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CASE STUDY FOR HYDROGEN PRODUCTION USING A MODULATED CURRENT SOURCE

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Hydrogen is a promising alternative fuel that can offer a range of benefits over traditional fossil fuel. The common element, water, is seen as the best renewable and non-polluting fuel on the planet. The article proposes and presents an analysis of water electrolysis using a PWM modulated current source in order to produce hydrogen fuel. The purposes of the work were to design and test the power supply and to evaluate its viability in hydrogen production. A microcontroller system using Arduino UNO and hydrogen transducers was also developed and tested for obtaining qualitative and quantitative measurements of gas production.

Keywords: clean energy, hydrogen, electrolysis, constant current, PWM modulation, gas concentration, gas production, Arduino UNO

1. Introduction

The dynamics of the modern society cover all the areas, including industry and engineering. Everything in the society is sustained or assisted by different forms of energy. One can notice that there were times when the energy source was of no importance (as long as energy was available). Nowadays we must accept the fact that clean sources of energy need to be used and developed and hydrogen is one of them [1] [2]. Using hydrogen as an alternative fuel suppose few key aspects: a) energy independence and security (as hydrogen can be produced from a variety of sources, including water, natural gas, and biomass, this enhances the energy independence and security); b) environmental sustainability (hydrogen is a clean fuel that produces no gas emissions or air pollutants when used in fuel cells; it can play a crucial role in reducing carbon emissions and combating climate change); c) energy efficiency (hydrogen fuel cells are much more efficient than traditional internal combustion engines; they convert more of the energy stored in the fuel into usable power, reducing waste and increasing energy efficiency) [3] [4] [5]; d) the economic competitiveness (as the demand for alternative fuels continues to grow,

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hydrogen has the potential to become a major player in the energy market; the development of a robust hydrogen infrastructure could create jobs and drive economic growth) [6]; e) transport of goods (hydrogen can be used as a fuel for cars, buses, and trucks, providing a zero-emission alternative to gasoline and diesel; when used in transport it can reduce the dependence on oil and improve air quality [7]); f) hydrogen can be green produced with renewable energy sources (solar, wind, hydropower).

Overall, hydrogen has the potential to meet many of our energy needs in a sustainable and efficient way. While there are still some challenges to overcome in terms of production and infrastructure, the benefits of hydrogen as an alternative fuel are clear [8]. The process of water dissociation into hydrogen and oxygen is known as electrolysis.

2. About electrolysis

When a continuous electric current passes through an electrolyte the ions of the electrolyte separate into positive ions (cations) and negative ions (anions). The cations are directed to the cathode (a reduction reaction takes place there) and the anions flow towards the anode where an oxidation reaction takes place.

A key aspect in electrolysis is the decomposition voltage which is the minimum voltage at which the process can take place. This voltage depends on the electrode potential, which in turn is related to the position of the substance in the series of electrochemical potentials. It is known that using acid or alkaline water for the process of electrolysis, hydrogen and oxygen are produced – the principle of the process is in Fig. 1, [7].

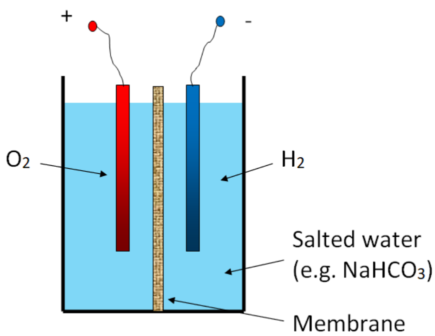

Fig. 1. Water electrolysis in physics

The electrochemical process is described by relations (1) and (2). In fact the process is more complex and depends on the catalysts [7].

(-) $2H_2O + 2e^- \rightarrow H_2(g) + 2HO$ (1)

(+) $2H_2O \rightarrow O_2(g) + 4H + 4e^-$ (2)

Hydrogen is generated at the cathode and oxygen at the anode. The supply voltage used for electrolysis consists of voltage drops on the electrodes, electrolyte and contacts. Three main electrolysis methods are used in industry: alkaline, proton exchange membrane (PEM) and solid oxide. Pure water is not suitable because it does not conduct electricity. The electrolyte should be an ionized (water) solution, e.g. KOH - potassium hydroxide, $NaHCO_3$ - backing soda. This work is about alkaline water electrolysis.

