Article

High Pulsed Voltage Alkaline Electrolysis for Water Splitting ‡

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‡ This paper is an extended version of our paper published in M. Albornoz, M. Rivera, R. Ramírez, F. Varas-Concha and P. Wheeler, "Water Splitting Dynamics of High Voltage Pulsed Alkaline Electrolysis," 2022 IEEE International Conference on Automation/XXV Congress of the Chilean Association of Automatic Control (ICA-ACCA), Curicó, Chile, 2022, pp. 1-7, doi: 10.1109/ICA-ACCA56767.2022.10006326..

Abstract: This paper considers the development of high efficiency plasma electrolysis using extremely short pulses of high voltage. The paper also considers the dynamic characteristics of this new type of water splitting for hydrogen production. Voltage pulses with a width of a few nanoseconds are used in the formation of a double layer of H_2O molecules. This double layer forms at the interface between the electrode and the electrolyte with a related capacitive effect with a capacitance which can be calculated from the geometry of the electrolysis cell. This chemical capacitance can be controlled by changing the electrical characteristics of the supply, the electrode separation and the density of the electrolyte. This chemical capacitance can be used to understand the mechanisms present in the water splitting process under these short voltage pulse conditions.

Keywords: Alkaline-Electrolysis; Capacitance; Cell; Chemical; Electrode; Electrolyte; Frequency; Geometry; Ionic; Pulse; High-Voltage.

Citation: Albornoz, M.; Rivera, M.; Wheeler, P.; Ramírez, R. High Pulsed Voltage Alkaline Electrolysis for Water Splitting. *Sensors* **2023**, *1*, 0. https://doi.org/

Received:
Revised:
Accepted:
Published:

1. Introduction

The predominant technology used at an industrial level in the decomposition of the water molecule to produce hydrogen by electrolysis is based on the application of large amounts of currents with low amplitude to an electrolyte composed of water with additives, a method called alkaline electrolysis. To obtain greater power, it is necessary to increase the size of the generating device, raising its cost. This is the main reason why hydrogen production is restricted to industrial processes. In order to make hydrogen production more accessible, it is necessary to make the process compatible with limited energy sources, such as a residential solar microgrid [1], [2] or a car alternator [3], [4], as well as cheaper equipment.

To optimize gas generation, the development of contemporary methods that have evolved from conventional DC electrolysis is sought, new technologies allow the implementation of advanced power sources. The pulsed power is shown as a promising variant that requires revision. This has been widely studied in the electrolysis process, obtaining improvements in the efficiency of the process and in parallel in the formation of plasma [5], granting greater control in the reaction chemistry by modulating the frequency and duration of the applied pulses. The study of pulsed power has grown in recent decades thanks to exponential improvements in solid-state switches, allowing full control over pulse characteristics, replacing older switching technologies [6]. These increasingly smaller semiconductors allow their implementation in smaller circuits and at lower cost, increasing the power density in relation to previous applications.

High voltage discharges are also introduced [7]. These generate an electric field that is capable of breaking the conductivity limit in different fluid media. When this limit is exceeded, an electric arc is produced where the charges find a medium that offers conduction with less resistance. This, in addition to being used in plasma generators, has possible applications in purification and decontamination of water or air, depending on the medium where the electric discharge is produced [8], [9]. In experiments with plasma electrolysis [10], significant increases in gas production efficiency have been achieved that require revision.

Next, a practical approach is made on the molecular dynamics of water under the application of pulsed voltage, seeking to break its conductivity limit for the formation of plasmolysis. First, the theory and current development of the technologies used are reviewed, then a system for monitoring the process is designed and built, together with a subsequent start-up, to finish with an analysis of the results. This work is based on the intention of reducing energy and implementation costs in hydrogen production, in order to bring it closer to communities as an accessible fuel alternative.

2. State of the Art

2.1. Electrolysis

Faraday's first law of electrolysis postulates that the amount of gas produced in the reaction is directly proportional to the current applied to the electrolyte, in this case the current is applied to water. Equation (1) relates the mass of the produced substance m, to the total charge circulated by the electrolyte Q, the molar mass of the substance M, the Faraday constant F and the valence number of the substance as an ion in the solution z.

$$m = \frac{Q}{F}\frac{M}{z}. \tag{1}$$

The electrolyte container next to the electrodes is called an electrolysis cell (Fig. 1), there are two electrodes, an anode and a cathode connected to the DC power supply in its most basic configuration. Oxygen is generated on the surface of the anode while hydrogen is generated on the surface of the cathode. For the specific physical situation under study, when the electrolyte to which an electric current is applied is water, the decomposition voltage is 1.23V at room temperature (reversible voltage), an overvoltage of approximately 0.4V must also be applied depending on the material of the electrodes, among other factors [11].

