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Original Article

Development and Validation of a Hybrid Hydrogen Gas Detection System: Integrating Physical Phenomena, Electrical Conversion, and IoT Data Acquisition with Raspberry Pi Pico W

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Abstract *- This study explores the detection and monitoring of hydrogen gas production by dry-cell hydrogen generators in physical, electrical, and Internet of Things (IoT) for real-time hydrogen detection and monitoring. The physical tests employ two types of testing: bubble and balloon tests. Meanwhile, the electrical test is that the hydrogen fuel cell is connected directly to the motor load, whose function is to convert hydrogen gas into electricity to run the motor load. Two hydrogen sensors are connected to Raspberry Pi Pico W, an IoT-based monitoring system, to collect hydrogen gas. The result showed an audible explosion from trapped hydrogen bubbles, and balloon buoyancy due to hydrogen's low density was recorded. This result confirmed the successful production of hydrogen by a dry-cell hydrogen generator. The electrical conversion of hydrogen by a fuel cell to power a motor further validated the system's functionality. Two hydrogen sensors (MQ-8) are connected to the IoT-based microcontroller to detect the amount of hydrogen gas production. The results showed that hydrogen bubbles were produced by the hydrogen generator, which created an audible explosion when a lighter was ignited near the bubbles. The integration of IoT connectivity analysed and confirmed the limitations of the MQ-8 hydrogen sensor's operational boundaries. The results demonstrated that the MQ-8 module's hydrogen sensor works effectively below 8000 ppm. Operating the MQ-8 hydrogen sensor at levels higher than 8000 ppm can cause it to burn.*

Keywords *- Hydrogen sensor, Raspberry Pi Pico, IoT, Microcontroller, Fuel-cell.*

1. Introduction

The Malaysian government is working with industry to promote the use of energy-based hydrogen in developing countries, especially in the state of Sarawak. The goal is to make hydrogen from biomass gasification and renewable energy sources, including wind, water, and solar power. Concerns about air quality and climate change around the world have led to the development of hydrogen-based renewable energy. Hydrogen is useful in many parts of the economy and the world since it is flexible, cheap, safe, and can be made at home. Countries that are developed have used hydrogen energy for several things, such as an alternate fuel source [1-3]. Hydrogen can be produced from several resources, either from fossil fuels or renewable resources. A variety of process technologies, such as chemical, biological, electrolytic, photolytic, and thermochemical methods [1-3]. Each technology is in a distinct developmental stage, possessing unique opportunities, benefits, and challenges. Recent research investigates how to enhance the efficiency and reduce the cost of hydrogen production through the optimization of water electrolysis, particularly with renewable energy sources such as solar and wind [3-5].

Current studies focus on optimizing water electrolysis using renewable energy sources, such as solar and wind, and on using different techniques to generate hydrogen from natural gas while capturing the resulting carbon emissions to increase performance and lower hydrogen production costs.

This includes research on advanced electrolyzer configurations and electrode materials. Additionally, scientists are looking into using microorganisms to produce biological hydrogen from biomass [5-7]. Hydrogen is used in industrial operations, as well as in energy applications in vehicles, to supply power generation and energy storage. The applications of hydrogen benefited from clean hydrogen production via renewable energy sources, diversification of energy supply, etc. [7-10].

In electrical applications, fuel cells are used for the conversion of hydrogen gas into direct current electrical power. Much research focused on enhancing fuel cell performance, improving cost-efficiency in the development of new electrode materials and catalysts, upgrading electrolyte membranes, optimizing fuel cell design and system integration, and investigating various fuel cell types, including Proton Exchange Membrane (PEM) and solid oxide [11-13]. The applications concentrated on transportation (fuel cell cars, buses, trains, ships, and aeroplanes), fixed power generation (backup power, distributed power), portable power applications (electronics, military usage), and supplying electricity for unmanned vehicles, among others [14-16].