A special membrane or diaphragm can be used to prevent mixing of the hydrogen and oxygen gases produced during the process - it is proton permissible and separates hydrogen of oxygen. The electrolysis can go on without a membrane but the resulting gas (mixture of hydrogen and oxygen, known in literature as HHO gas) is very explosive. In the presence of a membrane, only the desired ions are passing through (hydrogen ions at the cathode, and oxygen ions at the anode) [7]. A diaphragm, on the other hand, is a physical barrier that can be made of a variety of materials, including asbestos, ceramics, or synthetic fibers. Both membranes and diaphragms have their advantages and disadvantages. For obtaining pure gases and to efficiently control the flow of electrons a membrane must be used that conducts protons (H+) only. Electrons are guided through an external circuit from the anode to the cathode. By controlling the flow and direction of electrons, H_2O is used to produce H_2 and O_2 (electrolysis mode) or, reversely, H_2O can be produced from H_2 and O_2 (fuel cell mode) [7] [9].

The concentration of electrolyte affects the rate of electrolysis: the higher the concentration of electrolyte, the faster the rate of electrolysis. However, there is no specific optimum concentration for electrolysis as it depends on various factors such as the type of electrodes, distance between electrodes and electrolytic solution. An over potential or voltage excess is needed to overcome interactions at the electrode surface. The presence of oxidizing and reducing agents in the electrolyte and electrode potential also affect electrolysis.

We may notice a lot of work concerning water electrolysis and also for pulsed power used to split water [10]. There are studies dealing with the amplitude of the pulsed voltage and for its duration [11]. A new approach is presented in this work which consists of using a pulsed constant current as power supply. Furthermore, this current can be adjusted by its duty cycle.

3. The experimental setup

First of all, it is important to mention some remarks and precautions regarding the electrolysis process. The resulting gas is a combination of oxygen and hydrogen named HHO gas and has a high risk of explosion. It is more explosive than hydrogen because it contains oxygen. Thus, an important aspect is safety which involves that no spark can occur during experiments and the level of unused gas is as low as possible.

Other aspects must be taken into account:
- The contact area between the electrolyte and the electrodes has to be as big as possible, in order to maximize the number of released bubbles.
Also, the production of the gas is influenced by the mechanical profile (roughness) of the plates. Their preparation involves several steps: cleaning, coating (using a catalytically active material) and sintering (for forming a porous structure).
- The space between the electrodes plays its role in the process and it should be as small as possible.
- The electrodes are commonly made of a corrosion-resistant and durable material (nickel, stainless steel or other metals).
- The electrical current used for electrolysis is mostly influenced by the supply voltage and the concentration of the electrolyte.
A minimal theoretical value of 1.23-1.24 V is required for the process but in reality an overvoltage is necessary for covering any losses and nonideality aspects.

To avoid any voltage problems of the power supply a constant current source was proposed and tested. For optimization of the energy consumption, a PWM controlled amplification structure was used and the block diagram is in Fig. 2. A 12 V power supply was chosen for the experimental setup for portability reasons.

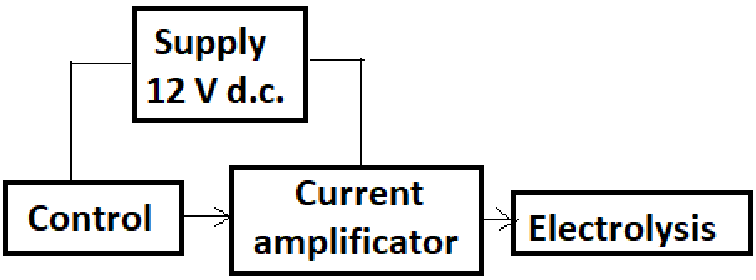

Fig. 2. The principle of operation

The gas resulting from the electrolysis process is captured and directed to a bubbler that also assures ignition protection. Fig. 3 shows a simple setup of an electrolysis cell using a glass container with two electrodes and sealed possibilities on top.

Fig. 3. The can used for gas capturing and filtering

Fig. 4 shows different electrolysis devices: some of them have as result the HHO gas and others give pure hydrogen and oxygen.

