JOURNAL OF SYSTEMS
AND INDUSTRIAL PROJECT ENGINEERING
JSIPE

*Vol.3, N° 1, January 2017*
*pp. 148-163*
*ISSN: 2411-7226*

# OPTIMAL CONCEPTION OF AN EMBARKED HYDROGEN GENERATOR FOR INJECTION OF AN AUXILIARY ADDITIONAL COMBUSTIBLE INTO GASOLINE ENGINES

**Pr. José Marie Michel ANDRIAMAMPIANINA**
**Lantosoa RATSIMAMANGA RAZANAMPARANY**
**Dolly Armel Sylvain ANDRIATOAVINA**
Institut Supérieur de Technologie d'Antananarivo. 101 Antananarivo. Madagascar.

**Pr. Adolphe Andriamanga RATIARISON**
Université d'Antananarivo. 101 Antananarivo. Madagascar.

## ABSTRACT

Internal combustion engines propel the economy of transport. They are fueled by fossil combustibles, which are becoming rare at a serious rhythm. Moreover, their combustion generates many harmful pollutants and damages the environment. It is high time we identified alternative fuels. For instance, bioenergy provides synthetic gases in which hydrogen, which is extremely flammable, brings some compromise solutions.

Hydrogen is an energetic vector of the future for the diversification of the sources of energy production. Its use as a clean and renewable energy becomes more and more attractive on account of environmental pressures and its efficiency on internal combustion engines, faced with the rise of petrol price. Safety remains one of the hindrances to its introduction to the market.

Indeed, hydrogen possesses a wide range of explosiveness and a low minimum energy of ignition at a stoichiometric concentration. Thus, the efficiency of hydrogen injection as an auxiliary additional combustible in gasoline engines is no longer a doubt, but no trace allows to scientifically affirming it with certainty.

From the results of electrochemical tests, an optimal conception of a vehicle-embarked hydrogen generator is proposed in this article. The aim of the work is to enrich the fuel with hydrogen through water electrolysis in gasoline engines.

This hydrogen generator is a partial alternative solution to the use of black gold using blue gold. Its conception, its production and its use as a fuel economizer are within the reach of the Malagasy people.

**KEYWORDS**: Electrolysis – Energy – Optimization – Generator – Hydrogen – Injection – Fuel – Engine

**MAJORS**: Mechanic and energetic engineering.

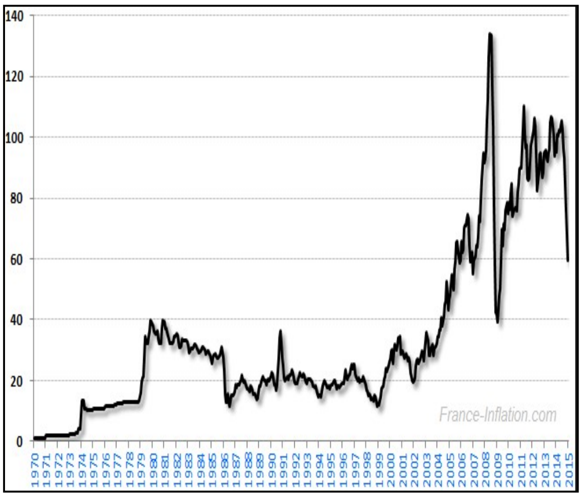


Figure 1.1: Record oil price in 2008 [2']

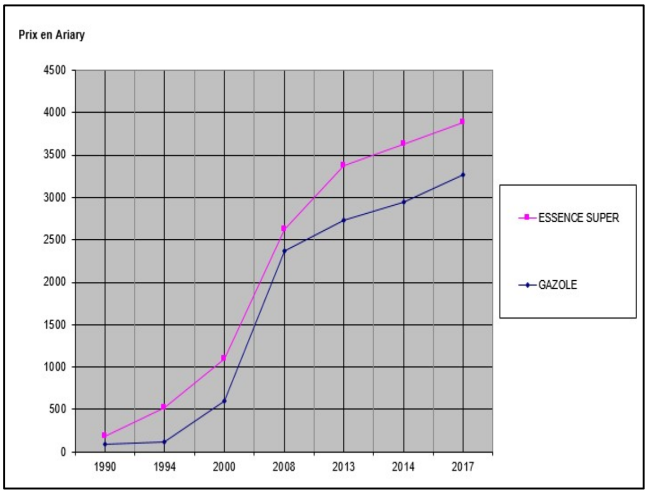


Figure 1.2: Annual evolution of fuel prices in Madagascar since 1990 [1']

## 1- INTRODUCTION [3] [4] [1'] [2'] [3']

Internal combustion engines have more than 150 years of history. They gave birth to what is arguably the largest mechanical system in the world. Their record is indeed impressive: 800 million passenger cars, an annual production capacity of nearly 80 million vehicles and a growth that does not seem to weaken despite global financial crises.

From the late 19th century, oil enabled the development of this engine, and subsequently made the use of cars, ships and aircrafts easy. All these devices, recent in the history of contemporary man, consumed a lot of energy in their beginnings because of their very low efficiency.

After the oil shock of 1973 (see figure 1.1), the price of a barrel of oil was trading in a range between $ 10 and $ 40 in the 1990s. It exceeded the fateful value of $ 100 on January 7, 2008 and reached the record value of $ 145 in one day in that same year. The balance of oil prices is broken. It gave rise to energy saving, which has become the primary goal of major energy-consuming countries faced with several concerns:

- fear of depletion of fossil fuels;
- global warming, which may result from greenhouse gas emissions linked to the high consumption of hydrocarbons;
- insecurity on the supply of energy due to the heterogeneous distribution of primary energies on the planet, thus generating important geopolitical stakes and technical-socio-economic interests;
- increase in the cost of energy resulting from the combination of these phenomena.

Oil is used in all sectors of production in the world. It has established itself as the main source of industrial energy. It is also used as a raw material in the manufacture of lubricants, tar, plastics, fertilizers and various synthetic products.

Madagascar imports oil to meet all its oil needs. Figure 1.2 shows the seven most significant prices at the pump since 1990. The evolution of these prices reflects the country's economic difficulties. There is a very rapid increase in fuel costs over time. The bad health of the national currency does not help. Coupling the rise in the price of oil with the devaluation of the national currency does not facilitate the control of inflation.

Numerous solutions have emerged to overcome this problem. The fluctuation of the price of oil encourages men to resort to other sources of energy, such as water. As a scarce resource, the object of all lusts, tensions and conflicts in certain countries, water justly deserves its reputation as blue gold. The emergence of renewable energies encourages the production of hydrogen from the electrolysis of water. Indeed, hydrogen ($H_2$) offers a very promising alternative to remedy the problems related to fossil energies, thanks to its physicochemical properties.