The integration of the Internet of Things (IoT) embedded in microcontrollers, such as the Raspberry Pi Pico, can capture real-time remote monitoring data, and analysis of hydrogen generation. The Raspberry Pi Pico, particularly the Pico W with integrated Wi-Fi, has emerged as a good option for IoT applications because of its affordability and adaptability. The Raspberry Pi Pico integrated Wi-Fi allows it to connect to network applications, including sensor data acquisition and transmission (temperature, humidity, pressure, etc.), home automation applications, environmental monitoring, industrial automation, and many more[17-19].

The Raspberry Pi Pico W, for example, can capture real-time data for remote monitoring and analysis of hydrogen generation. This may be applied in other applications, such as leak detection in hydrogen production, hydrogen storage, and transportation by sensing with hydrogen gas sensors. The Pico can be included in safety systems to facilitate real-time hydrogen monitoring and activate alarms in the event of dangerous situations. Furthermore, it functions as a data logger for further examination [19-21].

Most of the previous research studied the effect of current density, distance between the electrodes, and the temperature of the electrolyte on the bubble accumulation and, consequently, on the overall efficiency of water electrolysis at a particular concentration of the solution [17, 18].

Hydrogen gas is a very dangerous gas since it can explode when it comes into contact with fire. A monitoring system should be used when working with or conducting an experiment on hydrogen production. Furthermore, the accumulation of hydrogen bubbles on the surface of electrodes of a wet hydrogen generator had a negative impact on water electrolysis since the bubbles accumulated on the electrodes and rose to the surface slowly [22, 23]. An increase in the volume fraction of hydrogen or oxygen bubbles between the electrodes would cause an increase in the electric resistance in an aqueous solution, resulting in a decrease in the efficiency of water electrolysis. In contrast, the dry hydrogen generator can minimize the related issue.

This study presents the effective implementation of a customized system for generating hydrogen, along with the detection and monitoring of hydrogen gas by physical, electrical, and IoT testing methods. Limited research has been reported on the mini hydrogen generator regarding physical testing, electrical testing, and IoT testing using the Raspberry Pi Pico W.

This finding is important for determining whether a dry-cell hydrogen generator can produce more hydrogen than oxygen, as it produces Hydrogen-Hydrogen-Oxygen (HHO). Further studies could explore various other microcontrollers and different types of hydrogen generators, including wet cells and pure hydrogen dry cells powered by renewable energy.

2. Materials and Methods

A photograph of the completed custom-made hydrogen gas production system is shown in Figures 1 and 2. The main system comprises a dry cell hydrogen generator, a 100W, 12V power supply, and a PVC water tank (maximum 1 liter).

Silicon hoses are used to transport water and hydrogen gas between the PVC water tank and the dry cell hydrogen generator.

