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Investigation of the Hydrogen Gas Production by Using Solar Energy

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Abstract: Hydrogen is an energy source that offers both environmental benefits and reliability, making it a promising solution for promoting sustainable growth in various sectors worldwide. As businesses and societies increasingly seek sustainable alternatives, hydrogen has emerged as a key player in the transition to a low-carbon economy based on renewable energy sources. Consequently, hydrogen production holds immense potential for replacing traditional energy sources such as petroleum, natural gas, and non-renewable energy. Various methods can be employed for hydrogen production, including fossil fuel-based processes, nuclear energy, and renewable energy sources. To achieve the goal of zero emissions, the focus has shifted towards utilizing renewable energy, specifically through photovoltaic electrolysis, to generate hydrogen gas. Photovoltaic electrolysis employs solar energy to split water molecules into hydrogen and oxygen. However, the efficiency of this method is currently quite low. Temperature plays a crucial role in increasing the efficiency of water electrolysis, making it an important factor to consider in enhancing hydrogen gas production through photovoltaic electrolysis. Therefore, there is significant value in investigating the impact of temperature on the efficiency of hydrogen gas production in photovoltaic electrolysis. In summary, hydrogen energy production has emerged as a promising solution for sustainable growth, and renewable energy sources such as photovoltaic electrolysis hold great potential for achieving zero emissions. Exploring the influence of temperature on the efficiency of hydrogen gas production in photovoltaic electrolysis is of considerable interest, aiming to improve the overall process and enhance the viability of hydrogen as a sustainable energy source.

Keywords: Photovoltage electrolysis, hydrogen gas, water electrolysis, temperature

1. Introduction

Global warming and the energy crisis have emerged as two significant concerns that require attention. Governments and individuals are actively working together to find solutions that protectthe environment and reduce fuel costs. This has led to the exploration of exciting technologies, including on-demand hydrogen production, to address these issues [1]. An energy crisis occurs when the demand for energy exceeds the supply, leading to shortages, high prices, and rationing. Factors such as natural disasters, political conflicts, and economic downturns can contribute to an energy crisis. The use of fossil fuels and non-renewable energy sources also contributes toenvironmental degradation and climate change, further exacerbating the problem [1]. The global population continues to grow, increasing the need for energy as living standards rise. The combustion of fossil fuels emits carbon dioxide into the atmosphere, contributing to environmentalissues. According to the International Energy Agency (IEA), the utilization of fossil fuels is projected to result in a 57% increase in CO2 emissions from 2005 to 2030 (U.S. Department of Energy, May 2017). These factors have made the issue of energy resources a global concern [2]. While the efficiency of renewable energy like solar technologies is currently relatively low, and further improvements in materials and catalysis are needed to enhance their efficiency [3].

Hydrogen serves as a versatile energy carrier, enabling the integration of intermittent renewableenergy sources and

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promoting decarbonization within the energy sector. By substituting fossil fuel-based carbon with alternative sources like captured CO2, biomass, or recycled plastic waste, hydrogen facilitates the "defossilization" process in sectors heavily reliant on carbon from fossil fuels [4]. Hydrogen's significance extends beyond energy supply for power and transportation. It holds the potential to revolutionize the energy landscape and contribute to the United Nations Sustainable Development Goals. With alternative methods and renewable energy sources availablefor hydrogen production, the shift from fossil fuel-dependent practices becomes feasible [5]

To tackle these challenges, hydrogen energy has emerged as a promising alternative totraditional non-renewable energy sources [6]. Photovoltaic electrolysis, which utilizes solar energyto produce hydrogen without emissions, has gained attention. Photovoltaic electrolysis, a method used for hydrogen production, is considered to be one of the most expensive options when comparedto fossil fuel alternatives [7]. Besides, the efficiency of this method has been limited, necessitatingfurther exploration. Increasing the temperature has been identified as a viable approach to enhancethe efficiency of photovoltaic electrolysis [8]. By increasing the outlet temperature, the efficiency of the process can be significantly improved [9]. We explore its potential for success, the timing ofits adoption, and its contribution to the attainment of Goal 7, which emphasizes affordable and cleanenergy [10-11].