## 2- PRESENTATION OF THE WORKS [5] [13] [14] [4'] [5']

Since the creation of the first internal combustion engine by Etienne Lenoir in 1860, the evolution of technology and engineering has given rise to several types of engine and various sources of usable energy.

Although they are polluting, fossil fuels represent the vast majority of the energy sources used and are currently becoming depleted.

Numerous solutions have emerged to remedy this deficit, namely renewable energies, which are at the origin of the concept of the emergence of a new energy source: hydrogen ($H_2$). The latter has an energy density of 33 kWh/kg. It contains 3 times more energy than diesel and 2,5 times more energy than natural gas. In addition, a hydrogen-fueled vehicle is said to be "carbon-free" and is part of clean vehicles [7'] (see photograph 2.1).

*Hydrogen fuel enrichment* refers to technologies that primarily allow the addition of dihydrogen to hydrocarbons used in internal combustion engines. The main advantage of the device would be the reduction in pollutant emissions ($CO_2$, $NO_X$), while improving the thermodynamic efficiency of equipped engines.

There has been much research on the mixing of hydrogen, dioxygen and hydrocarbons. The result has been fuel savings and reduced emissions, thanks to the addition of hydrogen to conventional fuels.

Charles H. Frazer, an American, was the first in 1918 to file a patent for the improvement of the combustion in the engine by the addition of hydrogen.

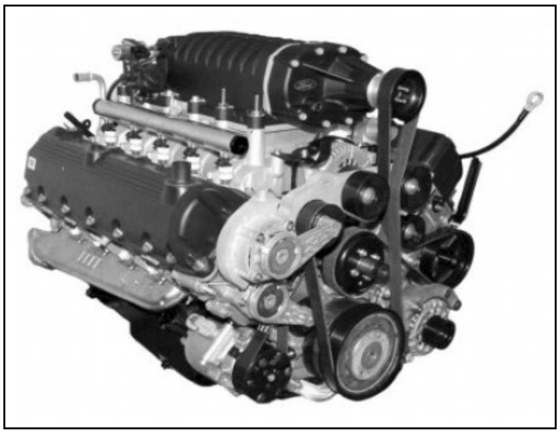
In 1974, researchers at the *Jet Propulsion Laboratory* of the *California Institute of Technology* published a paper titled "On-Board Hydrogen Generator for a Partial Hydrogen Injection Internal Combustion Engine" [9].

In 1977, NASA carried out a study using hydrogen as a fuel additive, or **auxiliary fuel** added to gasoline in an engine. The experiment was successfully carried out with the aid of a methanol vapor oxidizer.

In November 2007, the US Department of Transportation [4'] [15] published the official report "FMCSA-RRT-07-020" via the Federal Motor Transport Safety Administration, devoted to the use of **hydrogen as an additional fuel** for commercial heavy-duty diesel engines. The test devices have shown their effectiveness in optimizing primary carburization, mixed with hydrogen as fuel on an engine developed by Ford Motor Company (see photograph 2.2).

In summary, hydrogen enrichment of fuel by electrolysis is promoted on vehicles as a complement to a primary fuel: gasoline or diesel fuel. The improvement in efficiency does not therefore depend on the principle of "conventional fuel", but on the addition of dihydrogen ($H_2$) and dioxygen ($O_2$) to the air intake of the engine. This is referred to as **additional auxiliary fuel** optimizing the primary carburation of the engine, like the injection of gas from the turbocharger used in the automobile and aeronautics since the mid-20th century.

Photograph 2.1: A car running on hydrogen [6']



Photograph 2.2: Ford V10 engine with hydrogen as auxiliary fuel [15]

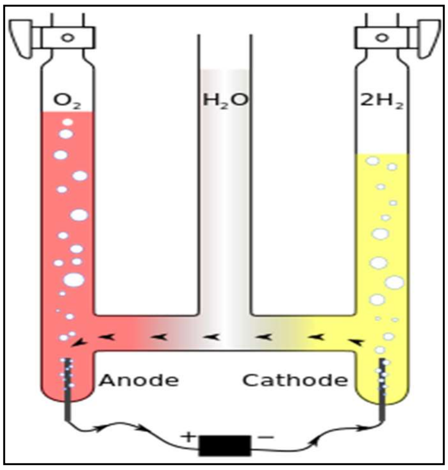


Figure 3.1: Hoffmann voltmeter used for electrolysis of water

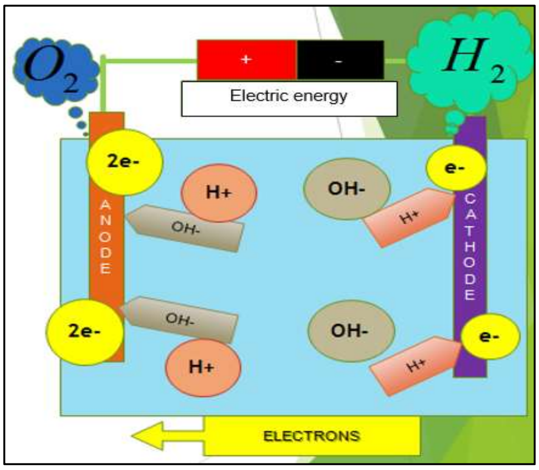


Figure 3.2: Block diagram of water electrolysis

## 3- WATER ELECTROLYSIS [8']

Electrolysis of water is an electrolytic process that decomposes water into *dihydrogen ($H_2$) and gaseous dioxygen ($O_2$)* using an electric current. The electrolytic cell consists of two electrodes immersed in an electrolyte and connected to the opposite poles of a continuous current source.

The electrodes are usually made of inert metal such as platinum. In this study, the electrolyte was water itself.

The first electrolysis of water was carried out on May 2nd,1800 by two British chemists, William Nicholson (1753-1815) and Sir Anthony Carlisle (1768-1840), a few weeks after the invention of the first electric battery published by Alessandro Volta on March20th ,1800.

### 3.1- PRINCIPLE AND DESCRIPTION OF THE ELECTROLYSIS PROCESS BY ELECTROCHEMISTRY [8']

Electrochemistry is the scientific discipline that deals with the relationship between chemistry and electricity. It describes chemical phenomena coupled with reciprocal exchanges of electrical energy.

