UNIVERSIDAD DISTRITAL
FRANCISCO JOSÉ DE CALDAS

Visión Electrónica
Algo más que un estado sólido
https://doi.org/10.14483/issn.2248-4728

VISIÓN ELECTRÓNICA

A RESEARCH VISION

Proposal for a hydrogen-based energy system for decarbonization applications in the Colombian Air Force.

Propuesta de un sistema energético basado en hidrógeno para aplicaciones de descarbonización en la Fuerza Aérea Colombiana.

Renso Mardu Molano Pulido[1], Daniel Alberto Arteaga Puentes[2], Luis Armando Ariza Ariza [3],

INFORMACIÓN DEL ARTÍCULO

Historia del artículo:
Enviado: 14/08/2025
Recibido: 01/11/2025
Aceptado: 17/11/2025

Keywords:
Prototype
Hydrogen generator
Electrolysis
Electrolyte
Voltaje

Palabras clave:
Prototipo
Generador de hidrógeno
Electrolisis
Electrolito
Electrolito
Voltaje

ABSTRACT

The objective of this study was the construction of a hydrogen generating prototype for use as an energy source in the Aeronautical Support Ground Equipment of the Colombian Air Force, which will reduce the generation of CO2, and thus help reduce environmental pollution and contribute to the decarbonization process of the institution.

In the present research, three phases were established in the design of the hydrogen generator prototype depending on the specific objectives. In the first phase, the criteria and technical specifications for the development of the hydrogen generator were established. In the second phase, the electrolysis method could be established, taking into account that it is the most mature and economical technology. And in the third phase, tests were carried out with the two prototypes designed.

In the different tests, it was recorded that as the concentration of potassium hydroxide increased, the production of hydrogen increased. In the tests with 6g of electrolyte in the solution and at 9v, between 200 to 360 parts per million of hydrogen were obtained, when the electrolyte was increased to 11g and at 9v, 300 to 400 parts per million of hydrogen were obtained. Another resulting aspect was that the electrolyte and the applied voltage increased, the greater the current. It was possible to conclude that with 19 % of electrolyte used, the voltage levels were between 3.7 to 6 volts, with a consumption of 12 to 15 amperes and a production of between 300 to 600 parts per million of hydrogen, being the most stable levels.

RESUMEN

El presente estudio tuvo como objetivo la construcción de un prototipo generador de hidrógeno para su utilización como fuente energetica en los Equipo Terrestre

1. Ingeniero Electrónico, Fundación Universitaria Los Libertadores, Colombia. Maestrando en Eficiencia Energética y Energías Renovables, UNADE, México. Docente: ESUFA, Colombia. E-mail: renso.molano@esufa.edu.co. ORCID: https://orcid.org/0000-0002-0646-3589

2. Ingeniero Aeronáutico, Fundación Universitaria Los Libertadores, Colombia. Maestrando en Ingeniería con énfasis en Mecánica, ECCI. Docente: ESUFA, Colombia. E-mail: daniel.arteaga@esufa.edu.co.

3. Técnico especialista en aviónica de aeronaves, Inter American Air Forces Academy, USA. Docente: ESUFA, Colombia. E-mail: luis.arizaa@esufa.edu.co.

Cite this article as: R. Molano, D. Arteaga, L. Ariza, "Proposal for a hydrogen-based energy system for decarbonization applications in the Colombian Air Force.", Visión Electrónica, vol. 19, no. 2, 2025.

de Apoyo Aeronáutico de la Fuerza Aérea Colombiana, que permitirá disminuir la generación de CO2, y así ayudar a la reducción de la contaminación del ambiente y contribuir al proceso de descarbonización de la institución.

En la presente investigación se establecieron tres fases en el diseño del prototipo del generador de hidrógeno en función de los objetivos específicos. En la primera fase se establecieron los criterios y especificaciones técnicas para la elaboración del generador de hidrógeno. En la segunda fase se pudo establecer el método de electrolisis, teniendo en cuenta que es la tecnología más madura y económica. Y en la tercera fase se realizaron pruebas con los dos prototipos diseñados.