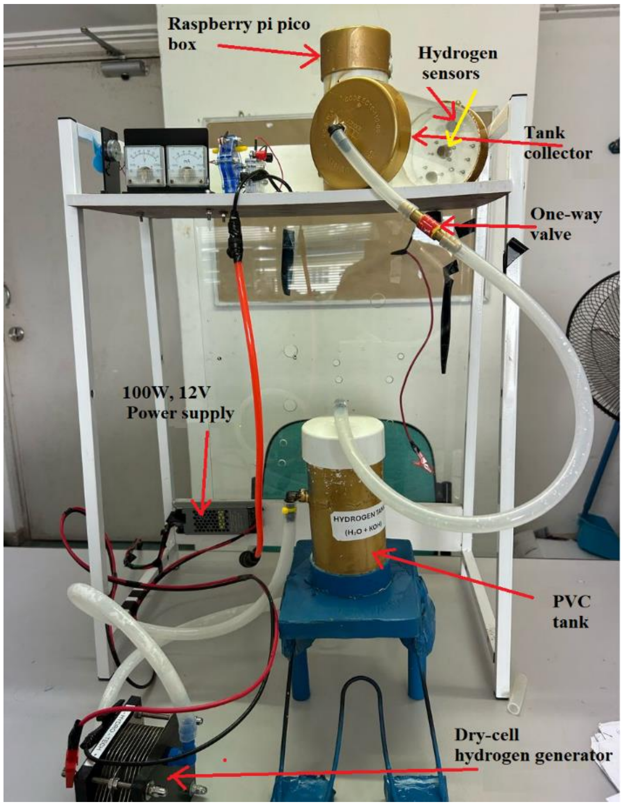


Fig. 1 Custom-made of hydrogen gas production and detection system

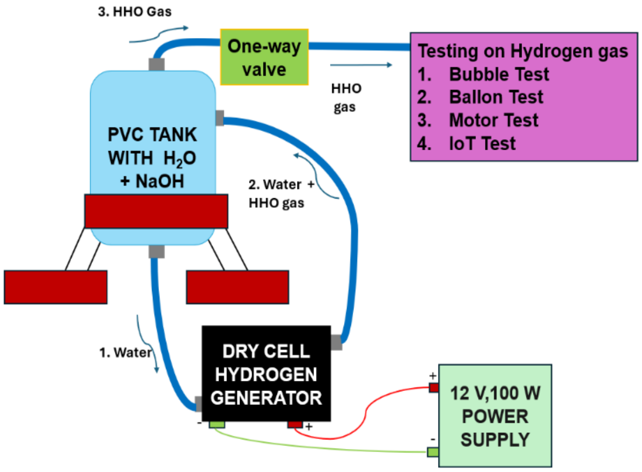


Fig. 2 Photograph of a custom-made hydrogen gas production and detection system

The developed system is equipped with a protected one-way valve, which ensures unidirectional hydrogen flow. A solution of potassium hydroxide (KOH) and water (H_2O) was prepared in the tank and circulated using the dry cell hydrogen generator. The KOH will dissociate in the water to form an aqueous solution of potassium and hydroxide ions. The process could be referred to as Equation 1 [24].

$$Na^{+}OH(s) + H_2O\ (liq) \rightarrow Na^{+}(aq) + OH^{-}(aq) \qquad (1)$$

When a solution of sodium hydroxide (NaOH) and water (H_2O) is passed through a dry cell hydrogen generator, the primary process that occurs is electrolysis (2).

$$\text{Electricity} + 2H_2O\ (liq) \rightarrow 2H_2(gas) + O_2(gas) \qquad (2)$$

In the electrolysis process, water molecules (H_2O) are split into hydrogen (H_2) and oxygen (O_2) as represented in Equation 2 [24]. The dry cell hydrogen generator separates water into hydrogen and oxygen when supplied with an electrical current. The sodium hydroxide (NaOH) acts as an electrolyte. This means it increases water's conductivity, making the electrolysis process more efficient. It does this by providing ions that carry the electrical current.

Several tests were conducted to verify the production of hydrogen gas by the generator, including non-electrical tests (balloon and bubble tests) and electrical tests (DC motor and hydrogen sensor tests within an IoT environment). Note that, all experiments are done separately. The balloon test involved directly connecting a balloon to the PVC tank's output, allowing it to inflate until it was sufficiently large and light. The bubble test employed a lighter to confirm the existence of hydrogen gas captured within soapy water bubbles.

Figure 3 depicts a pictorial diagram of the developed IoT monitoring system. The system, programmed in Visual Studio Code, utilizes a Raspberry Pi Pico W to coordinate all components. To enable data visualization on Adafruit IO, the platform was configured, and its DataStream feature was implemented.