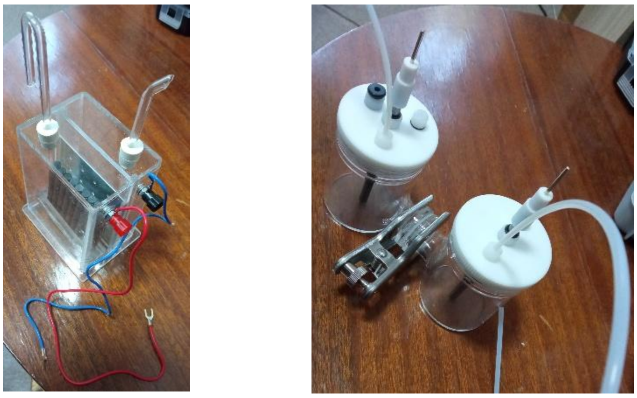

Fig. 4. An HHO generator (left) and hydrogen and oxygen generator (right)

Another aim of this work was to test and evaluate the viability of the proposed method. To measure hydrogen quantities, a MQ-8 hydrogen sensor, with Arduino UNO embedded system, were used – they are shown in Fig. 5.

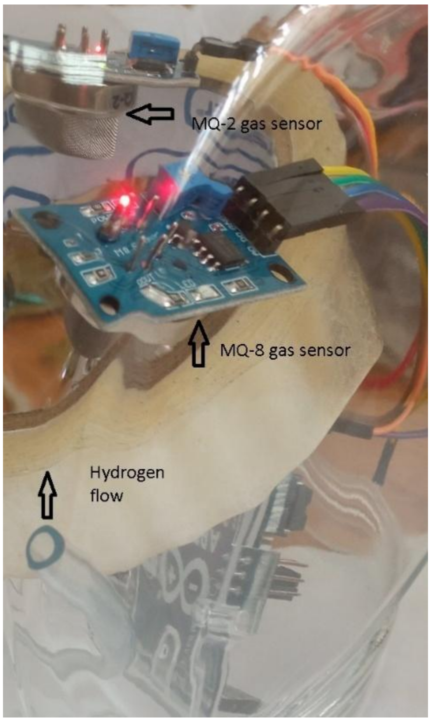

Fig. 5. Hydrogen sensors inside the collector vessel

A MQ-8 sensor is suitable for hydrogen measuring and gives a good sensitivity over a large range (100 – 10000 ppm). Additionally, a MQ-2 sensor was used which can detect several other flammable gases. The output of these sensors is analogical and data reading is easy by using a serial monitor window. Because the sensors and the entire electrical setup was inside of hydrogen collector vessel, special attention is needed to avoid any possible source of sparks (imperfect contacts). To evaluate the functionality of electrolysis cell, the sensors measure concentration of hydrogen, in ppm. Before taking any measurements, the sensors must enter the normal operation mode which takes approximately 10 minutes.

4. Description of the power supply

Considering that it is a new approach in hydrogen production, one first step was to design and test the power source: a current mirror type in cascode configuration with bipolar transistors T2, T3, T4, T5 and T6. This connection minimize variations due to voltage changes, has a high output resistance, wide bandwidth and ensures constant current output. The complete schematic is shown in Fig. 6. The command is taken by a PNP bipolar transistor T1 from the PWM block, with the signal active to ground.

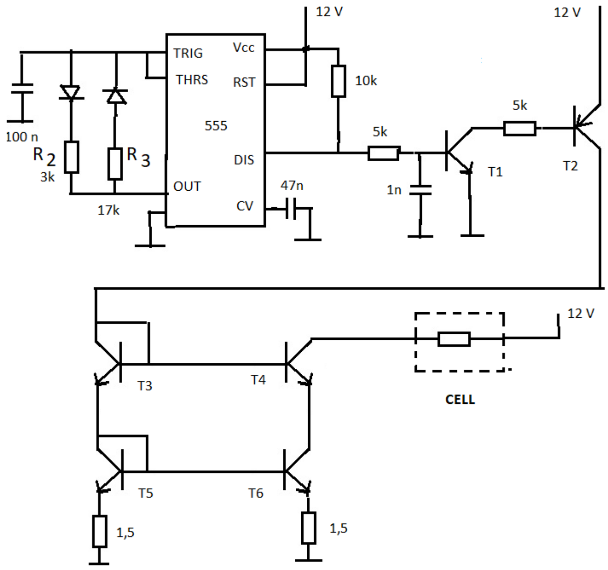

Fig. 6. The schematics used for hydrogen generator

The PWM block that drives the current source is made with a usual 555 integrated circuit offering an adjustable duty cycle – an example of the signal is shown in Fig. 7. It is the configuration of an astable circuit with the output on Discharge pin. This pin is in phase with the Output pin but works as open-collector. That is useful for driving any desired voltage, not being limited to the supply voltage of 555.