With this, the necessary voltage for the decomposition by electrolysis of water, starts around 1.63V (thermo-neutral voltage [12]). To obtain a higher production of hydrogen, under this law, it is necessary to increase the amount of current applied to the electrolysis cell. If the voltage is increased for this purpose, there is a limit related to energy efficiency, caused by the double capacitive layer effect of water, in addition to the ohmic losses [13], [14], [15]. If a voltage higher than the reversible voltage is applied, the additional power will be dissipated as heat because of the internal resistances of the cell. The reversible voltage refers to the voltage obtained in the reverse process, when electricity is obtained from the union of hydrogen and oxygen molecules, therefore it is the energy used entirely in the hydrogen production process and that is not wasted as heat. Knowing this principle, electrolysis cells currently used in industry use continuous voltages that do not exceed 2V per cell, to avoid a significant reduction in efficiency [11]. To regulate the amount of current circulating through the electrolyte, it is possible to modify the conductivity of the water by incorporating additives in the electrolyte solution, alkaline compounds such as sodium hydroxide (NaOH) or potassium hydroxide (KOH), among others [10], of which the second has had a greater use to show better results. Thus, it is possible to increase the power and production of hydrogen avoiding exceeding the established tensions.

2.2. Pulsed Electrolysis

At the instant that the voltage between the electrodes is applied, an internal movement begins in the molecules of the electrolyte, the polar molecules of the water are positioned in such a way that their electromagnetic orientations are ordered following the electric field

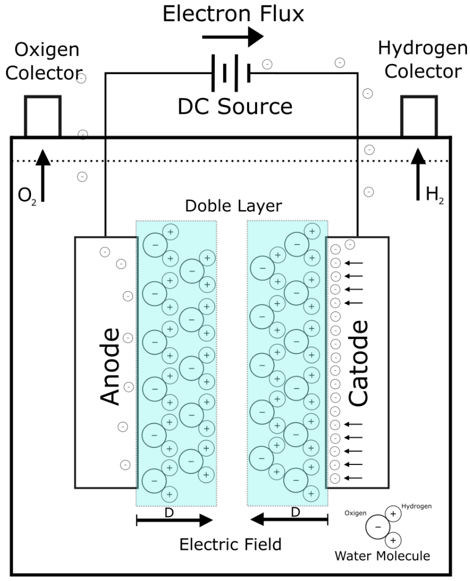

Figure 1. Electrolysis cell and formation of the double layer proportional to the electric field.

between electrodes. Before decomposing, the hydrogen atoms of the molecule approach the cathode and the oxygen atoms are located at the other end of the molecule, the same happens on the surface of the anode, only in the reverse situation. This effect is called double layer [13], [16], behavior that gives capacitor qualities to the electrolyzer. When this double layer is formed, the electrons coming from the source are limited in their passage to the electrolyte by the opposite charges present in the molecules, these are ordered causing an electric charge barrier proportional to the voltage applied on the surface of the electrode. Applying high voltages to the electrodes causes a greater internal resistance of the electrolyte, which explains the decrease in efficiency mentioned above.

This particular behavior of water takes a few milliseconds to form completely, for this reason, if instead of a DC power source, the voltage is applied pulsed and with a pulse width of the shortest possible duration with the available semiconductors [5], [17], it is possible to obtain improvements in efficiency. With pulses of electricity in the order of nanoseconds, the current is applied to the cell in such a way that molecular formation is avoided that prevents the free flow of electrons, for an instant of time these are able to circulate through the electrolyte without the opposition of the double layer. The electrons are injected into the electrolyte and it is "charged" with chemically stored energy that is used in the decomposition of water in the time after the pulse. The capacitive behavior of the cell, against a pulsed voltage with specific frequency, can be modeled as an equivalent circuit RC [13], where it is possible to find a natural frequency for the system [18], at this frequency there are reductions in the current of the system, maximizing the output or production of gas with respect to the power input, resulting in efficiency improvements.