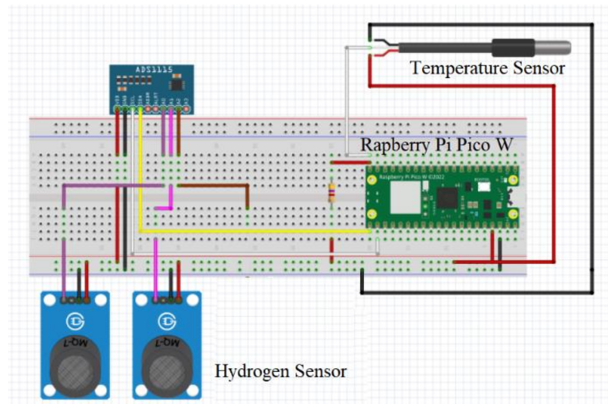


Fig. 3 A pictorial breadboard diagram of the developed IoT monitoring system by using Raspberry Pi W

This DataStream displays sensor data transmitted from the Pico via Wi-Fi, including temperature and hydrogen gas levels. Specifically, the DataStream maps 'gas1', and 'gas2' to the readings from the two MQ-8 hydrogen gas sensors, and 'temperature' to the DS18B20 temperature sensor. The IoT monitoring system comprises the Pico W, the DS18B20 sensor, and two MQ-8 sensors. The two MQ-8 sensors are positioned within an acrylic collection tank (as shown in Figure 1) to detect increases in hydrogen gas production. The DS18B20 sensor monitors the generator plate temperature, ensuring it remains below 55 °C to prevent malfunctions. Sensor data is recorded and collected within the IoT environment using Google Sheets for user analysis of hydrogen production.

3. Results and Discussion

3.1. The Bubble Test: A Preliminary Assessment of Gas Output

To test the hydrogen generator's ability to produce hydrogen gas, the hose nozzle was placed in a beaker containing soapy water, as shown in Figure 4. After more than 5 minutes, foam began to emerge from the nozzle and collect within the soapy water, as depicted in Figure 4.

The foam volume increased over time, indicating continued gas production. Hydrogen and oxygen gases produced from electrolysis are trapped and accumulated together to form a bubble in soapy water.

This phenomenon was explained in Equation 2. When a lighter was brought near the bubble foam, a rapid combustion and explosion occurred due to the presence of hydrogen reacting with fire. Hydrogen, oxygen, and fire can create combustion and an explosion. A one-way valve is attached to the system to protect the fire from reacting with hydrogen in the hydrogen generator.

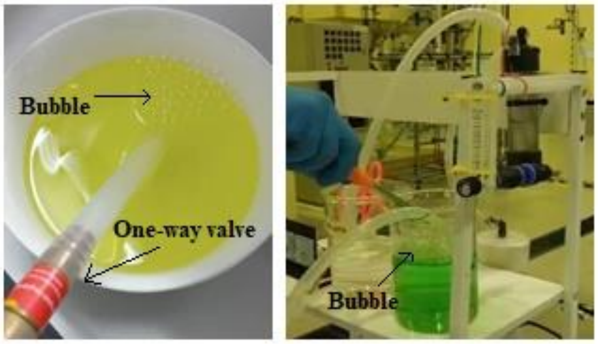


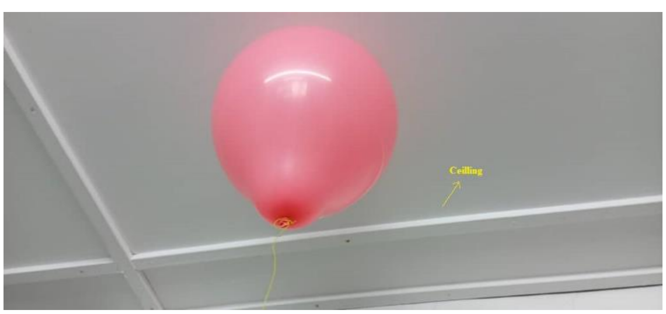
Fig. 4 Bubbles captured after 5 minutes supplied with power

This reaction demonstrates that the hydrogen generator successfully produced hydrogen gas, which then reacted with the flame, resulting in a loud explosion.

3.2. Ballon Test

Figure 5 shows the balloon test that was done 25 minutes later. (a) A balloon was attached to the PVC tank right away to speed up the production of hydrogen by the hydrogen generator. After more than 25 minutes, the inflated balloon reached the ceiling because it was big enough and buoyant enough.