En las diferentes pruebas, se registró que conforme aumentaba la concentración de hidróxido de potasio incrementaba la producción de hidrógeno. En las pruebas con 6g de electrolito en la solución y a 9v se obtuvieron entre 200 a 360 partes por millón de hidrógeno, cuando se aumentó el electrolito a 11g y a 9v, se obtuvo de 300 a 400 partes por millón de hidrógeno. Otro aspecto resultante fue al aumentar el electrolito y el voltaje aplicado, mayor era la corriente. Se pudo concluir que con un 19 % de electrolito utilizado los niveles de voltaje fueron entre 3,7 a 6 voltios, con un consumo de 12 a 15 amperios y una producción de entre 300 a 600 partes por millón de hidrógeno, siendo los niveles más estables.

1. Introduction

Over the past decade, the effects of global warming have continued to intensify due to various human activities, leading to an increase in greenhouse gas emissions and a rise in global surface temperatures of around 1.1°C. Unfortunately, global greenhouse gas emissions have kept climbing, mainly because the use of unsustainable energy sources persists [1].

Currently, fossil fuels remain the world's primary source of energy. According to the Energy Institute (IE), in 2022 fossil fuels still accounted for 82 % of global primary energy consumption [2]. Reducing our reliance on coal, oil, and gas is therefore a key objective of several international environmental programs, such as the 2030 Agenda and its Sustainable Development Goals (SDGs), as well as the Paris Agreement [3].

Lowering CO_2 emissions requires action across all economic, social, and academic sectors of a country. In Colombia's case, under the framework of the 2030 Agenda and the SDGs, the Colombian Air Force is committed to improving various operational processes and equipment to become more sustainable. These efforts align with the measures that must be implemented in the transportation sector, as outlined in Law 2169 of 2021. This law promotes low-carbon development across different economic sectors through the establishment of minimum targets and actions aimed at achieving climate neutrality and resilience. In the case of the transport sector, the Special Administrative Unit of Civil Aeronautics (Aerocivil) [4] must support these processes.

Colombia ranks 137th out of 184 CO_2-emitting countries, with the list ordered from least to most polluting [5]. Given this position, Colombia must take more decisive action to reduce CO_2 emissions. The aviation sector must play a significant role, as it has grown steadily by 3.3 % since 2010 and, despite ongoing efforts, remains one of the largest emitters of CO_2 within the transport sector [6].

In response to these challenges, there are several lines of research as internal as external have been developed focusing on alternative fuels. One such initiative proposes designing a prototype hydrogen generator to analyze the variables that affect hydrogen production under different conditions. The goal is to optimize the functionality of internal combustion engines and achieve a meaningful environmental impact. This project would be a pioneering effort within the institution, initially aiming to enhance the performance of vehicles currently using internal combustion engines within the Aeronautical Ground Support Equipment (ETAA) found in various Air Force units. If successful, the technology could later be applied to other equipment using similar engines.

1.1. State of the art

Hydrogen is currently in a highly favorable position within the renewable energy landscape. It is widely regarded as one of the most promising energy sources for the future, especially in terms of environmental sustainability. Over the past decade, studies have explored how increasing hydrogen usage could impact energy generation [7].

Recent research has focused on producing hydrogen more efficiently and at lower costs. One such study by Delfín Capote (2021) examined the energy balance of a hydrogen battery used to power a vehicle, aiming to reduce its CO_2 emissions.

Likewise, Sanz (2022), a student from León, Spain, emphasized the critical role of hydrogen in decarbonization efforts. His work highlighted green hydrogen as a viable solution for meeting the emission reduction targets set by various international climate agreements.