2. Materials and Methods

In this case study, there were 15 equipment were used which were solar plane, power inverter, car battery, pulse-width modulation (PWM), wire, U-tube, lead, iron, salt water, gas syringe, thermometer,temperature sensor heater, plastic tube connector, rubber stopper for laboratory and stainless steel pot. While this equipment and material was set up successfully as shown in Figure 1.

2.1 Methodology Flow Chart

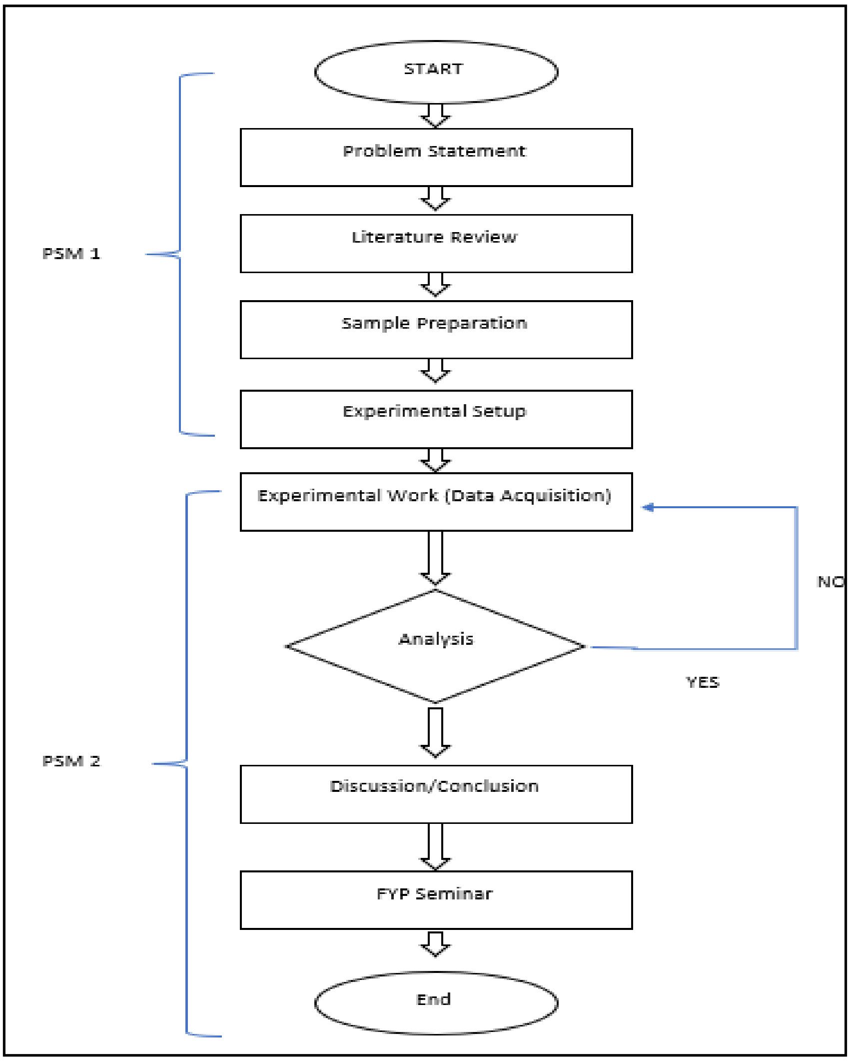

Fig. 1 - Research flowchart

2.2 Materials

Figure 2 shows photovoltage electrolysis was built in with 15 material and apparatus equipment. Photovoltage electrolysis can be divided into three parts which is solar system part, water electrolysis part and a part of heating. All the experiment procedure and preparation will be discussed in this chapter.

