based system reached the temperature of 63.5 °C, respectively.

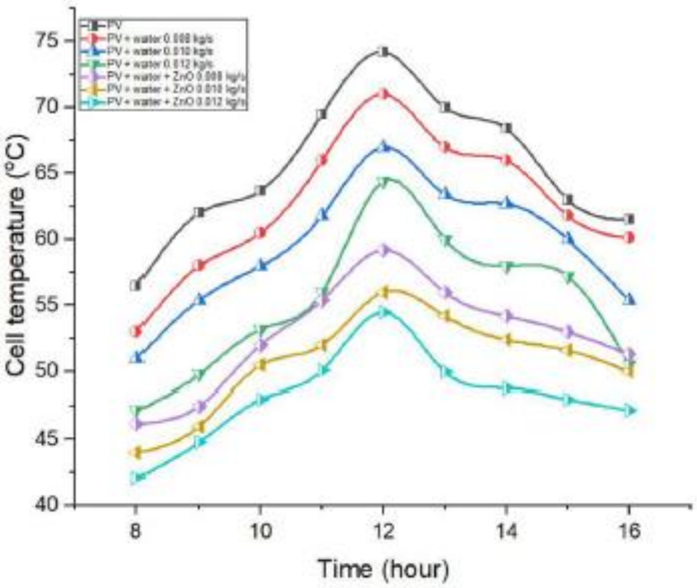


Fig. 4 – Cell temperature variation for various specimen.

Cell temperatures of 74.2 °C and 71.4 °C were reported in air-based and water-based at the mass flow rate of 0.008 kg/s PVT solar collectors, respectively, at the same time. The heat was removed from the panel by conduction and convection, which caused these changes in the cell temperature that occurred between the different time intervals. As a result of the improved thermal conductivity of the nanoparticles that are spread throughout the fluid, the temperature of the cell has decreased as the mass flow rate of the nanofluids has increased. Pumping the fluids at a greater mass flow rate results in a reduction in the amount of surplus heat on the surface of the PV panel **[32,35]**. As the mass flow rate increased, the surface temperature fell across the board for all coolants because the coolant was able to carry more heat.

Fluid outlet temperature

There is a correlation between the temperature at the exit of the fluid and the temperature at the surface of the PV panel. The fluid outlet temperature is shown in **Fig. 5** for various coolants used at different times of the day. The panel surface temperature will drop in direct proportion to the elevation of the fluid output temperature. When the flow rate is increased, a greater quantity of fluid is drawn into the thermal collector. Because of this increased contact between the fluid and the panel surface, the rate at which heat is transferred also rises. Because of this factor, the PVT/water solar collectors that have a mass flow rate of 0.0012 kg/s attain the maximum outlet temperature **[32,36]**. For the reason that of its increased thermal conductivity, the ZnO nanofluid absorb a greater amount of surface temperature than the previously utilized fluids. The highest temperature of the selected coolants medium of air, PV + Water 0.008 kg/s, PV + Water 0.010 kg/s, PV + Water O. 012 kg/s, PV + Water 0.008 kg/s, P + Water + ZnO 0.010 kg/s and, PV + Water + ZnO 0.012 kg/s at 12:00 P.M. were 35 °C, 37 C, 39.2 °C, 40.1 °C, 42.3 °C, 45 °C and 47.2 °C respectively. It is proved that the higher order of the better heat conductivity is air, water then nanofluid at a higher mass flow rate.

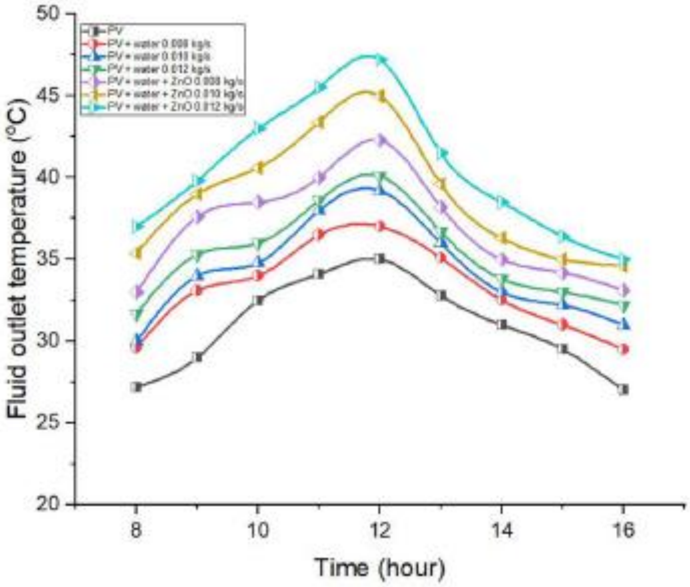


Fig. 5 – Fluid outlet temperature variation for various specimen.