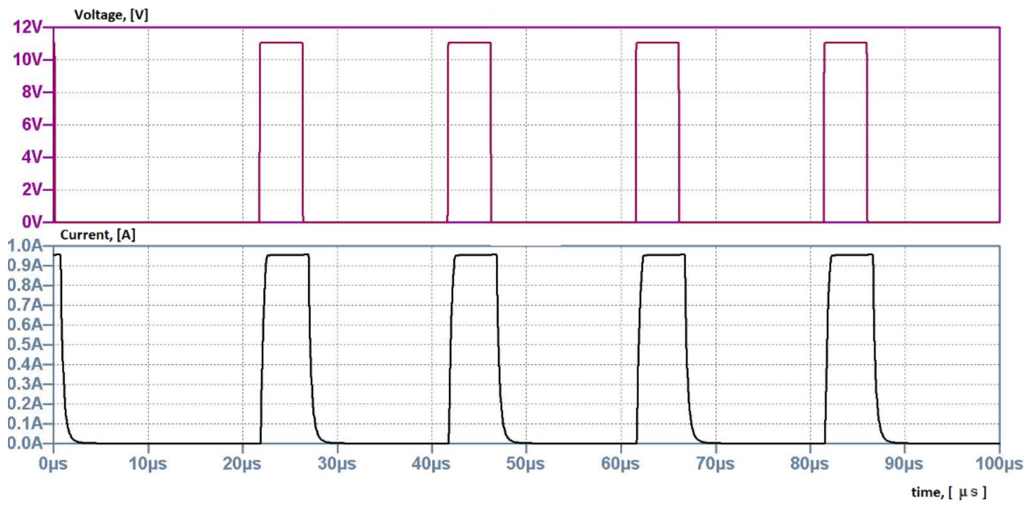

Fig. 7. PWM output for 25% duty cycle

The duty cycle adjustment is realized by varying resistors R_2 and R_3 while keeping constant the sum of their values (according to Fig. 6). The ratio of the currents from the current mirror is 10. This value offers a convenient linearity of the current source and a reduction of the dissipated power. A 50 kHz frequency was used for the experiments, considering some results on pulsed voltage for electrolysis [11]. Values of 1-2 A are near the working current of electrolysis cell [12] [13] [14].

5. Results and experimental data

At first, a characteristic of the average value of the charged current as a function of duty cycle (D) was determined that shows linearity and stability for the power supply, as shown in Fig. 9. Secondly, because the resistance of electrolysis cell varies around 1 Ω, its influence was tested from 0.1 to 1.5 Ω and the results are in Fig. 10.