(a)



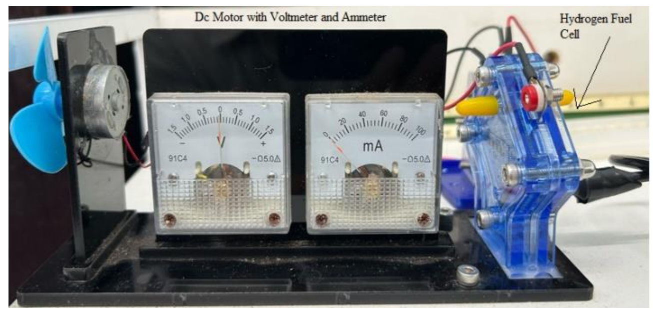
(b)

Fig. 5 Illustrates the balloon test after 25 minutes: (a) a balloon directly connected to the PVC tank, and (b) the inflated balloon rising to the ceiling due to its buoyancy

The hydrogen generator produced a combination of hydrogen and oxygen, or HHO, with a ratio of 2:1. When the balloon was connected to PVC (refer to Figure 5(a)), the number of gases (a combination of HHO) that entered the balloon was high, resulting in the inflated balloon. The inflated balloon is not enough to raise the balloon until the hydrogen inside the balloon is higher than the air pressure. This test revealed that hydrogen gas can elevate the balloon when its density is significantly lower than that of air, as hydrogen is lighter than air. The results indicated that hydrogen levels were adequately elevated when the inflated balloon was seen after 25 minutes.

3.3. Motor Performance and Reliability Test

Figure 6 demonstrates the successful operation of the motor under test load using a hydrogen fuel cell. Note that the motor test load is very sensitive to low current (below 20 mA) and voltage (below 1V).



(a)

(b)

Fig. 6(a) Motor stops when no hydrogen gas is received by the hydrogen fuel cell, and (b) Motor runs after the fuel cell converts hydrogen gas into current.

It was recorded from the motor test, only 0.7 V and 15mA current was used enough to make the motor run. The motor runs when enough current and voltage are supplied to the motor.

A hydrogen fuel cell converts the chemical energy of hydrogen into electricity through an electrochemical reaction. A fuel cell has two electrodes: an anode (negative) and a cathode (positive). Hydrogen is fed to the anode, where a catalyst splits it into protons and electrons. Protons pass through an electrolyte membrane to the cathode.

Electrons, unable to pass through the membrane, flow through an external circuit, creating an electric current. At the cathode, protons, electrons, and oxygen combine to form water.

3.4. IoT Test

The Raspberry Pi Pico W, connected to temperature and hydrogen sensors, provides remote monitoring through an IoT connection. The Raspberry Pi Pico W collects temperature and hydrogen levels and sends the data to an IoT platform. Figures 7 and 8 show the results of temperature and hydrogen gas in parts per million (ppm), respectively.

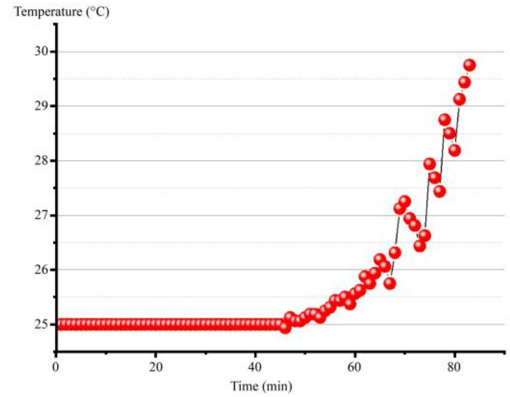


Fig. 7 Metal plate temperature of hydrogen generator versus time

Figure 7 illustrates the temperature readings recorded by the sensor on the metal plate of the hydrogen generator throughout a duration of 0 to 80 minutes by Raspberry Pi Pico W in an IoT environment. It is found that the temperature sensor remains unchanged from 0 to 40 minutes. After 50 minutes, the temperature rose slightly from 25°C to approximately 26°C. After 70 minutes, the temperatures increased consistently from 27°C to 30°C. The results indicate that an increase in time considerably affects temperature variations. Nonetheless, this temperature is typically below 55°C under normal conditions. It can be concluded that the supplied power of 12V and 100W is appropriate for this application.