In terms of practical applications, Cabrera (2022) designed and assembled a small-scale hydrogen generator for integration into a gasoline engine. The goal was to reduce emissions of both CO_2 and nitrogen oxides (NOx).

In Mexico, studies have explored hydrogen generation and applications. One investigation involved the development of a modular reaction system to evaluate the production of hydrogen and oxygen through water electrolysis, considered the most environmentally friendly method. A device was built to perform electrolysis using a dry-cell system, powered by solar panels, allowing researchers to compare the energy input required for hydrogen and oxygen generation [8].

De la Fuente (2019) proposed three design variations for a hydrogen generator using the same materials, with differences in the steel plates used to facilitate the electrolysis process that separates water molecules into hydrogen and oxygen.

Rojas (2020) designed and built a direct current-powered electrolyzer, equipping it with suitable instruments to measure the amount of hydrogen produced.

In Honduras, Matamoros (2020) studied the separation of hydrogen from water, noting that a sufficiently high voltage is needed to break the chemical bond. His findings showed that higher voltages improved hydrogen production.

At the regional level, Ecuador developed and installed a hydrogen generation system in a Corsa vehicle. This system included hydrogen-producing cells, a storage tank, various electrical components, piping, and chemical agents to enhance the water reaction during electrolysis. After many tests—supported by the Environmental Department of Quito—the project yielded positive results in reducing gas emissions and fuel consumption [9].

In Peru, a dry-cell hydrogen generator was installed in a gasoline engine vehicle to reduce CO_2 emissions. The aim was to improve fuel efficiency and reduce greenhouse gas emissions by enriching the fuel mixture with hydrogen rather than completely replacing gasoline. Different concentrations of electrolytes were tested to find the most efficient hydrogen flow rate before installing the system in the vehicle's engine [10].

Similarly, in Colombia, Guerrón (2022) proposed a green hydrogen generator designed for marine conditions, incorporating an electrolyzer that could function directly with seawater. The objective was to maximize renewable energy use in coastal regions, which hold significant potential for clean energy development.

Another Colombian project involved the design and construction of a hydrogen generator prototype through microfabrication, with the goal of storing solar energy for thermal heat generation applications [11].

In another case, Rojas and Quilaguy (2016) developed an alkaline water electrolyzer for hydrogen production, optimizing the system by adjusting the concentration of potassium hydroxide (KOH) electrolyte—finding that 30 % concentration yielded the best hydrogen output [12].

In recent years, different studies around the world have focused on hydrogen generators and their diverse applications—from welding torches and stove burners to natural gas replacements and even two-stroke engines for bicycles. For example, Rodríguez and collaborators (2022) designed, built, and tested a hydrogen generator for a two-stroke motorized bicycle as an alternative urban mobility solution in Bogotá. Their aim was to leverage hydrogen (H_2) to create innovations that help mitigate the city's environmental impact [13].

1.2. Methodology

1.2.1. Research Design and Type

The approach of this research is mixed method, as it incorporates both qualitative and quantitative methods to integrate multiple perspectives and achieve the stated objective.

On the qualitative side, the study involved the collection, review, and analysis of bibliographic sources, including research articles related to the topic. Theses focused on the construction and implementation of hydrogen generators in internal combustion engines, as well as specialized databases outlining the parameters of the most mature technologies used in hydrogen production.

On the quantitative side, data were gathered through a survey administered to personnel responsible for the various Aeronautical Ground Support Equipment (ETAAS) across the different Commands and Air Groups of the Colombian Air Force (FAC) nationwide. This survey provided statistical insight into the number of active ETAAS units. Additionally, measurements were taken of hydrogen flow to determine how much hydrogen the generator produced under different voltage levels, helping to establish behavioral patterns and validate the research hypothesis.