Thermal efficiency

Fig. 6 shows a graph between the temperature of the fluid used as coolants and the time of day. In this relation, a pattern resembling the output fluid temperatures was seen. The ability to absorb heat will grow as the medium's conductivity increases and increases thermal efficiency. The thermal efficiency of solar panels is known to vary owing to global radiation because it mostly depends on the temperature applied to them. The utilized fluids were most effective at 12.30 P. M. compared to other timings. ZnO achieved the maximum thermal efficiency of all the coolants used, and that too at 12.30 P.M. The higher the mass flow rate, the higher the thermal efficiency will be for the fluid medium used **[37,38]**.

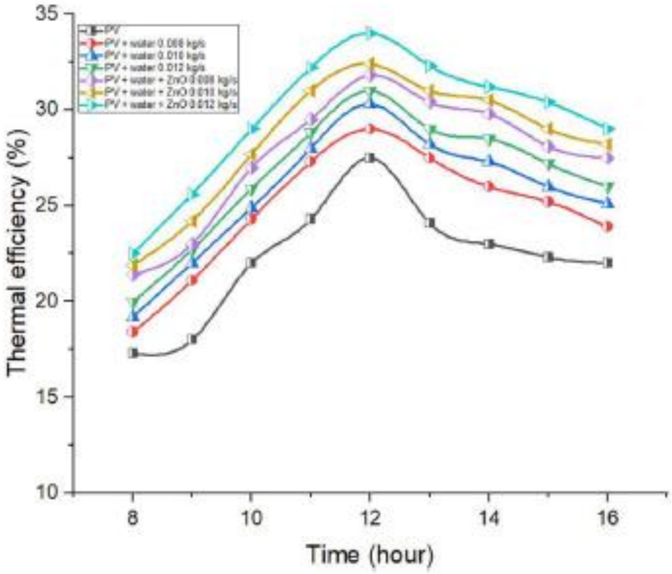


Fig. 6 – Thermal efficiency variation for various specimen.

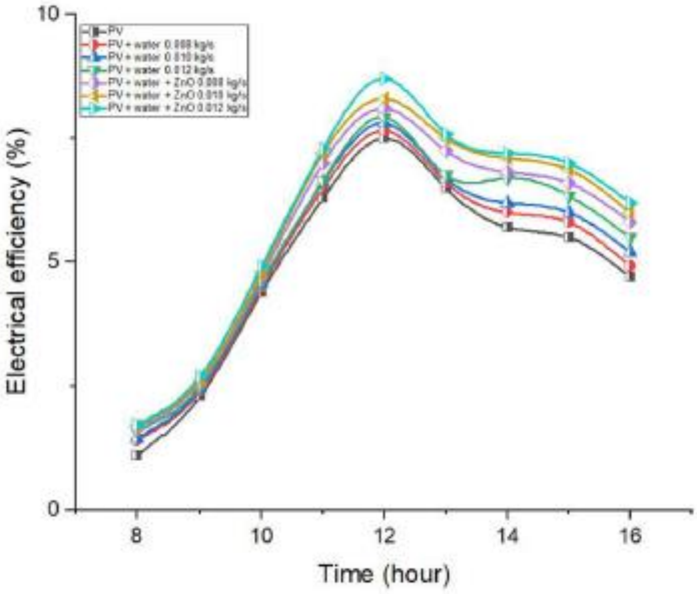


Fig. 7 – Electrical efficiency variation for various specimen.

As a result of it, the mass flow rate of 0.012 kg/s mass flow rate showed better thermal efficiency than the flow rate of 0.008 kg/s and 0.0010 kg/s. The thermal efficiency of the coolants used of PV + air, PV + Water 0.008 kg/s, PV + Water 0.010 kg/s, PV + Water 0.012 kg/s, PV + Water 0.008 kg/s, PV + Water + ZnO 0.010 kg/s and, PV + Water + ZnO 0.012 kg/s were 27.5%, 29%, 30.3%, 31%, 31.8%, 32.4% and 34% respectively.