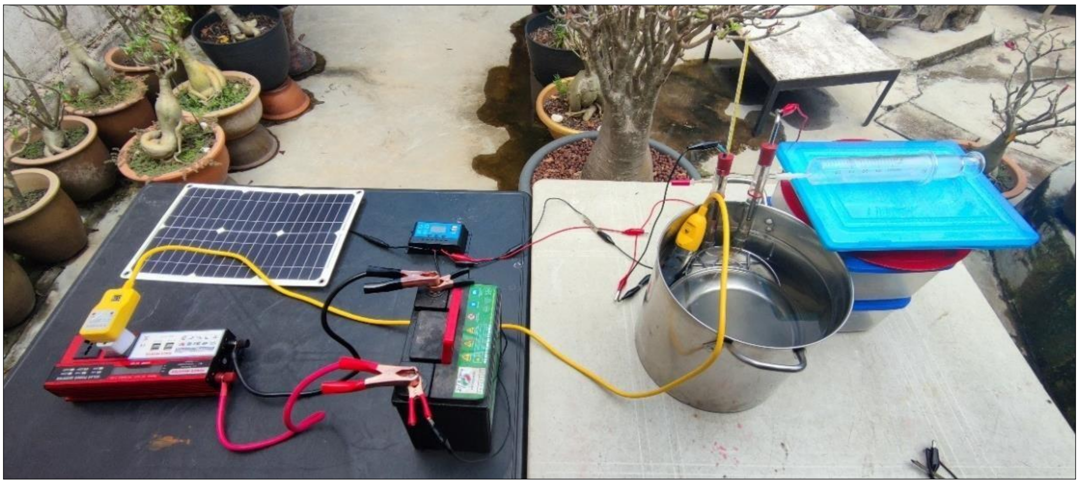

Fig. 2 - Photovoltage electrolysis system (front view)

Table 1 - Specification of the material and apparatus equipment

Component	Description
Solar Plane	18-Watt solar panel used in the experiment for photovoltaic electrolysis.Offers energy efficiency, sustainability, and cost-effectiveness.
Power Inverter	Device that converts DC electricity to AC electricity. Used to power AC appliances and devices.
Car Battery	12-volt lead-acid battery used for providing electrical energy to the experiment.
Pulse-Width Modulation (PWM)	Technique for controlling power delivery to electrical loads by rapidly turning the power on and off.
Wire	Flexible material made of metal (e.g., copper) used for conducting electricity.
U-Tube	Apparatus used to measure pressure differences. Can be heated externally or indirectly.
Lead	Heavy metal element (Pb) used as an electrode for conductivity.
Iron	Chemical element (Fe) commonly used as an electrode in electrolysis for hydrogen gas production.
Salt Water	Electrolyte solution used in electrolysis due to its conductivity, availability, cost-effectiveness, stability, and compatibility with electrode materials.
Gas Syringe	Device used to measure the volume of gases.
Thermometer	Instrument used to measure temperature.
Temperature Sensor Heater	Device combining temperature sensing and heating capabilities, powered by 12 volts.
Plastic Tube Connector	Device used to securely join plastic tubes or hoses.
Rubber Stopper for Laboratory	It is used to seal the openings of containers, preventing leakage and contamination.
Stainless Steel Pot	It is resistant to corrosion, conducts heat well, and comes in various sizes and shapes. While this stainless-steel pot was used in order to act as the medium equipment to indirect heating the U-tube through the water.