The application of pulsed power has had several appearances in research on hydrogen generators, some improvements in energy efficiency of the electrolysis process have been witnessed, in addition to some behaviors that had gone unnoticed in electrolysis cells powered by DC power. An investigation was based on an inductive pulse generator circuit to supply the power to an electrolysis cell [19], with this circuit it was proven that it is possible to increase the voltage of the source without reducing its efficiency, or resistive losses, which directly increases the energy density of the device. In another work with pulsed electrolysis [20], conclusions were obtained about the influence of the alkalinity of the electrolyte, depending on this, with a supply voltage of 1V it is possible to have pulses of hundreds of volts between the electrodes, the peak value of this pulse increases as the conductivity of the electrolyte decreases. With a lower resistance, the power is reflected in a higher current instead of a high voltage. Also, it was seen that for pulses with a duration of less than 1μs, the cell behaves like a high capacitance capacitor, where the charging and discharging behavior turns out to be dependent on the conductivity of water.

2.3. High Voltage Electrolysis

The application of high voltage to the electrolysis cell is an area that is little studied, although it is possible to find some authors who have worked on the topic [10], [21], [22]. In the aforementioned situation a continuous voltage of 200V DC was applied to an electrolyzer, with this there was an increase in temperature that made the liquid boil in the vicinity of the reaction, together with an increase in the production of hydrogen and oxygen it was possible to saturate the medium with gas, after a point, When the excitation of the charges reaches a sufficient energy to jump to the gaseous medium formed, a plasma discharge occurs, because of this the current decreases drastically without making it so the production of gas. The temperature of the electrolyzer stabilizes around 90°C, entering the denomination of cold plasma. This considering the average temperature of the electrolyte, however, the formation of plasma brings with it the generation of high temperatures at the site of the reaction, in this way, efficiency characteristics of high temperature steam electrolysis can be obtained (High Temperature Steam Electrolysis [12]), which exceed the efficiency of low temperature alkaline electrolysis.

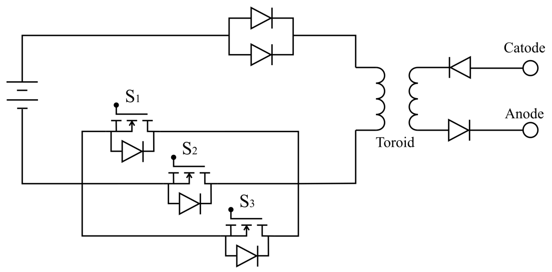

Figure 2. Schematic circuit of the inductive pulse generator.

This situation occurs at voltage levels that can vary between 200V and 800V [10], [23], [24], depending on the concentration of additive in the electrolyte and the separation between electrodes. Plasma electrolysis has a great advantage over low-voltage electrolysis, when a stable plasma is formed in the reaction, drastic decreases in the current circulating through the cell can be observed, without decreasing the flow of gas produced. At high voltages, gaseous media behave as good electrical conductors, so electrons circulate through the gas present between the electrodes, preventing circulation through the electrolyte that offers greater resistance. This situation shows that the production of hydrogen can have characteristics that do not respond to the amount of charge applied on the electrolyte as proposed, new phenomena arise related to the decomposition of water by the force of the electric field that require attention. Research on pulsed electrolysis is discussed at a sufficiently high frequency to produce plasma in the electrolyte. With this technology, high energy densities can be achieved for short periods of time, being able to create generators of high power and reduced dimensions.

These technologies open the doors to the investigation of a new electrolyzer system, simple to implement since it does not require complex materials of high thermal resistance or difficult to acquire, of low cost due to its small size and high efficiency. There is the possibility of increasing the power and frequency beyond the studies carried out to date, where frequencies around 200kHz [25] and voltages of 140V [19] have been reached, seeking to reach the point of making stable plasma formation viable. Achieving this goal can make it possible to implement hydrogen-generating devices for domestic purposes, such as in energy storage and transportation.