The electric current dissociates the molecule of water ($H_2O$) into hydroxide ($HO^-$) and hydrogen ($H^+$) ions: in the electrolytic cell, hydrogen ions accept electrons at the cathode in an oxidation-reduction reaction to form gaseous dihydrogen ($H_2$), depending on the *reduction* reaction

$$2\,H^+ + 2\,e^- => H_2\,(gas) \qquad (3.1)$$

whereas an *oxidation* of the hydroxide ions, which thus lose electrons, occurs at the anode in order to "close" the electrical circuit. Then, there is the balanced reaction in terms of charges

$$2\,H_2O\,(liquid) => O_2\,(gas) + 4\,H^+\,(aqueous) + 4\,e^- \qquad (3.2)$$

that gives the following equation of decomposition by electrolysis (see figure 3.1):

$$2\,H_2O\,(liquid) => 2\,H_2\,(gas) + O_2\,(gas) \qquad (3.3)$$

It can be seen that the reaction on the cathode consumes two electrons (see figure 3.2), while the one occurring at the anode releases four, thus producing more dihydrogen ($H_2$) than dioxygen ($O_2$). The amount of dihydrogen gas ($H_2$) produced is thus twice that of dioxygen ($O_2$). According to the Avogadro law, *the recovered volume of dihydrogen gas ($H_2$) produced is also twice as large as that of dioxygen ($O_2$).*

By convention, the current moves from the anode (positive electrode) to the cathode (negative electrode) electrically, but chemically speaking, the electrons move from the negative electrode to the positive electrode in the opposite direction.

## 3.2- HYDROGEN GENERATORS

The first electrolyzers had multipolar electrodes (see figure 3.3) for the production of dihydrogen ($H_2$). Each anode is connected to the positive pole and each cathode to the negative pole of an electric accumulator. This multipolar device has the disadvantage of consuming a lot of electricity because the electrodes are mounted in parallel.

According to Faraday's law and taking into account the thermodynamic parameters at 25 °C, the electrolysis of the water in an electrolytic cell can theoretically take place from a low voltage of

$$E_{Th} = 1{,}23\ V \qquad (3.4)$$

between the electrodes [11']. Thus, to compensate for the shortcomings of the multipolar generator (see figure 3.3), a bipolar generator (see figure 3.4) can be envisaged, comprising a *neutral electrode module connected in series to the electrodes* in order to reduce the voltage and the intensity of the current per cell of the generator during the electrolysis of the water, while producing more dihydrogen.

By replacing the electrodes of the electrolyzer with stainless plates, a "dry cell" hydrogen generator is obtained (see photograph 3.1). Its particularity is to have electrodes in the form of plates, which, in contrast to the "wet cell" type, possess more metallic surfaces in contact with water. Thus, the current sent to the "dry cell" is used more efficiently, which makes it possible to produce more gases at low voltage and intensity per cell.

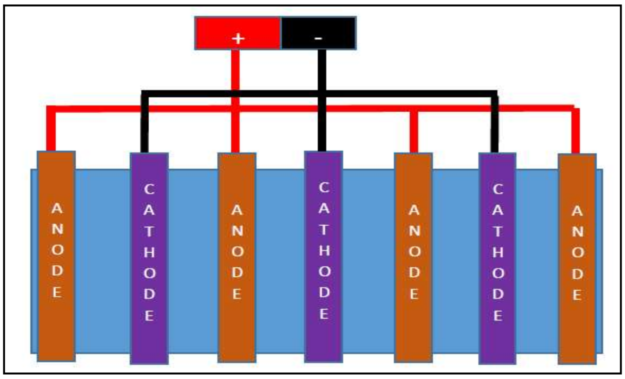


Figure 3.3: Multipolar hydrogen generator

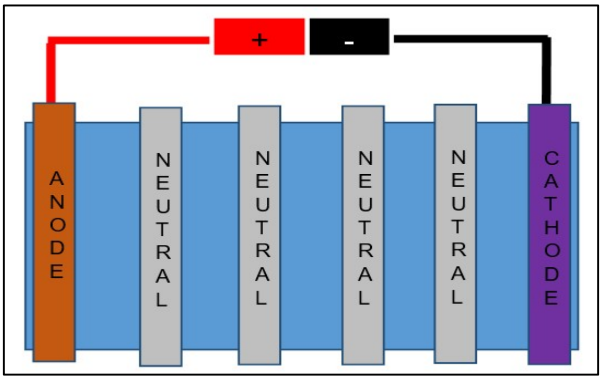
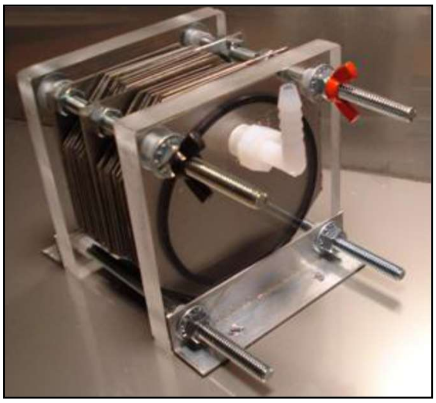


Figure 3.4: Bipolar hydrogen generator



Photograph 3.1: Dry cell hydrogen generator

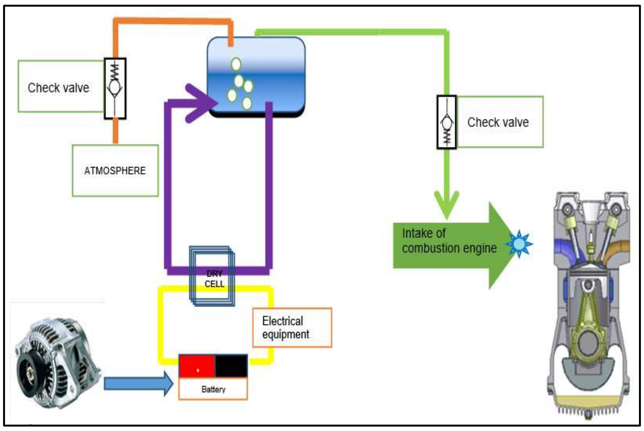


Figure 3.5: Mounting the dry cell on an internal combustion engine

## 4- FARADAY'S LAWS

In 1834, Michael Faraday established the relationship between the quantity of chemicals formed at the electrode and the amount of charge or electrons passed during electrolysis.

The measured electrical current is the number of electrons transferred per second

$$Q = I \,.\, t$$

Q being the charge in Coulomb, I the intensity in Ampere and t the time in seconds.

The Author has stated the following two laws which make it possible to determine the magnitude of the electric charge borne by the two ions.