This study also adopts experimental research methodology. Once the prototype was designed, a series of tests were conducted to evaluate its efficiency. One of these tests involved using potassium hydroxide (KOH) as the electrolyte in the electrolysis process. The concentration of KOH in the distilled water solution, in which the electrodes were submerged, was carefully controlled. The voltage supplied to the hydrogen generator was also regulated. The aim was to determine the optimal combination of KOH concentration and voltage for maximizing hydrogen production.

1.2.2. Evaluation Instruments

In this study, the design of the hydrogen generator prototype was structured into three phases, aligned with specific research objectives.

In the first phase, the technical criteria and specifications for building the hydrogen generator were established. To do this, a comprehensive information-gathering process was conducted, focusing on hydrogen generation techniques and various design approaches. This information was sourced from books, academic theses, and research studies from several countries, all accessed through verified repositories of well-known universities.

The second phase involved selecting the electrolysis method, as it is considered the most mature and cost-effective technology for hydrogen production. This method requires electrode to be made from a material that is resistant to water corrosion, as it remains submerged during the process.

In the third phase, tests were conducted using the first prototype. This initial model was assembled in a glass container measuring 17 cm in height and 7 cm in diameter. The electrode consisted of 16 washers made from 304L stainless steel, resulting in a total length of 11 cm. Following this, a second, larger prototype was constructed. This version was assembled in a cylindrical container with a 1.6-liter capacity. The electrode for this second prototype consisted of 20 hexagonal plates of 304L stainless steel, measuring 23 cm in length.

2. Prototype Development

2.1. Criteria and Technical Specifications

To define the criteria for the hydrogen generator, research was conducted using seven books focused on hydrogen theories, which explored various hydrogen production methods. This helped determine the most suitable method for building the prototype. The most important criterion considered was selecting the most mature and cost-effective technology for hydrogen production. Based on this, materials were chosen that were easy to obtain, affordable, and resistant to water corrosion.

Regarding the technical specifications, information was gathered by reviewing various hydrogen generator designs. This research drew on fifty theses and academic studies from different countries, sourced from verified repositories of well-known universities. The technical specifications indicate that the generator must include both an anode and a cathode, which must be fully isolated from each other to prevent accidents making careful electrode assembly essential. The electrode is submerged in a solution composed of distilled water and 30 % KOH electrolyte. Additionally, a bubbler must be inclded as a safety mechanism to protect the electrode from any potential backfire and prevent damage to the prototype.

2.2. Identification and Selection of Materials

With the criteria and technical specifications of the prototype clearly defined, the method for hydrogen generation and the necessary materials for assembling the prototype were established. Electrolysis was chosen as the method—a process in which electricity is applied to water to cause the dissociation of hydrogen and oxygen. As defined by Guerrón (2021) in the description of the electrolyzer, this method also was used in the research by Fuente (2019).

Based on this, it was determined that a corrosion-resistant material was needed, as both water and the electrolyte cause a chemical reaction. Various studies that used electrolysis for hydrogen generation were consulted. Accordingly, 304L stainless steel sheets were used in both prototypes developed in this study, which aligns with the findings of Cabrera (2022). In industry, the most efficient electrodes are made from platinum and iridium, but these materials are rare and expensive, which goes against one of the established criteria: the use of cost-effective and easily accessible materials.

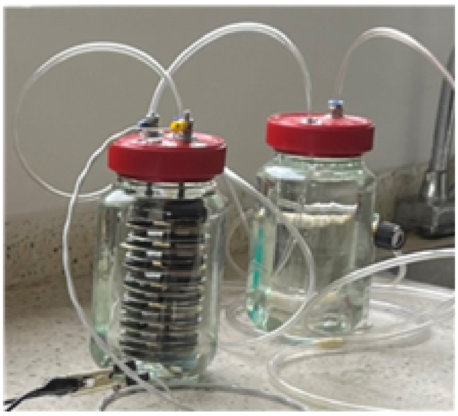
Based on the above and the findings from multiple studies, stainless steel was identified as the most suitable material for building the electrode due to its affordability and availability. For the construction of the electrode, 304L stainless steel washer-shaped pieces were used, each with a diameter of 40.95 mm, a thickness of 1.35 mm (Figure 1), and a weight of 10.6 g. Each washer had two holes allowing them to be mounted onto a 3/16-inch stainless steel threaded rod, using stainless steel nuts, silicone gaskets, and heat shrink tubing to insulate the anode from the cathode.