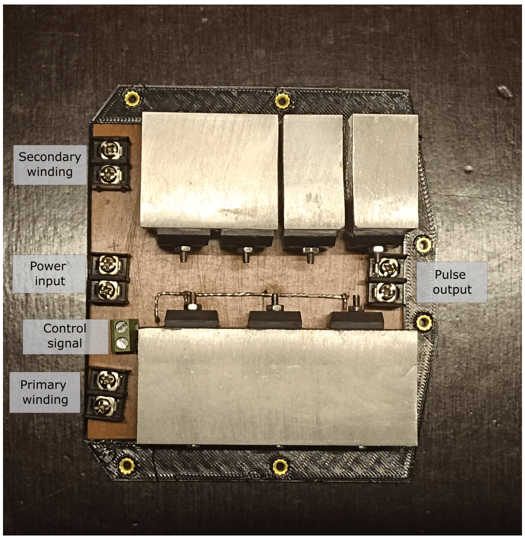

Figure 3. Assembled pulse generator circuit.

3. Hydrogen Generator

3.1. Circuit

The inductive pulse circuit in Figure 2, based on previous work [19], has a coil that is magnetized when the 3 switches close allowing current to circulate in the primary circuit, at the moment when the switches change state again the circuit opens allowing the abrupt discharge of the inductor. The only path available for the energy stored in the magnetic field with this topology is to be induced in the secondary circuit and circulated through the charge (electrolysis cell). 3 mosfets are used in parallel to reduce the impact of the current causing heat in the semiconductors, in addition the equivalent resistance of the circuit is decreased, each switch has a certain internal resistance.

The current of an inductor is governed by the equation:

$$i_L(t) = i(t_0) + \frac{1}{L}\int_{-\infty}^{t_0} V(t)\,dt. \quad (2)$$

This increases in the form of a ramp over time, inversely proportional to the magnitude of the inductance, the magnetic field formed is proportional to the current that circulates it. To work with high frequencies, a relatively low impedance is needed, so the current can reach a significant value in a short time, allowing a complete discharge and higher power.

The parallel diodes located at the positive terminal of the power supply fulfill the function of protecting both the source and the mosfets from the peak of inductive voltage produced in the inductor at the time of opening the circuit. The voltage is presented at both ends of the toroidal transformer, but on the contrary, the current only has output through the secondary circuit, so it is necessary to prevent the semiconductors from receiving a pulse that exceeds their breakdown voltages. The function of the diodes in the secondary circuit is to prevent the circulation of reverse currents, allowing the passage of voltage pulses with a defined polarity, and not alternating currents. The construction of the circuit was carried out on a copper plate where only the solid state semiconductors were located (Fig. 3), the coils, signal generator and actuator driver were implemented separately to obtain a modular design that facilitates modifications.

There is the possibility of achieving a pulse-generating device that delivers a stable and previously determined voltage, in addition to offering greater control over the waveform. This can be achieved with capacitive discharges, this type of circuit implies a greater degree of complexity in the manufacture and control, specifically in relation to the implementation of a high voltage capacitor capable of storing the voltage necessary for the formation of plasma, or failing a set of capacitors stacked in series to reach the necessary voltages. The idea is to control the voltage of the stored energy using a boost converter and then discharge the capacitors abruptly using mosfet switches. This is left for future research due to the limited resources and time of the present study.

3.2. Plasmolysis Cell

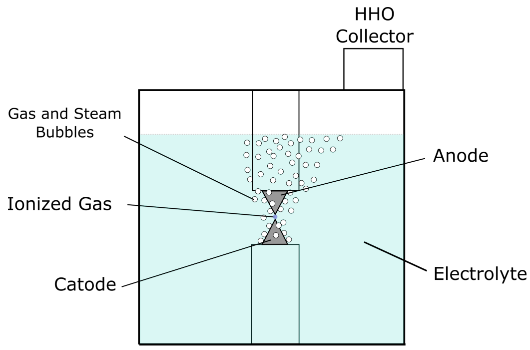

Figure 4. Pulsed plasmolysis cell diagram (front view).