Electrical efficiency

The electrical efficiency shown in **Fig. 7** is typically used to determine the overall efficiency of a PV/T system. Fluid temperature and cell temperature readings were commonly used to determine electrical efficiency. As cell temperatures rise, so does the system's overall efficiency. So, the computation of fluid outflow and cell temperatures is essential. The nanofluids performed better than air and water. Adding the nanofluids improved the overall electrical efficiency by a significant margin during the course of the experiment **[34]**. Thus, in the long run, nanofluids for electrical efficiency maximization in the long term to satisfy the energy requirements were a feasible method to make. The ZnO nanofluid was one of several samples that demonstrated greater efficiency because of the nanofluids thermal conductivity and panel temperature. As the photovoltaic (PV) panel temperature dropped, the levels of thermal stress dropped. Another good reason to increase performance is that the number of stress drops has decreased **[38,39]**. The lowest electrical efficiency was obtained at 8:00 A.M. in the morning due to the lowest heat received from the sun while the highest efficiency was noted at 12:00 P.M. This is because of the higher heat rays received from the sun on the panel after which the efficiency is gradually reduced **[40]**. The respective electrical efficiency at 8:00 A.M. and 12:00 P.M. were 1.1%, 1.4%, 1.45%, 1.6%, 1.65%, 1.7%, 1.72% and 7.5%, 7.65%, 7.8%, 7.92%, 8.1%, 8.3%, 8.7% for air, PV + Water 0.008 kg/s, PV + Water 0.010 kg/s, PV + Water 0.012 kg/s, PV + Water 0.008 kg/s, PV + Water + ZnO 0.010 kg/s and, PV + Water + ZnO 0.012 kg/s.

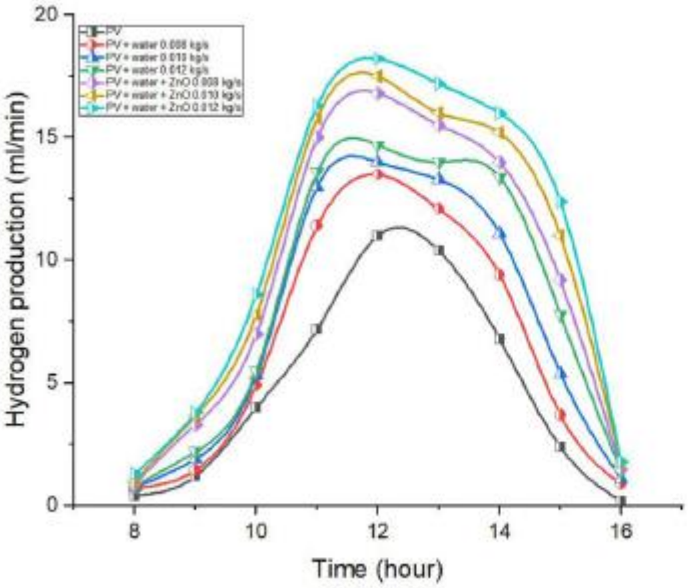


Fig. 8 – Hydrogen production variation for various specimen.

Hydrogen production rate

Electrolysis is often affected when there is a drop in global radiation. As the nanofluid mass flow rate rises, cell temperature and electrical efficiency both contribute to an increase in hydrogen generation. Using energy generated by the PVT panel, a PEM electrolyzer generated hydrogen from the water by electrolyzing it. **Fig. 8** represents the production of hydrogen at various operating conditions. A rise in electrical power generation has coincided with a rise in earth's irradiation levels. The electricity generated has grown in parallel with the rise in the earth's average irradiance. Because of this, the generation of hydrogen has a direct impact on the amount of irradiance that is produced **[33,34]**. When there is a drop in the amount of radiation in the environment, this clearly affects the electrical output, which in turn impacts the electrolysis process. The cell temperature and the electrical efficiency of the hybrid system both improve in response to an increase in the mass flow rate of the nanofluid. This increases the amount of hydrogen that is produced **[41]**. Since the electrical efficiency is directly proportional to the produced hydrogen rate, a similar trend was noticed in the hydrogen results. The lowest was observed at 8:00 A.M. and the highest was noted at 12:00 P.M. Moreover, the nanofluids with a higher mass flow rate produced higher hydrogen. However, the water produced a lower hydrogen rate compared to ZnO nanofluids **[43]**. By comparing all the results, the mass flow rate of 0.012 kg/s generated more hydrogen with a value of 14.7 ml/ min. The ZnO nanofluid-produced hydrogen quantities were 16.8 ml/min, 17.5 ml/min and 18.2 ml/min for the mass flow rates of 0.008 ml/min, 0.010 ml/min and 0.012 kg/s ml/min at 12:00 P.M. respectively.