Figure 1: Measurements of the stainless-steel washers.

Source: Own.

Two glass containers measuring 17 cm in height and 7 cm in width were also used—one to hold the electrode and the other to function as the bubbler. Each container was fitted with a customized lid: the electrode container included the electrode and its corresponding outlet, while the bubbler had one inlet for the gas coming from the generator and another outlet for the released hydrogen, as shown in Figure 2.

Figure 2: Hydrogen Generator and Bubbler



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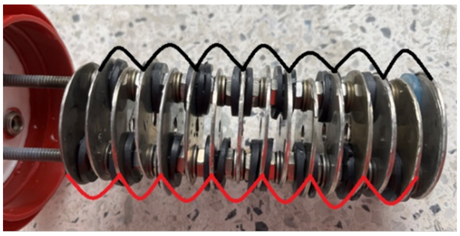
2.3. Assembly of the First Hydrogen Generator

With all materials selected and organized, the assembly of the electrode began, considering the technical specifications for the anode and cathode. Stainless steel washers, threaded rods, nuts, steel washers, silicone gaskets, and heat-shrink tubing were prepared—essential elements to ensure proper insulation between the anode and cathode. This structure follows the design proposed by Cabrera (2022) and Tito (2022), who also developed hydrogen generators. The assembly started by placing the first washer onto a threaded rod and securing it with metal washers and nuts. Then, the second rod was insulated using a silicone washer and heat-shrink tubing. It was inserted into the opposite hole of the washer, so that one washer was in direct contact with the rod while the other remained insulated. This alternating pattern was continued for the entire structure. Once completed, a thorough check was performed to ensure that the anode and cathode were fully insulated from one another, preventing any possible accidents. Each stainless-steel plate was confirmed to be properly separated, as shown in Figure 3.

Figure 3: Structure and insulation check of the anode and Cathode.



Source: Own.

Subsequently, the electrode was installed onto the lid of one of the selected glass containers. It was securely fastened and sealed to prevent any hydrogen leakage. Then, the gas outlet was created, and a quick-connect fitting was used to attach the hose that channels the gas to the previously assembled bubbler. The complete prototype can be seen in Figure 4.

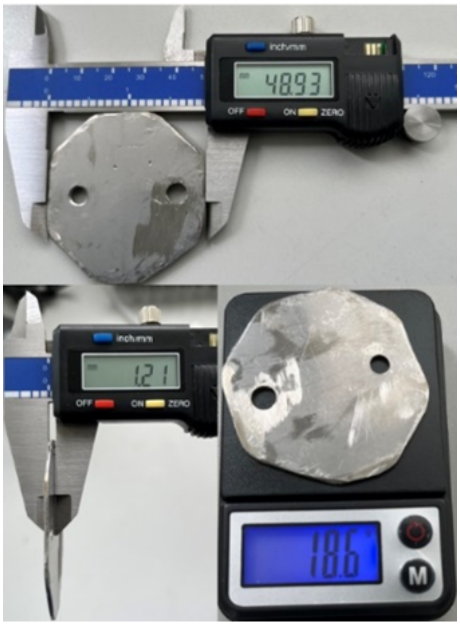
Figure 4: Structure and insulation check of the anode and Cathode.

Source: Own.