A pulsed plasma electrolysis cell has basically the same components as a conventional electrolysis cell, the main differences being the arrangement and size of the electrodes (Fig. 4). In this case the electrodes have a needle tip shape, with this it is sought to limit the surface area to a minimum, reducing the electrical capacitance to work with high frequencies, and also concentrate the power of the electric field at a specific point. Plasma formation requires high energy density, and the geometry of the electrodes influence the shape of the electric field that occurs between two conductors of opposite polarity. With an electric field concentrated in a small point it is expected to locate a large production of gas, which would be the medium for plasma formation. The frame of the cell built for this study is made with a UV resin used in 3D printing with LCD technology, this resin is able to withstand temperatures around 200°C. There are three windows to observe the reaction inside the cell, constructed of 4mm thick glass fixed to the base with structural silicone. The electrodes correspond to stainless steel bolts fixed by an internal thread printed as part of the frame of the cell, the end is sanded in the form of a needle tip. To adjust the separation between electrodes, simply turn the bolts to the appropriate position.

4. Experimentation

4.1. Circuit

The response of the circuit used in the study was analyzed with a Keysight DSOX1102G oscilloscope. In addition, this instrument allows to perform the function of generator of the control signal for the actuation of the gate driver.

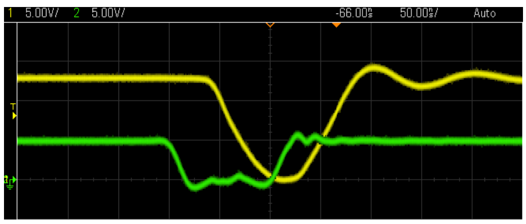

Figure 5. Estimated response of a 100ns pulse.

Figure 5 represents the control signal together with the driver's response to it for a pulse of 100ns, the yellow curve represents the output of the gate driver, while the green line represents the actuation of the control signal for a pulse of 100ns. Both signals have different voltage levels, depending on the device they seek to control, for the driver a 5V signal is used. The signal coming from this, which has the purpose of switching the state of the switch has a voltage of around 12V in its high state. A delay of approximately 20ns can be seen after receiving the state change command. The driver switching times turn out to be around 50ns each (fall-time and rise-time), for a pulse of 100ns, the gate driver delivers a signal of approximately 30ns in low state. Experimental evidence shows that the pulses carried out are of shorter duration than scheduled.

The behavior of the circuit is mainly defined by the nature of the inductor, the experiment varies the frequency of the pulses, however the duration of these is maintained. A low frequency in the repetition of pulses, with a duration of around 200 nanoseconds, it turns out that the inductor has a longer charging time per cycle, more energy accumulates compared to the same situation with a higher frequency. Figure 6 shows what has been said, a comparison of the response of the cell against two different frequencies is shown, the pulse duration configured in the driver is exactly the same for both, in the lower graph the frequency is set to twice the upper graph. When the inductor has exactly half the time to gather energy, you get, as expected, half the voltage in the pulse. The oscillation in the voltage of the cell after the application of the pulse is related to the response of an RLC circuit, the secondary winding of the transformer forms a circuit of this type thanks to the capacitive and resistive characteristics of the cell.

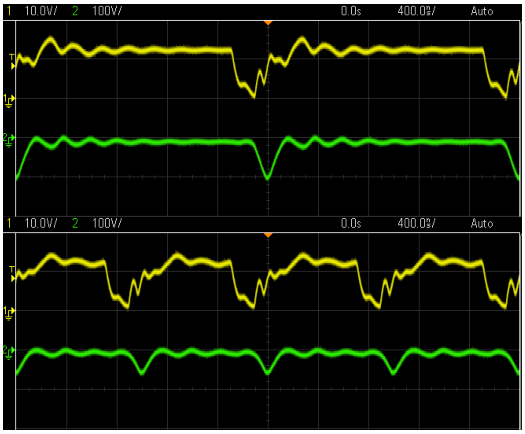

Figure 6. Voltage pulses obtained with voltage of 4V in the power supply, separation of 1mm between electrodes, frequency of 500kHz (upper) and 1MHz (lower) in drinking water. The yellow line represents the action of the driver and the green line the voltage in the cell.

4.2. Measurement System

In this study, it is necessary to contain the volume of gas produced in order to quantify it, the volume of gas used for the calculations will be the totality of the gas produced in the decomposition reaction of the water molecule, two molecules of hydrogen and one of oxygen, this gas that contains both elements is called oxyhydrogen or HHO. The accumulated gas pressure will cause an increase in the height of the water column inside a transparent hose, this increase will be measured thanks to a ruler located parallel to the hose containing the water, similar to a simple water level (Fig. 7). After taking the data, the pressure is released through a waste valve located in the bubbler lid. To obtain a characterization of this cell, its response to a series of frequencies, voltages, electrolytes and separation between electrodes will be reviewed. The electrolyte with which the main characterization will be carried out will be drinking water without additives, then the most relevant parameters are used for comparison with other electrolytes. The first series of tests performed on the electrolysis cell consists of varying the frequency of the voltage pulse delivered, for this the voltage of the power source is kept constant, as well as maintaining the separation between electrodes. The graphed production is calculated with the power delivered by the power source, the efficiency of the process is evaluated without analyzing the efficiency of the circuit itself.