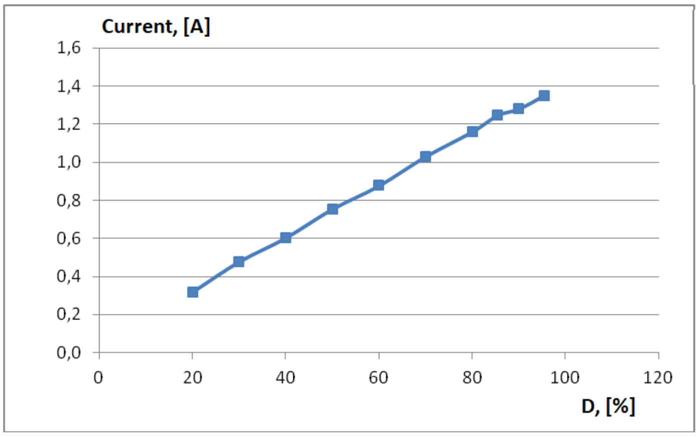

Fig. 9. The experimental characteristic of the control current

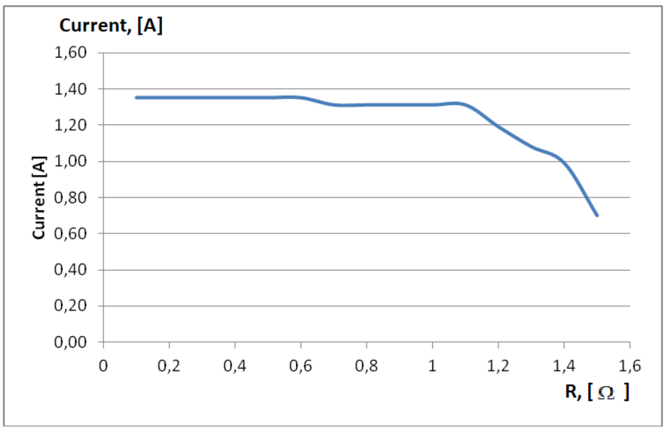

Fig. 10. Current variation over cell resistance

For testing the process of electrolysis, the hydrogen concentration was measured in a volume of approximately 1.5 liters. The testing conditions were for two different concentrations of electrolyte (1 M and 2 M NaOH) and two different currents (1 A and 2 A). The MQ-8 sensor measures the hydrogen concentration and MQ-2 sensor detects and measures other flammable gases like liquefied natural gas (LNG), butane, propane, methane, alcohol, smoke – results are presented in Fig. 11 and Fig. 12.

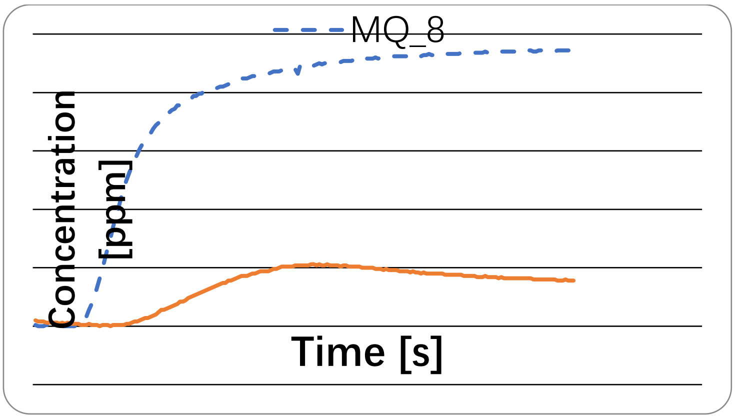

Fig. 11. The signals from sensors MQ-8 and MQ-2 if in air there are additional flammable gases (alcohol) for 1A current and 1 M NaOH

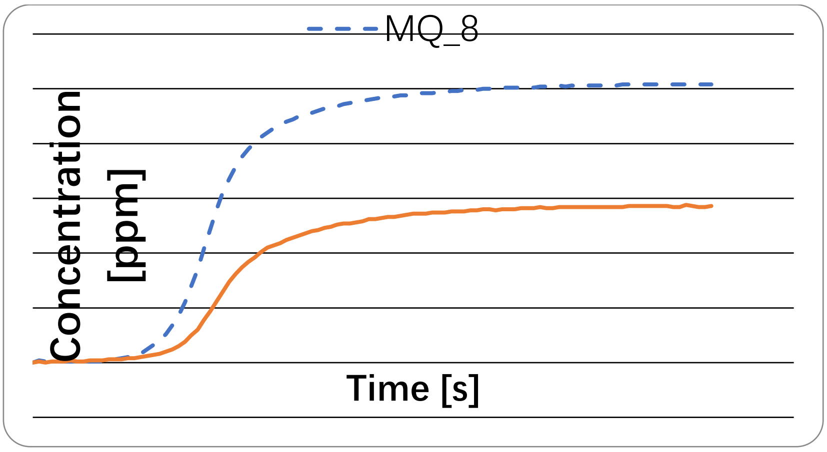

Fig. 12. The signals from sensors MQ-8 and MQ-2 for 1A current and 2 M NaOH

The influence of current to hydrogen concentration was tested, and also the influence of electrolyte molar concentration to hydrogen concentration increasing speed. The results were conducted until concentration was steady state. The lower explosive level (LEL) of hydrogen is generally considered to be 4 % by volume (4 % v/v). At 4 % it can burn or explode if there is an ignition source. 4 % v/v of hydrogen is the same as 100 % LEL of the explosive concentration. 100% LEL = 4

% Hydrogen = 40,000 ppm hydrogen. For an easier interpretation of the results, Fig. 13 shows an additional representation of data for the hydrogen sensor MQ-8.