### 4.1- FARADAY'S FIRST LAW

The amount of substance released during electrolysis at an electrode is proportional to time and electrical current.

For a Faraday $F_r$ of charges, **one mole of gas** produced is obtained by

$$F_r = N_a \,.\, e = 96\ 485\ \text{Coulomb/mol} \qquad (4.1)$$

$F_r$ being the Faraday constant, Na the Avogadro number (6,02214040 x $10^{23}$ $mol^{-1}$), and e the elementary charge of **an electron** (1,602 x $10^{-19}$ C).

## 4.2- FARADAY'S SECOND LAW

The weights of various bodies separated from the electrodes by the same quantity of electricity are to each other as their chemical equivalents. This law connects the mass formed at an electrode with the released charge.

$$m = \frac{M \cdot Q}{z \cdot F_r} = \frac{M \cdot I \cdot t}{z \cdot F_r} \qquad (4.2)$$

m being the mass [g] formed at the electrode, M the molar mass [g/mol], z the valence of the substance (1 for hydrogen, 2 for oxygen), I the intensity [A] of the current, t the time [s] and Q the charge in Coulomb.

## 5- CHEMICAL THERMODYNAMIC APPROACHOF A HYDROGEN GENERATOR

The principles of thermodynamics, in fact principles because not demonstrated, are the principal laws governing thermodynamics:

- first principle of thermodynamics: principle of conservation of energy by introducing the internal energy function U;
- second principle of thermodynamics: principle of evolution, creation of entropy S;
- third principle of thermodynamics or Nernst principle: the entropy of a pure body is zero at the temperature T of 0 °K.

There are sometimes two other principles:

- zero principle of thermodynamics: temperature is a markable quantity;
- fourth principle of thermodynamics, as the name given to Onsager's theory: there exists a linear relation between volumetric currents and thermodynamic forces.

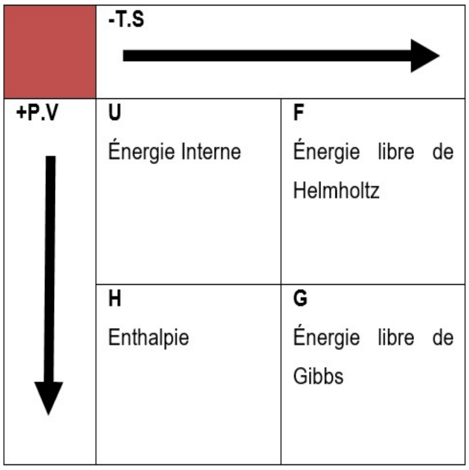


Figure 5.1: Hoffmann voltmeter used for electrolysis of water

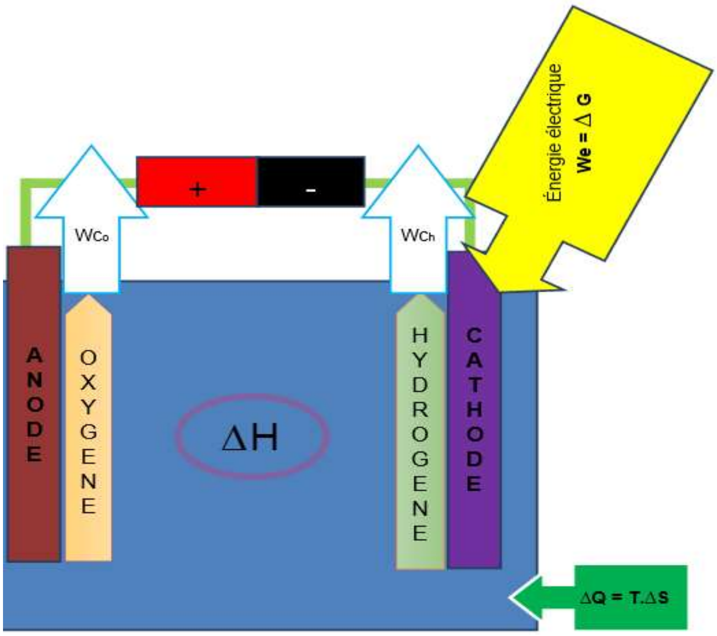


Figure 5.2: Block diagram of water electrolysis

| STATE FUNCTION | WATER $(H_2O)_{LIQUID}$ | HYDROGEN $(H_2)_{GASEOUS}$ | OXYGEN $(O)_{GASEOUS}$ | ENERGY VARIATION |
|---|---|---|---|---|
| Enthalpy H [kJ/mol] | 285,83 | 0 | 0 | ΔH = 285,83 |
| Entropy S | 69,91 [$J.K^{-1}$/mol] | 130,68 [$J.K^{-1}$/mol] | 0,5 x 205,14 [$J.K^{-1}$/mol] | Q = T.ΔS = 48,7 [J/mol] |

Table 5.1: Thermodynamic state function values at temperature T of 298 °K and at atmospheric pressure

## 5.3- CHEMICAL THERMODYNAMIC APPROACH OF WATER ELECTROLYSIS [8']

The water molecule $H_2O$ is formed by two hydrogen atoms and one oxygen atom. It is a pure substance and can only be broken by physical means. Electrolysis of water is the process which, thanks to **an electrolytic cell**, allows the separation of the water molecule into its two constituent elements: dihydrogen and dioxygen.

### 5.3.1- Modeling of the process of dissociation of water into hydrogen and gaseous oxygen

By supplying electrical energy to an electrolytic cell, water can be dissociated into diatomic molecules ($H_2$ + ½ $O_2$). Figure 5.1 shows the different chemical thermodynamic potentials.

In figure 5.2, we define:

- ΔH, the variation of the total energy of the system for one mole of water;

- $\Delta Q$, the amount of heat for one mole of water supplied by the environment, including temperature and entropy ($\Delta Q = T.\ \Delta S$);
- $\Delta Wc$, the variation of the kinetic energy of hydrogen gases ($\Delta Wc_h$) and oxygen ($\Delta Wc_o$) products. It represents the overall movement of the outgoing gases for one mole of water ($\Delta Wc = \Delta Wc_h + \Delta Wc_o$);
- $\Delta G$, the variation of the free energy necessary for the decomposition of one mole of water.

Electrolysis of one mole of water produces one mole of hydrogen and a half mole of oxygen in the form of gas. The process of dissociation of water into hydrogen and oxygen is modeled using the first principle of thermodynamics and chemical thermodynamic potentials.

Assuming a thermodynamic evolution at 298 °K (25 °C) and at atmospheric pressure, the thermodynamic values obtained from the various state functions are deduced from table 5.1.