2.4. Assembly of the Second Hydrogen

The same assembly procedure used for the first prototype followed for the second one, with the main difference being the use of 304L stainless steel plates in this version. These plates measured 48.93 cm in length, had a thickness of 1.21 cm, and weighed 18.6 g (see Figure 5)

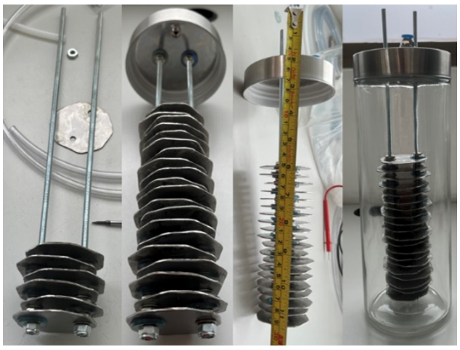
Figure 5: Dimensions of the Steel Components in the Second Prototype.



Source: Own.

The electrode assembly followed the same guidelines as the first prototype, with particular care taken to ensure the anode was properly insulated from the cathode. The main difference in this electrode was the size of the steel plates and the number of pieces used—20 steel plates were assembled, and the electrode measured 30 cm in length, compared to the 11 cm length of the first prototype. The assembly process is shown in Figure 6.

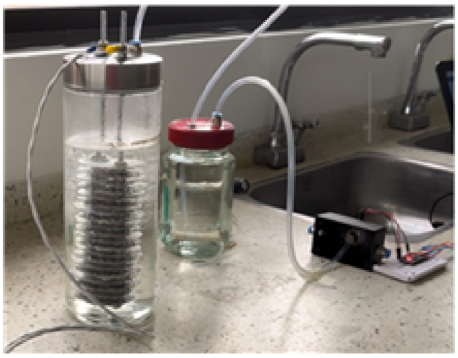
Figure 6: Assembly of the second electrode.



Source: Own.

Once the generator was assembled, it was interconnected with the bubbler (Figure 7), it is like the first prototype. The difference from the previous one was the outlet hoses: in this case, one-fourth (1/4) inch hoses were used, which are of a larger gauge than the 3/16-inch hoses used in the first prototype.

Figure 7: DSecond prototype assembled.



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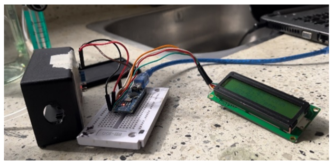
3. Results of the Two Hydrogen Generator Prototypes

Due to the difficulty in acquiring a hydrogen gas meter—primarily because of its high cost—a method for measuring hydrogen gas was explored. As a result, the MQ-8 hydrogen sensor was identified as a suitable alternative, given its high sensitivity to hydrogen concentrations in the air and its detection range from 100 to 10,000 ppm (parts per million). Notably, this sensor was also employed in the study conducted by Matamoros (2020). A digital measurement system was subsequently developed using the MQ-8 sensor (see Figure 8), incorporating an Arduino Nano microcontroller, a 2x16 LCD display, and serial communication with a personal computer. This system enabled the acquisition and visualization of hydrogen production data in ppm, allowing for both data logging and graphical representation of the process.

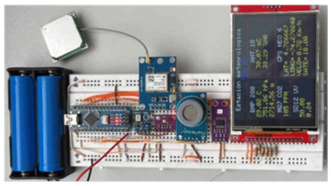
Figure 8: Digital Hydrogen Meter.



Source: Own.

Due to the production of gas, it was necessary to consider meteorological conditions. For this reason, measurements were taken of altitude, atmospheric pressure, UV intensity, CO_2 concentration in the air, GPS location coordinates, humidity, and temperature of the laboratory where the tests on both prototypes were conducted. A meteorological station was set up for this purpose, as shown in Figure 9.

Figure 9: Meteorological station.



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3.1. Testing of the First Hydrogen Generator.