2.3 Experiment Set Up

- Position the solar panel or solar system in a location where it receives maximum sunlight exposure.
- Connecting the solar panel to the PWM controller using appropriate wiring, ensuring properpolarity and secure connections.
- Using suitable cables to store excess electrical energy into car battery from the PWM controller which had stabilised the current to avoid the over current flow in through the carbattery.
- Using the PWM controller to adjust the power output to the power inverter and load (anodeand cathode), allowing control over the current flow during the electrolysis process.
- While the temperature sensor heater was connected with power inverter to obtain the powersupply.
- Preparing the electrolysis cell setup by using the U-tube for holding the electrolyte.
- Filling the U-tube with the saltwater as electrolyte solution, ensuring a sufficient volume(60ml) to cover the electrodes.
- Inserting the iron electrode (cathode) and the lead electrode (anode) into the electrolyte,making sure they were adequately spaced and do not touch each other.
- Connecting the lead and iron electrodes to the positive and negative terminals of the powersource, respectively.
- Attaching a plastic tube connector to the gas syringe and connect it to the U-tube.
- Sealing the hole of anode side U-tube to ensure no pressure run away.
- Filling the water to the stainless pot in order to heating the water to act as a medium toindirect heating a U-tube.
- Immersing the U-tube to the stainless-steel pot half way to indirect heating the U-tube whilethe stainless-steel pot water was also act as a medium to transfer heat to U-tube.
- Position the thermometer in the electrolyte (U-tube), ensuring accurate temperaturemeasurement during the experiment.

2.4 Experiment Procedure

- Beginning by measuring and recording the initial temperature of the electrolyte using thethermometer.
- Start the experiment by activating the solar panel or solar system to provide power to theelectrolysis cell setup.
- The beginning electrolyte temperature was started with 30 ℃ which was not heated.
- Monitoring and recording the current flow (fix current flow), gas production (in gassyringe), and electrolysis time.
- Each 5 minute, the volume gas production was recorded until 20 minutes.
- After 20 minutes (duration), stopping the electrolysis process and recording the finalcurrent flow and gas volume.
- Adjusting the temperature sensor heater to the second desired temperature (e.g., 40℃) andwait until the electrolyte reaches the target temperature.
- Once the desired temperature is reached, start the experiment by activating the solar panelor solar system to provide power to the electrolysis setup.
- Monitor and record the current flow, gas production, and electrolysis time.
- As similar, recording the data in each 5 minutes, stopping the electrolysis process at 20minute and recording the final current flow and gas volume.
- Repeating steps g-j for each desired salt water temperature (50℃, 60℃, 70℃, 80℃),adjusting the temperature sensor heater accordingly.
- Thoroughly clean the electrodes, electrolysis cell, and other equipment before proceedingto the next temperature setting.

2.5 Data Analysis

a. Compiling the recorded data, including each 5 minute and final temperatures, gas volume,and electrolysis times for each temperature setting.
b. Analysed the data to determine the effect of temperature on the photovoltage electrolysis process using iron and lead electrodes.
c. Calculate the rate of hydrogen gas production at each temperature condition by dividing the change in volume by the corresponding time interval. This will provide a quantitative measure of the rate at which hydrogen gas is produced for each temperature.
d. The calculation formula is such as below

Rate of hydrogen gas production at each temperature condition

$$= \frac{final\ volume\ of\ gas\ production - iniatial\ volume\ of\ gas\ production}{final\ time - initial\ time}$$

e. Present the data in a clear calculation utilizing tables and graphs.

2.6 Chemical Reaction Analysis in Electrode Cell

The electrolysis process using iron electrodes in saltwater (NaCl) electrolyte can be representedby the following chemical reactions and equations:

At the anode (oxidation reaction):
$2Cl^-$ (aq) → Cl_2 (g) + 2e-At the cathode (reduction reaction):
$2H_2O$ (l) + 2e- → H_2 (g) + $2OH^-$ (aq)
Overall reaction:
2NaCl (aq) + $2H_2O$ (l) → Cl_2 (g) + H_2 (g) + 2NaOH (aq)

In the process of electrolysis using iron electrodes in a saltwater (NaCl) electrolyte, Raza et al.(2014) explain that specific chemical reactions occur. At the anode, chloride ions (Cl-) are oxidized, resulting in the production of chlorine gas (Cl2). The choice of chloride ions for oxidation is due to theirabundance in the saltwater electrolyte. Meanwhile, hydroxide ions (OH-) are not selected for oxidationas they are more stable and require higher energy input compared to chloride ions. At the cathode, watermolecules (H2O) undergo reduction to form hydrogen gas (H2) and hydroxide ions (OH-). Overall, thiselectrolysis process leads to the generation of chlorine gas, hydrogen gas, and the presence of sodium hydroxide (NaOH) in the aqueous solution [1].