The enthalpy represents the expansion energies of the produced gases and the dissociation of water into hydrogen and gaseous oxygen.

By neglecting the variation of the kinetic energy of the outgoing gases ($\Delta Wc = 0$) *at the beginning of the reaction*, the variation of the total energy $\Delta H$ of the system cannot represent alone the electrical energy consumed. As the S entropy increases during the thermodynamic transformation, the environment provides *the heat quantity $T.\Delta S$* at the temperature T of 298 °K. Therefore, the minimum electrical energy supplied by the battery under *favorable conditions* is therefore the variation of the free energy of Gibbs

$$\Delta G = \Delta H - T.\ \Delta S = 237{,}13 \text{ kJ/mol} \qquad (5.1)$$

Starting from the relation (4.1), Faraday's law states that the variation of the free energy necessary for the decomposition of one mole of water is written [7] [13']

$$\Delta G = n_e\ .\ F_r\ .\ E_{Th} \qquad (5.2)$$

under a potential difference $E_{Th}$ under *favorable conditions*, while consuming two electrons (3.1) at the beginning of the reaction, at the cathode and then releasing four at the anode (3.2). It is then deduced from the relation (5.2)

$$E_{Th} = \frac{\Delta G}{2\ .\ F_r} = 1{,}228 \text{ V} \sim \mathbf{1{,}23\ V} \qquad (5.3)$$

The law of Faraday (3.4) is deduced. These considerations make the conversion of water into hydrogen and gaseous oxygen difficult in a normal environment, which is difficult to carry out without the contribution of electrolyte solution.

### 5.3.2- Kinetics of water electrolysis reaction [7]

Two water electrolysis voltages can be defined from the equation (5.1):

- the first is obtained from $\Delta G$, and only corresponds to the electrical energy demand necessary for the electrolysis reaction of the water, called minimum thermodynamic voltage. This represents the reversible voltage for the water dissociation reaction;
- the second is the enthalpic voltage, also known as the thermo-neutral voltage of the reaction. It is obtained from $\Delta H$ and represents the total energy required for the reaction to take place. These two characteristic voltages of the water dissociation reaction can be defined as follows:

$$U_{Reversible} = U_{Thermodynamic} = E_{Th} = \frac{\Delta G}{2\ .\ F_r} = 1{,}23 \text{ V} \qquad (5.4)$$

$$U_{Enthalpic} = U_{Thermoneutral} = \frac{\Delta H}{2\ .\ F_r} = 1{,}48 \text{ V} \qquad (5.5)$$

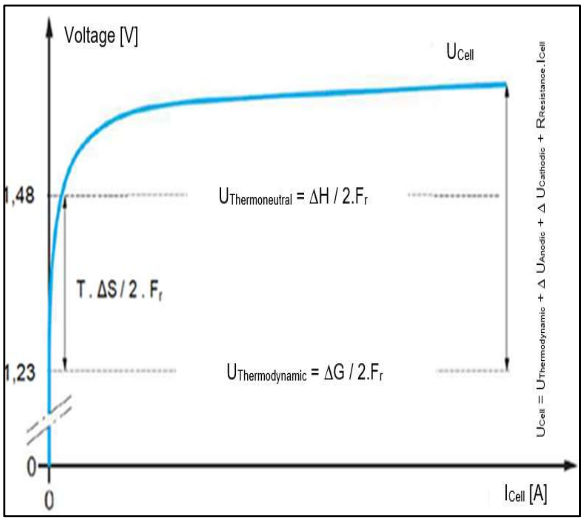


Figure 5.3: A characteristic curve of the voltage across the electrodes of an electrolyte cell as a function of the current intensity [7]

Figure 5.3 shows the evolution of the phenomena characterizing the main results obtained by electrochemical and thermodynamic approaches. In practice, the electrolysis of water can only be carried out at a **voltage well above 1,48 V**

$$U_{Cell} >> U_{Thermoneutral} = 1{,}48 \text{ V} \qquad (5.6)$$

in order to ensure correct dissociation of water into hydrogen and gaseous oxygen. Indeed, the second Faraday's law (4.2) demonstrates that the mass of gas formed at an electrode is proportional to the intensity $I_{Cell}$ of the current, whatever the voltage applied between the terminals of the cell is. *The $I_{Cell}$ intensity is then the predominant parameter in the formation of hydrogen.*

## 6- EXPERIMENTAL METHOD OF ELECTROLYSIS

The proposed experimental method consists of scientifically testing the validity of previous approaches by repeated experiments. Using physical measurements and new qualitative and quantitative data allows us to confirm the initial hypotheses.

Indeed, nowadays, there is no judicious formulation exhaustively dealing with the enrichment of fuel by hydrogen. To be credible, scientific experiments are distinguished by the application of a protocol of measurements, allowing a precise reproduction of a particular electrolysis.

For this purpose, it was decided to carry out the measurements on a cell of a hydrogen generator of the "dry cell" type.

## 6.1- GEOMETRIC CONFIGURATION OF THE HYDROGEN GENERATOR

Figure 3.5 shows an installation kit. The water is stored in a reservoir placed at the top of the "dry cell" type generator (see photograph 3.1). It descends by gravity towards the plate-shaped stainless electrodes, which are closely spaced apart by seals, thus forming one or more series of bipolar electrolytic cells called modules (see figure 3.4). A module connection in parallel defines the essential elements of the hydrogen generator.

Figure 6.1 shows a "dry cell" type generator composed of two modules connected in parallel. In this study, each module has three electrolytic cells mounted in series (see figure 6.2). The mounting of the neutral plates between the electrodes increases the metal surface in contact with the water, which makes it possible to produce more hydrogen for the same intensity of current passing through a module.

When the generator is powered with electricity, there is production of high pressure gas, which naturally rises by partially bringing the water back into the tank (see figure 3.5). The gas then escapes through an outlet situated above the level of the water of the tank in order to be injected into the air intake pipe and then sucked by the pistons of the engine. This allows not storing hydrogen for safety reasons. This system is fuel efficient and less polluting.

## 6.2- GEOMETRIC DEFINITION OF HYDROGEN GENERATOR

A module is defined in figure 6.2 by an assembly of bipolar plates delimited by the anode and the cathode. In this example, there are two neutral plates and two electrodes forming three electrolytic cells connected in series.

In a generator composed of several modules (see figure 6.1), the neutral (grey), positive (red anode) and negative (green cathode) plates are geometrically defined in figures 6.3 and 6.4.