The initial conditions were established by preparing the generator with 600 cc of distilled water and 5.5 g of KOH. Once sealed, the system was connected to the digital meter. The voltage variable was modified at different levels. Initial testing was conducted at 3.7 V. It was observed that the digital meter presented issues due to the MQ8 sensor being enclosed in a plastic case with only one inlet and one outlet. However, the hydrogen concentration exceeded the sensor's threshold, saturating it and thereby disabling the measurement system. To address this issue, the sensor housing was opened, leaving the sensor exposed. The hose from the bubbler outlet—where the hydrogen exits—was placed near the sensor, allowing for stable readings to be obtained. These results (see Table 1) are consistent with findings reported by Matamoros (2020), who observed that increasing the voltage applied to the electrode led to higher hydrogen production.

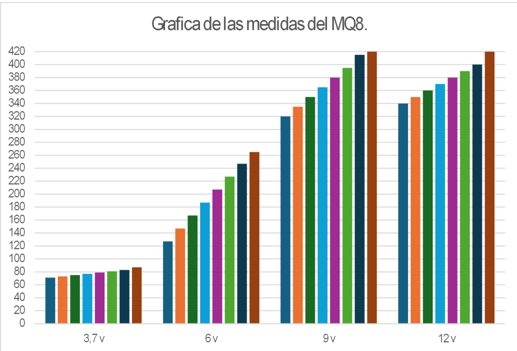
Table 1: Results of the Tests with the MQ8 Digital Sensor

Electrolyte KOH (g)	Voltage (v)	Current (A)	Atmos. pressure (hPa)	Temp. (°C)	Prod. (ppm)
5,5	3,7	3,80	753,17	27,52	71 – 87
5,5	6	8,95	753,17	27,52	127 – 265
5,5	9	10,60	753,17	27,52	320 – 420
5,5	12	10,59	753,17	27,52	340 – 420

Source: own elaboration.

With the help of the tool provided by the Arduino IDE and through serial communication, a graph of the various data obtained was generated (see Figure 10)

Figure 10: Graph of the test results using the MQ8 digital sensor.



Source: Own.

After obtaining the results from the previous tests, the concentration of KOH in the solution increased to 11 g, and tests were conducted using different voltage levels: 3.7 V, 6 V, 9 V, and 12 V. The results are presented in Table 2.

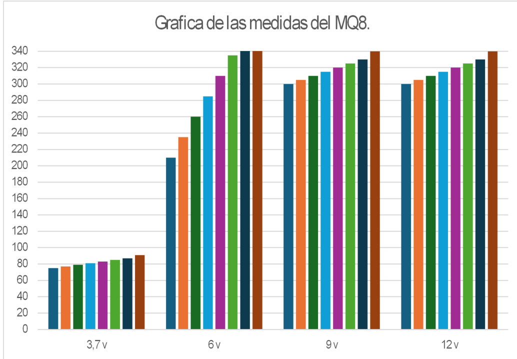
Table 2: Results of the test with 11 g of KOH

Electrolyte KOH (g)	Voltage (v)	Current (A)	Atmos. pressure (hPa)	Temp. (°C)	Prod. (ppm)
11	3,7	4,67	750,71	28,60	75 – 91
11	6	10,12	750,71	28,60	210 – 365
11	9	10,59	750,71	28,60	300 – 340
11	12	10,60	750,71	28,60	300 – 340

Source: own elaboration.

Figure 11 shows the characteristic curves of hydrogen production at the different voltages applied to the generator.

Figure 11: Graph of the test results using the MQ8 digital sensor.



Source: Own.

By comparing the results in Table 1, which used a concentration of 5.5 g of KOH, with those in Table 2, which used 11 g, it was observed that increasing the amount of KOH led to a 4.8 % increase in hydrogen production at 3.7 V. At a voltage of 6 V, the increase was 31.8 %. However, at 9 V and 12 V, hydrogen production decreased by 13.5 % compared to the tests conducted with 5.5 g of KOH.