3. Results and Discussion

3.1 Identify The Optimal Temperature Conditions by Using Calculation Method

In order to identify the optimal temperature condition, the calculation about the rate of hydrogengas production at each temperature condition by dividing the change in volume by the corresponding time interval is applied. This calculation also provided a quantitative measure of the rate at which hydrogen gas is produced for each temperature. While the calculation is summarized as shown in Table 2 and Figure 3.

Table 2 - Data table for average rate of hydrogen gas production at different time intervals and temperatures

Temperature	**Time Intervals**			**Average ml/min**
	5-10 mi/min	**10-15 ml/min**	**15-20 ml/min**	
30℃	1.6	1.4	1.8	**1.6**
40℃	1.6	1.8	1.4	**1.6**
50℃	1.6	2.0	1.6	**1.73**
60℃	2.2	2.2	2.0	**2.13**
70℃	2.0	2.2	2.2	**2.13**
80℃	2.2	2.4	2.0	**2.2**
Averageml/min	**1.87**	**2.0**	**1.83**	**-**

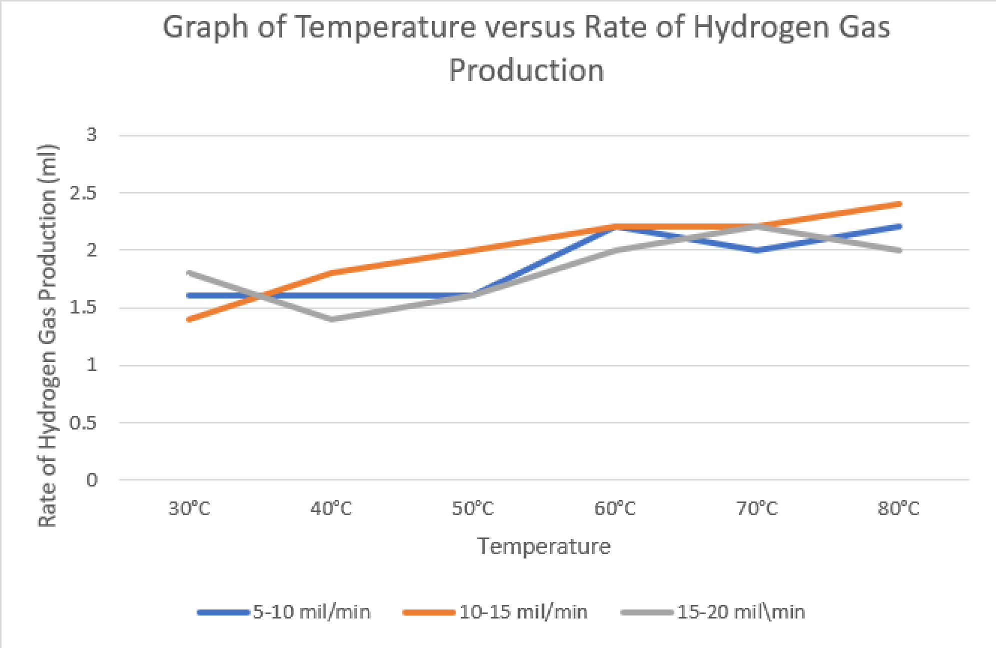

Fig. 3 - Graph of temperature versus rate of hydrogen gas production

3.2 Analysis the Optimal Temperature Conditions for Maximizing the Efficiency of Photovoltage

The highest average rates of hydrogengas production were consistently observed at a temperature of 80℃ across multiple time intervals. During the 5–10-minute interval, the rate was 2.2 ml/min at 80℃, while during the 10–15-minute interval, the rate was 2.4 ml/min at the same temperature as shown in Table 2 and Figure 3. Similarly, during the 15–20-minute interval,the rate was 2.0 ml/min at 80℃. The second highest rates were consistently seen at 60℃. Based on these findings, it can be concluded that 80℃ is the optimal temperature for achieving high efficiency in photovoltage electrolysis