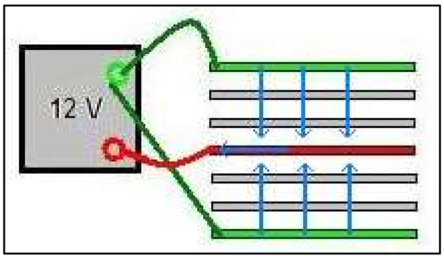


Figure 6.1: A "dry cell" type generator composed of two modules connected in parallel

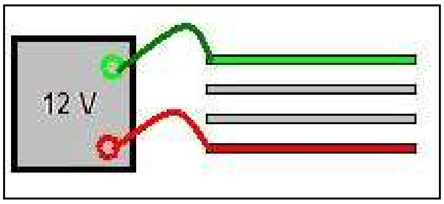


Figure 6.2: A "dry cell" type generator equipped with three cells mounted in series

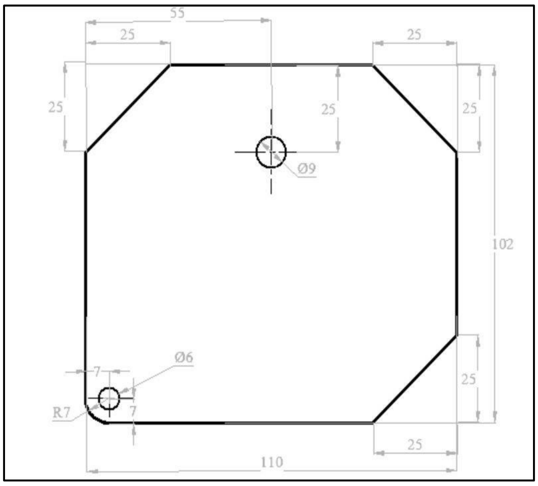


Figure 6.3: Geometric definition of neutral and positive plates

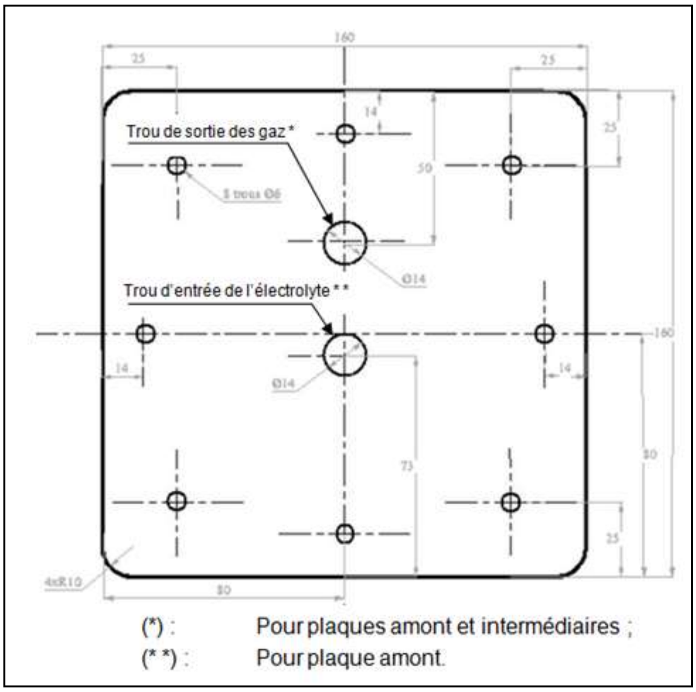


Figure 6.4: Geometric definition of the three types of negative plates: upstream, intermediate and downstream.

Photograph 6.1: An aqueous electrolytic solution

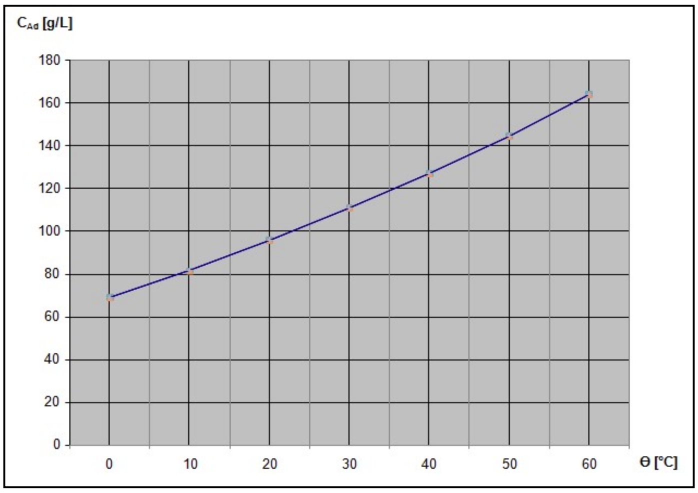


Figure 6.5: Evolution of the aqueous solubility of sodium bicarbonate as a function of temperature

## 6.3- EXPERIMENTAL CHARACTERIZATION OF A CELL OF THE GENERATOR

Pure water conducts little electricity, which leads to the use of a water-soluble additive, called electrolyte (see photograph 6.1), to improve its conductivity, in other words, to ensure that the electrical potentials involved allow the chemical reaction.

### 6.3.1- The electrolyte used [16']

Generally, potassium hydroxide (KOH)or sodium hydroxide (NaOH) or sodium bicarbonate ($NaHCO_3$) is used in order of efficiency in the hydrogen generators embedded in the vehicles. However, sodium bicarbonate ($NaHCO_3$, see photograph 6.1) was chosen because of its benefits:

- available at the local grocery store;
- cheap;
- safe;
- very good gas production.

### 6.3.2- Physicochemical properties of sodium bicarbonate [17']

Sodium bicarbonate ($NaHCO_3$) has a low aqueous solubility. To avoid the formation of electrolyte deposits in the generator, its mass concentration C in a liter of water must not exceed the maximum permissible values $C_{Ad}$, which are a function of the temperature Θ of the electrolyte (see figure6.5). Below these limits:

- 69 g of sodium bicarbonate in one liter of cold water at a temperature Θ of 0 °C;
- 81,5 g/L at 10 °C;
- 96 g/L at 20 °C;
- 111 g/L at 30 °C;
- 127 g/L at 40 °C;
- 144,5 g/L at 50 °C;
- 164 g/L at 60 °C;
- and 197 g/L in hot water at 80 °C.