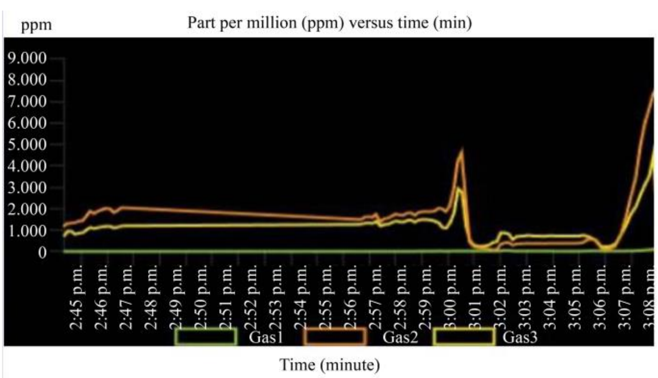
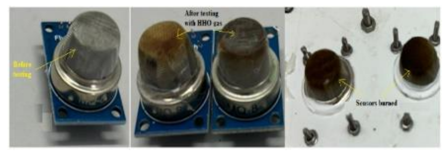


Fig. 8 Hydrogen gas collected over time by using hydrogen gas sensors in an IoT environment

Figure 8 shows the collection of hydrogen gas within 15 minutes in an IoT environment. As can be shown in Figure 8, two hydrogen gas sensors (orange and yellow lines) successfully responded to hydrogen gas testing, with the highest value obtained around 8000 ppm (orange line) and 6000 ppm (yellow line). The orange line on the hydrogen sensor displayed a higher value than the yellow line. This indicated that the hydrogen sensor's location affected the results. Within 15 minutes, the amount of hydrogen gas produced is around 2000 ppm. The power shut-off after 15 minutes led to a drastic decrease and subsequent drop in hydrogen gas. When the power is on again, the high concentration of hydrogen gas captured increases from 1000 ppm to 8000 ppm. Numerous retests reveal that the maximum concentration of hydrogen gas does not exceed 9000 ppm. The hydrogen sensor was burnt out; it reached above 8000 ppm.



(a) Before testing, (b)-(c) After testing
Fig. 9 (a) The Hydrogen Sensor before testing, and (b) and (c) the physical damage to the Hydrogen Sensor after exposure to high concentrations.

The experiment also showed an operational limit of the MQ-8 hydrogen gas sensors. As the hydrogen concentration approached and then surpassed 8000 ppm, the sensor represented by the orange line became saturated, or "burnt out". Figure 9 shows, (a) the hydrogen sensor before testing, and (b) and (c) the physical damage to the hydrogen sensor after exposure to high concentrations. This failure indicates that the sensor's measurement capabilities were exceeded (refer to Figure 9(b) and (c)), indicating its maximum operational limit. This observation is crucial for understanding the system's performance and highlights the need for sensors with a higher detection range for applications that might produce higher concentrations of hydrogen gas.

4. Conclusion

A preliminary test of gas output confirmed that this system produced hydrogen gas, which resulted in explosive phenomena when it was exposed to fire. The secondary test showed the balloon became bigger and buoyant over time, while the third test demonstrated that this gas successfully ran a motor through a mini fuel cell. Furthermore, the integration of a Raspberry Pi Pico W-based IoT system enabled real-time monitoring and data collection that significantly enhanced both safety and data accessibility. Operational boundaries, or saturation points, for the hydrogen sensor MQ-8 operated well below 8000 ppm and burned above 8000 ppm. These findings validate hydrogen generation by this system but also determine the critical limitations of the hydrogen gas sensor.

Acknowledgments

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