4.3. Caracterization

In the bar graph of Figure 8, the production of HHO in milliliters per watt of power in relation to the pulse rate is shown, a clear trend of increase in the efficiency of the process can be seen as the frequency is increased. This information allows us to intuit the possibility of avoiding working with frequencies that are too low, since they do not provide relevant data for the rest of the research on the efficiency of the process. By observing the pulse voltage data, obtained with the previous experiment, maintaining the separation between electrodes of 0.1mm and the voltage of 4V at the power source, a variation in the maximum voltage of the pulse that responds inversely proportional to the increase in frequency can be observed (Fig. 9). The behavior of the circuit is mainly defined by the nature of the inductor present, the experiment varies the frequency of the pulses, however the duration of these is maintained. When a low frequency in the repetition of pulses with a duration of around 200 nanoseconds is observed, the inductor has a longer charging time per cycle and more stored energy compared to the same situation with a higher frequency. When the inductor has exactly half the time to gather energy, is obtained as expected, half the voltage in the pulse. A not so obvious or intuitive process behavior that takes place in the electrolyte with a voltage pulse is the incidence of separation between electrodes. Figure 10 shows a trend of voltage increase proportional to the increase in distance between electrodes.

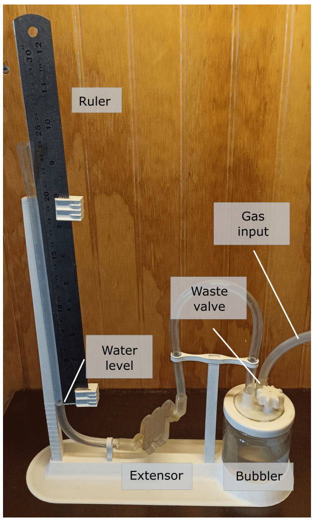

Figure 7. Assembled measurement system.

It was established that the pulse voltage depends partially on the resistance of the circuit. When the energy accumulated in the inductor in the form of a magnetic field is abruptly discharged, and the circuit has low resistance, the power can flow with a high current, the voltage varies its intensity according to the current to maintain the power ratio. If the distance that the current must travel inside the electrolyte is increased, the resistance of the circuit is directly increased, resulting in a higher voltage, unlike when the electrodes are closer to each other or in a lower resistance configuration. After reviewing the influence of frequency and resistance in the process, the possible effects of capacitance are introduced, which in an environment dominated by frequencies tends to produce resonance phenomena. The electrolysis cell has a composition that is basically a capacitor, there are two electrodes separated by an electrolyte, the capacitance in these components increases as the surface area of the electrodes grows and the separation between them decreases. In this case the electrodes were optimized to concentrate the electric field with a needle tip shape, leaving only one variable to control the capacitance of the cell, the separation of electrodes. Following this analogy, if the electrodes move away, the capacitance decreases, changing the resonant frequency of the circuit. A capacitor with a lower capacitance has a shorter charge and discharge time, therefore, it is able to work at higher frequencies without maintaining a constant voltage.

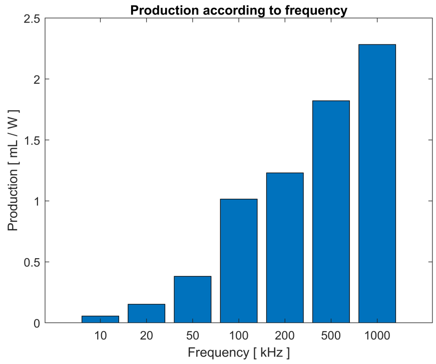

Figure 8. Gas production according to applied pulse frequency, with 4V at the source and 0.1mm separation between electrodes.