Overall efficiency

Fig. 9 depicts the overall efficiency about the mass flow rate of ZnO across varies timeline. The overall effectiveness values are raised from 8:00 A.M. to 12:00 P.M. and then gradually down until 16:00 P.M. The overall efficiency provides information on both the efficacy of the coolants that were employed and the electrical efficiency of the PVT that was utilized.

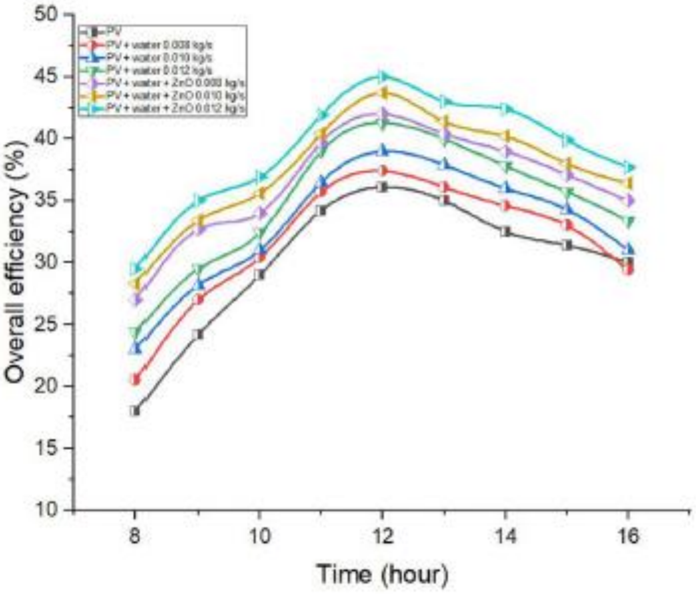


Fig. 9 – Overall efficiency variation for various specimen.

The total efficiency is increased when both the mass flow rate and the thermal conductivity are higher, as well as when measured at 12:00 P.M. **[33,42]**. The highest overall efficiency of PV + water + ZnO 0.012 kg/s at the time from 8:00 A.M. to 16:00 P.M. with 1 h interval were 29.5%, 35%, 36.9%, 41.9%, 45%, 43%, 42.4% and 39.9% respectively. Along with the properties of used material as coolant, the earth's temperature variation also plays an important role in the overall efficiency of the entire unit. Apart from the type, the temperature variation in sun rays created significant variation in all measured parameters.

Conclusion

In the current study, the impacts of a nanofluid on a PVT hybrid system that was linked with an electrolyzer were investigated. Nanofluids were utilized to bring the temperature of the panel down while simultaneously increasing the amount of electric power generated. This electricity was then put to use in the electrolysis process to generate hydrogen. Calibration of the overall system's performance was accomplished by measuring the temperature of the outlet fluid, the temperature of the PV cell, thermal efficiency, electrical efficiency, hydrogen production, and overall efficiency. Among various mass flow rates 0.012 kg/s reported the maximum thermal efficiency for both water and nanofluids. Both water and nanofluids are observed to produce higher electrical output irrespective of the irradiance levels than air. The temperature of the outlet fluid, thermal efficiency, electrical efficiency, hydrogen production rate and overall efficiency of the ZnO nanofluid with the mass flow rate of 0.012 kg/s were 47.2 °C, 8.7%, 18.2 ml/min, and 45% at the time 12:00 P.M. The respective drop in surface cell temperature for the same case with a higher mass flow rate was 54.5 °C. Similarly, however, the water produced lower efficiency than the used nanofluids due to its lower thermal conductivity, it was still higher than air. The main reason for the improved efficiency in the use of nanofluids is their physical and chemical properties as lower heating value than water and air. According to the findings, the nanofluids have the potential to be exploited for the maintenance of solar-based energy production in a sustainable manner. In addition, the system's output of hydrogen may be converted into a fuel that is both clean and environmentally friendly for use in the place of fossil fuels as an efficient alternative and renewable fuel. With regard to the economic viability, use of the PEM is expensive which relatively increases the overall cost of the hydrogen production. Hence finding the cheapest options for the hydrogen production is mandatory to ensure the PVT based hydrogen production is sustainable.

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