3.2. Test of the second hydrogen generator

In this prototype, the initial conditions were determined: the generator was filled with 1100 cc of distilled water and 6 g of KOH, then sealed and connected to the digital meter. The voltage variable was modified at different levels, as done with the first prototype, yielding the results shown in table 3.

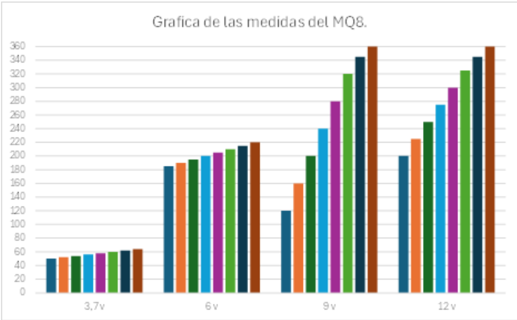
Table 3: Test results using 6 g of KOH

Electrolyte KOH (g)	Voltage (v)	Current (A)	Atmos. pressure (hPa)	Temp. (°C)	Prod. (ppm)
6	3,7	3,52	750,71	28,60	50 – 64
6	6	8,48	750,71	28,60	185 – 220
6	9	10,60	750,71	28,60	120 – 360
6	12	10,62	750,71	28,60	200 – 360

Source: own elaboration.

Figure 12 presents the resulting curves of hydrogen production at the different voltage levels applied to the hydrogen generator.

Figure 12: Graph of the Test Results Using 6 g of KOH.



Source: Own.

Based on the results presented in Table 1, using 5.5 g of KOH, and those in Table 3, using 6 g, it is evident that with similar KOH concentrations but an increased electrode size (from 11 cm to 30 cm), hydrogen production at 3.7 V decreased by 27.8 %. At 6 V, the reduction was 3.21 %; at 9 V, it reached 35.13 %; and at 12 V, hydrogen production decreased by 26.32 %. In light of these findings, the amount of electrolyte was increased by 9 % (100 g) relative to the volume of water used in the generator (1100 cc). Environmental conditions were kept constant, and the tests were conducted using two DC power sources. The results confirmed that electric current is a variable that has a notable influence on hydrogen production—surpassing even the impact of the applied voltage. Subsequently, the concentration of KOH increased to 210 g, equivalent to 19 % relative to the 1100 g of distilled water used in the generator. This adjustment followed the approach of Cabanillas (2022), who reported improved outcomes with a 14 % electrolyte concentration. However, increasing the electrolyte concentration led to a significant rise in the generator's operating temperature. As a result, the minimum current required increased to 12 A at 3.7 V. Furthermore, as voltage was increased, the current demand rose to 20 A. Despite these challenges, hydrogen production increased considerably, reaching 300 ppm at 3.7 V and up to 600 ppm at 6 V. At higher voltages, hydrogen output stabilized between 500 and 600 ppm, indicating that maintaining a voltage range between 3.7 V and 6 V is optimal for maximizing hydrogen production in the system.

4. Conclusions

The criteria and technical specifications for the design and construction of the hydrogen generator were successfully established, supported by the various studies conducted on two types of hydrogen generators used in internal combustion engines: the dry electrode and the wet electrode generator, the latter being the one implemented in this research.

Suitable materials for constructing the hydrogen generator prototypes were identified and selected. It was concluded that AISI 304L stainless steel would be used as the primary material for the electrodes. This choice was made due to the material's resistance to the corrosion generated during the electrolysis process. Additionally, stainless steel 304L was easily accessible and significantly more affordable compared to other materials such as nickel and platinum, which are costly and difficult to acquire.

Based on the tests performed on the prototypes, it was concluded that the diameter of the plates used in the construction of the electrode is a crucial variable, as an increase in plate size affects hydrogen production. Likewise, the optimal amount of KOH electrolyte is essential in the electrolysis process used to generate hydrogen. It was also observed that a higher percentage of electrolyte results in increased current consumption by the generator, which in turn raises the operating temperature and enhances hydrogen production.

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