Since the dissolution is practically carried out at a temperature Θ of 20 °C, the following rule was generally used:

$$C < C_{Ad} = 96 \text{ g/L} \qquad (6.1)$$

### 6.3.3- Intensity of the current through a cell as a function of the concentration of the electrolyte

Starting from the energy balance of the electrolysis of water in a cell of the generator (see figure5.2), the voltage at the terminals of the cell transforming water into gas can be written (see figure 6.6) as follows:

$$U_{Cell} = (R_{Thermodynamic} + R_{Electrodes} + R_{Resistance}) \,.\, I_{Cell}$$

wether

$$I_{Cell} = G \,.\, U_{Cell} \qquad (6.2)$$

where G is the conductance of a cell.

For a given concentration of electrolyte (C = 48 g/L, see figure 6.7), the intensity $I_{Cell}$ of the cell and the voltage $U_{Cell}$ were measured using a Metrix. The electrochemical reaction started at 3 V. Subsequently, significant and continuous gas production was observed at 4 V. Above the latter, the heat generated by the generator manifested itself.

By applying a voltage of $\mathbf{U_{Cell} = 4\ V}$ to the terminals of an electrolytic cell, figure6.7 shows the evolution of the $I_{Cell}$ intensity as a function of the concentration C in one liter of water at 20 °C. By satisfying the solubility conditions (6.1), the higher the concentration of the electrolyte is, the more its electrical conductivity improves and the more the intensity passing through the cell increases until the permissible concentration $C_{Ad}$ (6.1) is affected. This has the consequence of increasing the production of gas according to Faraday's law (4.2). Moreover, the intensity of the cell decreases for high concentrations due to the saturation of the electrolyte.

As part of the design of a hydrogen generator, the electrolyte used will be defined in the region of solubility of figure 6.7. To do this, the electrolysis can be simulated by linearly approximating the curve representing the evolution of the intensity of a 4 V cell in this zone as a function of the concentration C in one liter of water [g/L] at 20 °C, in order to optimize the generator from the equation

$$I_{Cell} = 0{,}01045\, C + 0{,}56818 \qquad (6.3)$$

which remains valid for a concentration C,

$$48\ g/L \leq C < 96\ g/L \qquad (6.4)$$

or in terms of intensity

$$1,07\ A \leq I_{Cell} < 1,53\ A \qquad (6.5)$$

### 6.3.4- Faradic efficiency of the electrolytic cell

The Faradic yield of the electrolytic cell is determined by the equation

$$\eta_F = \frac{E_{Th} = 1,23\ V}{U_{Cell} = 4\ V} = 30,75\ \% \qquad (6.6)$$

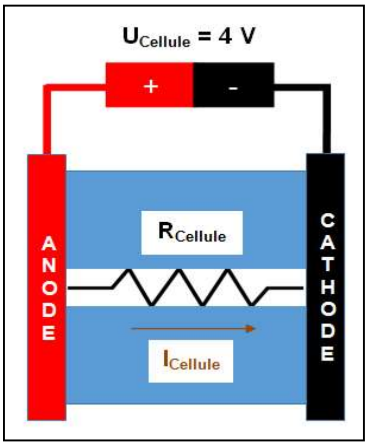


Figure 6.6: Electrical analogy at the terminals of an electrolytic cell

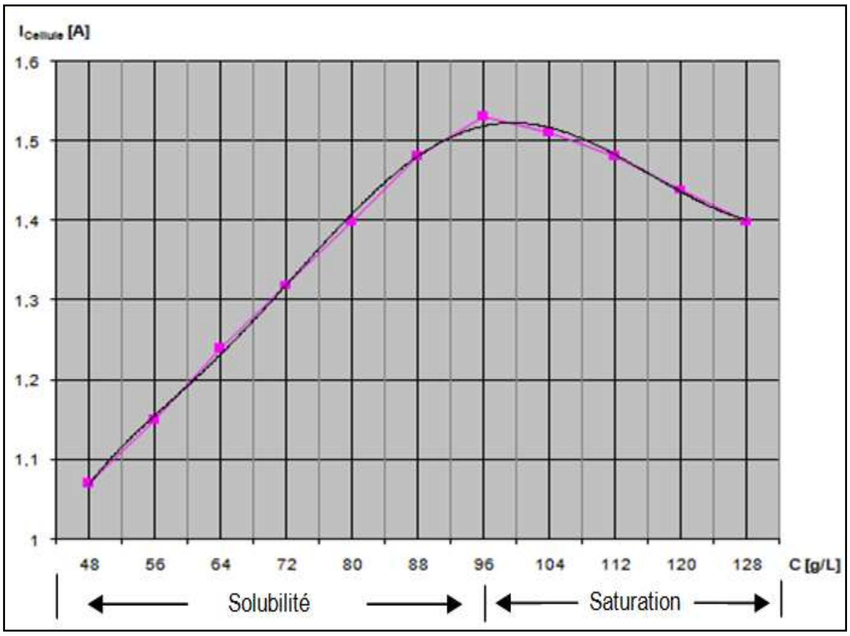


Figure 6.7: Intensity evolution of a cell 4 V as a function of the mass concentration C of the electrolyte in one liter of water at 20 °C

## 7- OPTIMAL DESIGN OF THE HYDROGEN GENERATOR

Hydrogen has a wide explosion range between 4 % and 75 % at ambient pressure and temperature (see figure 7.1). Its minimum ignition energy varies depending on the concentration of hydrogen and oxygen. At the stoichiometry defined by the reaction of a hydrogen molecule with an oxygen half-molecule, or by 29,5 % in volume of **hydrogen in the air**, this energy is only **17 µJ** (see figure 7.1), while a spark plug must provide a spark energy of more than **10 mJ** to initiate combustion in gasoline engines [8].

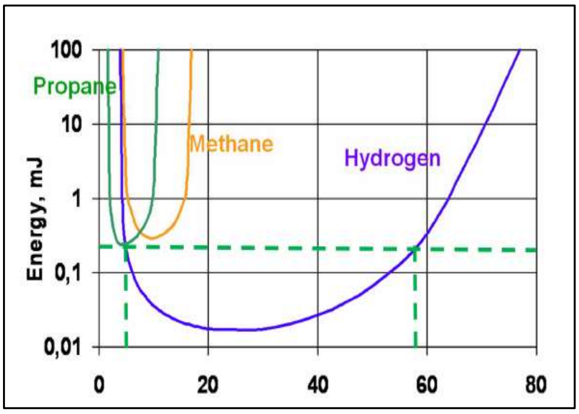


Figure 7.1: Hydrogen explosion range [6]

**The self-ignition temperature of hydrogen is 585 °C**. It is higher than that of most other flammable gases [6].

In a confined explosion, the rate of deflagration of the hydrogen flame is fairly stable. It can reach more than **30 m/s** at the end of the combustion, which is higher than that of conventional fuels of thermal engines [11] [20'].