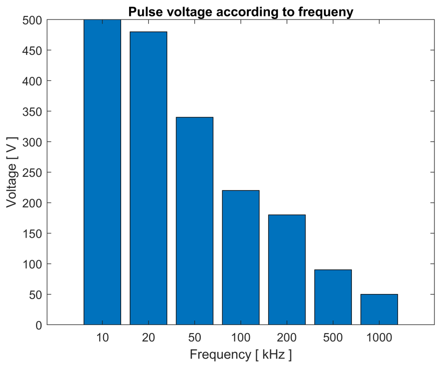

Figure 9. Pulse voltage obtained according to application frequency, with 4V at the source and separation of 0.1mm between electrodes.

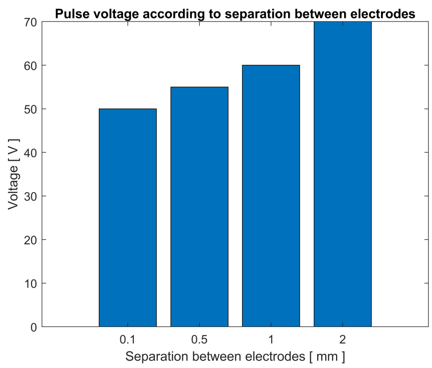

Figure 10. Pulse voltage obtained according to separation between electrodes, with 4V at the source and pulse frequency of 1MHz.

Figure 11 shows the production in relation to the separation between electrodes, along with a variation in the voltages of the power supply. The graph starts with a minimum of 4V, when using lower voltages, the production is too low to obtain comparable results and it would be necessary to extend the experimentation time too much. For 4V and 6V voltages, the highest output is found when the electrodes are very close to each other, as they move away production decreases. It is different in the case of higher voltages, for 8V and 10V the production pick is at 0.5mm, a slightly longer separation. The fundamental difference of the pulsed electrolysis process with conventional electrolysis is that by applying extremely fast pulses, the current is able to enter the electrolyte before the breakdown of the water molecule occurs, the decomposition continues until after the pulse is finished. But it is glimpsed that, depending on the electrolyte, there is a limit to how much energy can be

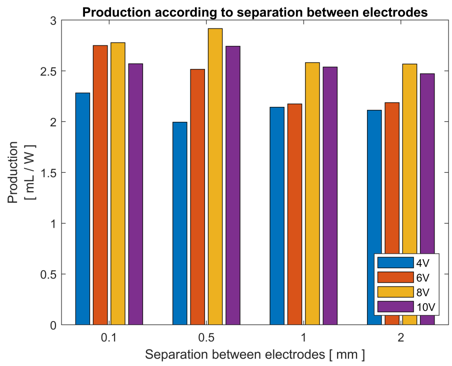

Figure 11. Gas production according to separation between electrodes, with a variation of 4 to 10V in the power source and pulse frequency of 1MHz.

entered and chemically accumulated in the liquid. A distinction must be made between two capacitive behaviors present in the electrolysis cell. One is the ability to store or accumulate chemical energy in the electrolyte, after the pulse this energy is used to break down the molecules of H_2O, this will be referred to as chemical capacity. The other capacitive behavior is the physical property that two conductors have under a potential difference, represented by the electrodes positioned very close to each other, this characteristic is diminished when using needle-tipped electrodes, this principle is the cause of the double layer. Applying the theory of the capacitor to the electrolysis cell, it has that in each voltage pulse a certain amount of current is injected into the cell, this current is greater when the voltage is greater. Taking into account that the gas or decomposition of H_2O is produced in the vicinity of the electrodes, a saturation of the medium in which the current is applied, in this case water, can be proposed. In this way, by increasing the separation of the electrodes, the area available to collect charge is expanded, or it could be related to a volumetrically increased chemical capacity. Separating the electrodes brings with it other effects, in addition to increasing the chemical capacity, the electrical capacitance is reduced and also increases the resistance of the circuit. The distance between electrodes must be carefully studied for the frequency and voltage to be applied in the electrolysis cell. During tests with rainwater as an electrolyte, this was the first to present high levels of voltage in the pulses, a couple of hundred volts due to its low conductivity. Rainwater, similar in purity to distilled water, although it may contain minerals or particles corresponding to environmental conditions, due to this it has a low ionic concentration that reduces its chemical capacity compared to drinking water. Around a frequency of 500kHz, a voltage of 10V in the power supply and with a separation of 0.1mm between electrodes, pulses of 430V were reached, which caused the formation of electrical sparks in the vicinity of the electrodes. This phenomenon was not present constantly, it was exhibited intermittently as small bubbles were formed that were adhered between the tips of the electrodes, a location conducive to the ionization of the gaseous medium, by further decreasing the distance between them, it was possible to evidence the formation of plasma.