3.3 Comparing The Effects of Temperature and Electrolysis Time on The Efficiency of Photovoltage Electrolysis

In our study comparing the effects of temperature and electrolysis time on the efficiency of photovoltage electrolysis, we analyzed the average rates of hydrogen gas production at different timeintervals for each temperature condition.

Regarding temperature comparison, we consistently observed the highest average rates of gasproduction at 80℃ across all time intervals (5-10 minutes, 10-15 minutes, 15-20 minutes, and overall). As the temperature increased from 30℃ to 80℃, the average rates of gas production generally increased or remained stable. This suggests that higher temperatures enhance the efficiencyof the photovoltage electrolysis process.

From a thermodynamic perspective, conducting electrolysis at higher temperatures is advantageous because a significant portion of the required energy is provided in the form of thermal energy. This reduces the primary electrical energy demand and improves reaction kinetics, resulting inlower electrical losses within the cell. Therefore, higher temperatures contribute to improved efficiency in photovoltage electrolysis [11].

Regarding time comparison, we found that the average rates of gas production were similar across different time intervals for all temperature conditions. Within the tested time range, electrolysistime did not have a significant impact on the process efficiency.

Overall, our findings indicate that temperature has a more pronounced effect on the efficiencyof photovoltage electrolysis compared to electrolysis time. Higher temperatures, particularly 80℃, result in higher average rates of hydrogen gas production. Electrolysis time within the tested range didnot show a substantial impact on efficiency.

These results highlight the importance of considering temperature as a key factor in optimizing the efficiency of photovoltage electrolysis for hydrogen gas production. By operating at higher temperatures, we can harness the benefits of improved reaction kinetics and reduced electrical losses,leading to enhanced overall efficiency in this sustainable energy conversion process.

4. Conclusion

In conclusion, our analysis of the data highlights the significant impact of temperature on the efficiency of photovoltage electrolysis for hydrogen gas production. Increasing the temperature from30℃ to 80℃ resulted in higher average rates of gas production, indicating that higher temperatures enhance the efficiency of the process. The optimal temperature conditions for maximizing efficiencywere consistently found to be 80℃, with the highest average rates of gas production observed at thistemperature. On the other hand, electrolysis time showed minor variations in the average rates of gas production, suggesting that it has a limited effect on the efficiency of photovoltage electrolysis. Further research is needed to fully understand the relationship between electrolysis time and gasproduction rates.

Overall, the findings emphasize the importance of temperature as a key factor in optimizing the efficiency of photovoltage electrolysis. The data indicate that variations in temperature have a morepronounced impact on the process efficiency compared to changes in electrolysis time. Moving forward, we recommend further research in the field of photovoltage electrolysis. Exploring advanced catalyst materials and electrode architectures can enhance system performanceand stability. Additionally, conducting experiments with a wider range of temperatures and electrolysis times will provide a more comprehensive understanding of their effects on efficiency. Furthermore, investigating alternative electrolyte compositions, such as non-aqueous or solid-state electrolytes, can offer opportunities for improved ion conductivity and overall system efficiency. These recommendations aim to contribute to the development and optimization of sustainable energy generation systems based on photovoltage electrolysis. By advancing our knowledge and understanding of this process, we can pave the way for more efficient and environmentally friendly hydrogen production, ultimately contributing to a greener and more sustainable future.

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