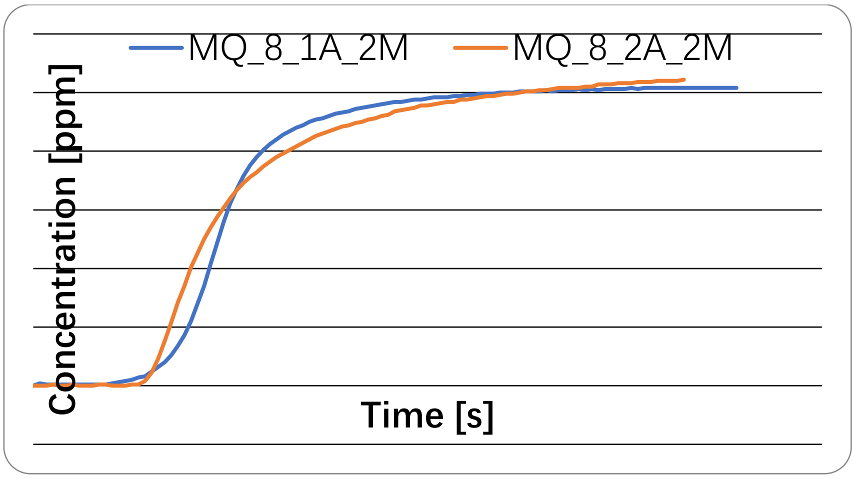

Fig. 13. The signals from MQ-8 sensor for 1A and 2A current and 2 M NaOH

It is remarkable (from Fig. 13) that when the concentration increases, the current is not so important related to evolution (speed) of hydrogen concentration.

For quantitative analysis of hydrogen production, a mass flow transducer with threaded flow body (Thermatel TA2) was used. It is able to measure small flows (0.04 - 2.5 m/s) and does not require pressure or temperature input for density correction. After diameter configuration of the pipe, the results are displayed in units of m^3/min, l/min or kg/min. The following conditions were set up: 2 A peek current, 2 M NaOH concentration of electrolyte and 30%, 60%, 90% duty cycle. The data obtained are:

a) for duty cycle D=30%, the r.m.s value of the current is I_1=1.1 A, the electrical power consumed is P_1=1.3 W but the indicated flow of hydrogen is ambiguous – this situation was chosen on purpose for verification of the setup and the process; the 1.1 A current determines a water splitting voltage close to the theoretical minimum value of 1.23 V so the necessary overvoltage is too small;

b) for D=60%, the current is I_2=1.55 A, the consumed power is P_2=2.71 W (cell resistance is 1.13 Ω) and hydrogen mass flow is 0.98 mg/min;

The corresponding efficiency of production is 2.765 Wmin/mg= 46 kWh/kg, whilst 100% efficiency corresponds to 39.4 kWh/kg and industrial electrolysis requires about 48-55 kWh/kg.

c) for D=90%, the current is I_3=1.9 A, the consumed power is P_3=5.15 W and hydrogen mass flow is 1.73 mg/min;

The efficiency is 2.977 Wmin/mg= 49.6 kWh/kg.

6. Conclusions

Building a water electrolysis system is a complex process and requires knowledge of electrical engineering, chemistry and materials science. The quantities of oxygen and hydrogen produced by water electrolysis depend on several factors, including the amount of electrical current applied, the surface area and composition of the electrodes, the type of electrolyte used and the temperature and pressure conditions. A membrane or diaphragm is necessary for preventing the mixing of the hydrogen and oxygen gases that are produced. Another solution, used in this experiment, was to surround each electrodes by a collector cone for directing and collecting the gas.

There are many studies about pulsed voltage for water electrolysis but the novelty of this work is on using a constant pulsed current that can be adjusted by its duty cycle. An important observation was that the initial resistance of the electrolyte solution of the experimental device is high, but the value of the resistance drops rapidly to a value of ohms, at the moment when the chemical reactions start to take place. The purposes of this paper were to design and test a proper current supply for the proposed approach, to study different configurations of electrolysis experimental setup (different currents and different electrolyte concentration) and to test and evaluate the viability of the method. Qualitative experiment shows that the method is viable, the gas production is sustained and quantitative measurements denote a good efficiency compared to industrial status of hydrogen production. Based on the proposed approach, a further research will be conducted on a larger scale, using an industrial stack for alkaline water electrolysis.

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