At the time of plasma formation, it can be noticed that gas bubbles begin to be produced in greater proportion directly from the ionized gas zone. Unfortunately it was not possible to stabilize the phenomenon, the electrodes had to approach a distance of less than 0.1mm to stabilize it for a few seconds, after a while it became intermittent. Due to this, it was not possible to carry out the corresponding gas production efficiency tests. Despite the drawback, this experiment allowed to rescue information on the needs that must be covered for the formation of stable plasma. The pulses must be above a voltage approximately 500 volts for this distance (less than 0.1mm), for the electric arc to be viable at a greater distance between electrodes, the voltage must increase proportionally. For the formation of plasma in any electrolyte to be possible, it is necessary that the pulse-generating circuit is capable of producing these with a voltage independent of the resistance of the liquid medium, that is, at a constant voltage. The latter can be achieved by performing abrupt and intermittent discharges from a high-voltage stabilized direct current source, possibly a high-voltage capacitor. Current technology allows the implementation of solid-state voltage boosters that could be suitable for this application.

Figure 12. Plasma formation inside the electrolysis cell.

5. Conclusions

Pulsed electrolysis offers new parameters to control the efficiency and production of the process, which in turn presents new characteristics that require study to be optimally configured. The efficiency of pulsed electrolysis depends on a marked separation between voltage pulses, if a constant or quasi-constant voltage is maintained within the cell, without the potential being neutralized between pulses, the process takes on the characteristics of conventional electrolysis causing the formation of the double layer. The chemically accumulated energy is not reflected in a voltage observable with the measuring instruments, a saturation of this type can be witnessed when applying a greater power, the production increases and not the efficiency of the process, inevitably, to develop the process, this must be established in an adequate or satisfactory chemical capacity. The positioning and geometry of the electrodes also proved to affect this characteristic of the cell, the chemical capacitance can be found closely linked to the volume of liquid in the vicinity of the electrodes. With the tests and experiments carried out in this study, it can be established that, to achieve a characterization in greater depth, it is necessary to have a high-definition current sensor, which provides the ability to analyze the current pulse applied in the cell. This information allows a reliable comparison of the energy used in both electrolysis processes, as well as offering more data that would facilitate the identification of the parameters necessary for an efficient decomposition of water. Another important point that would allow a better obtaining of results is the implementation of a circuit capable of delivering a certain voltage independent of the purity of the electrolyte, this would allow the possibility of investigating the formation of plasma in the electrolytes that offer greater efficiency in the process. To achieve this, the application of pulses from a stable high-voltage source is proposed.

A possible improvement in efficiency in hydrogen generation, with the simple fact of modifying the power sources that currently supply the power to the generators present in the industry, could radically change the hydrogen economy. Greater production at a lower cost would mean a significant advance for the emerging hydrogen industry in Chile and the world.

Author Contributions: "Conceptualization, M.A. and M.R.; methodology, M.A.; software, M.A.; validation, M.A.; formal analysis, M.A., M.R. and P.W.; investigation, M.A., M.R., P.W. and R.R.; resources, M.A., M.R. and P.W.; data curation, M.A.; writing—original draft preparation, M. A.; writing—review and editing, M.A., M.R. and P.W.; visualization, M.A., M.R., P.W. and R.R; supervision, M.A., M.R. and P.W.; project administration, X.X.; funding acquisition, M.R. and P.W.. All authors have read and agreed to the published version of the manuscript.".

Funding: "The authors appreciate the support of the Project Fondecyt Regular 1220556, FONDAP SERC Chile N°15110019, CLIMAT AMSUD 210001 and ANILLO-ANID ATE220023".

Institutional Review Board Statement: "Not applicable".

Informed Consent Statement: "Not applicable".

Data Availability Statement: "Not applicable".

Acknowledgments: The authors thanks the support of the Universidad de Talca and University of Nottingham.

Conflicts of Interest: "The authors declare no conflict of interest."

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