**The term "HHO" refers to the stoichiometric mixture resulting from the electrolysis of water**. Indeed, twice as much gaseous dihydrogen ($H_2$) as dioxygen ($O_2$) is produced by volume. Thus, the electrolysis of water is a "HHO" generator that produces not only hydrogen, but also oxygen. Hydrogen is injected as an auxiliary combustible, and the oxygen produced as a supplemental oxidizer in internal combustion engines.

From the test results, Ford Motor Company [4'] [15] developed a motor allowing to optimize primary carburization mixed with hydrogen as a fuel (see photograph 2.2). Hence, the motor operates with a **HHO-gasoline mixture as high as 86-1, compared with that of air-gasoline 15-1 for conventional gasoline engines**, which offers:

- rapid ignition because hydrogen has a very low ignition energy to ignite poor mixtures;
- more complete combustion reaction;
- **final combustion at low temperature**;
- a reduction in emissions of pollutants in exhaust gases, such as nitrogen oxides;

- and an improvement of approximately 25% in engine efficiency, resulting in significant fuel savings.

According to Faraday's second law (4.2), the gas production capacity is proportional to the intensity passing through the generator. Thus, the mass concentration C of the electrolyte (see figure 6.7) plays a major role in the search for the maximum flow rate of the gases produced and injected into the engine. But, it is not the only factor. There are also:

- the temperature. Indeed, if the water of the electrolyte is hot, the solubility (see figures 6.5 and 6.7) improves, thus also the electrical conductivity. As a result, the powering intensity increases and the generator produces more HHO gas;
- the maximum voltage per cell limiting electrical losses transformed into heat by joule effect. In this case, it is fixed at 4 V at the terminals of a cell (see figure 6.6). Below this value, the generator produces less gas;
- the electrolysis surface, that is, the larger the area of the plates (see figures 6.3 and 6.4) in contact with the electrolyte is, the more the generator produces HHO gases.

In summary, the number of plates and their mounting modes, in series and in parallel, in a bipolar generator (see figures 3.4 and 6.1) and the mass concentration of the electrolyte play an important role in the search for the optimum production capacity of a hydrogen generator.

## 7.1- MODELING OF A MODULE OF THE HYDROGEN GENERATOR

There is no universal formula determining the hydrogen production capacity of a generator as a function of the intensity, or the concentration C in electrolytes of the water because of the points mentioned above. Indeed, the electrical and geometrical configurations of a generator can vary according to designers and vehicles.

### 7.1.1- Electrochemical definition of a module

A module is defined in figure 7.2 by an *electrical connection of cells in series*. If a vehicle equipped with a 12 V ($U_{Module}$ = 12 V) battery is used, with a voltage limit of 4 V per cell ($U_{Cell}$ = 4 V) as defined by the results of electrochemical and thermodynamic tests (see figure 6.6), three cells ($N_{Cell}$ = 3) should be assembled in series per module. From the Ohm's law and the relation (6.4), the intensity passing through a module is deduced as a function of the concentration C of electrolytes in the solubility zone of figure 6.7.

$$I_{Module} = I_{Cell} = 0{,}01045\ C + 0{,}56818 \qquad (7.1)$$

### 7.1.2- Hydrogen production capacity per module

According to Faraday's law (4.2), the mass [g] of gas produced by an electrode in this case, that is to say, by the surface of a plate in contact with the electrolyte in figure 7.2, is written

$$m = \frac{M\ .\ I_{Module}\ .\ t}{z\ .\ F_r} \qquad (7.2)$$

where M is the molar mass (2,01588 ± 0,00014 g/mol for hydrogen), z the valence of the substance (1 for hydrogen), $I_{Module}$ the current intensity and t the time. Thus, the surfaces of the five plates ($N_S$ = 5, see figure 7.2) supplying hydrogen have a production capacity [g/s] per module

$$C_{PModule} = m\ /\ t = \frac{N_S\ .\ M\ .\ I_{Module}}{z\ .\ F_r} \qquad (7.3)$$

or numerically as a function of the intensity passing through a module

$$C_{PModule} = 104\ 466\ .\ 10^{-9}\ .\ I_{Module} \qquad (7.4)$$

or as a function of the concentration C of the electrolyte (7.1)

$$C_{PModule} = (1\ 091{,}67\ C + 59\ 355{,}49)\ .\ 10^{-9} \qquad (7.5)$$

### 7.1.3- Power per module supplied by hydrogen

Hydrogen is the most energetic chemical per unit of mass [18']. Its calorific value $P_C$ is between the two following values:

$$120\ \text{kJ/g} < P_C < 143\ \text{kJ/g} \qquad (7.6)$$

The power $\mathcal{P}_{Module}$ provided per module can be calculated as a function of the mass production capacity $C_{PModule}$.

$$\mathcal{P}_{Module} = P_C\ .\ C_{PModule} \qquad (7.7)$$

Considering the lower calorific value of 120 kJ/g and introducing the intensity using the relation (7.4), this power (7.7) is expressed in Watts [W].

$$\mathcal{P}_{Module} = 12{,}536.\ I_{Module} \qquad (7.8)$$

By using the mass concentration C of the electrolyte through the relation (7.1), the latter expression is written

$$\mathcal{P}_{Module} = 0{,}131\ C + 7{,}1227 \qquad (7.9)$$

## 7.2- OPTIMUM CONFIGURATION OF THE HYDROGEN GENERATOR

To ignite, the air-gasoline mixture contained in the cylinder must undergo an increase in temperature, allowing to **carry a *part of its mass* above its ignition temperature of 380 °C**. The ignition of gases is caused by the electric arc of the spark of a spark plug placed in the combustion chamber. The calorific energy of the gases, generated by the electrical energy of more than **10 mJ** of this spark [8], raises the temperature of the mixture locally and ignites it in a small area close to the spark plug. As the combustion is triggered, the rest of the mixture ignites in successive layers around the ignition point (see figure 7.3). In other words, the ignition system must convert low-voltage electrical energy into sufficient heat energy to initiate combustion of the air-gasoline mixture.

Hydrogen is an extremely flammable gas. **Its minimum ignition energy is only 3 µJ in pure oxygen and 17 µJ in the air** (see figure 7.1). It is much more inferior than the energy of the electric arc of a spark plug, which is more than **10 mJ** [8], *an asset and an important point for the safety of the electrolyzers and the hydrogen generators*.

Thus, the injection of hydrogen as an auxiliary fuel into gasoline engines stores additional energy, making it possible to condition the calorific energy generated by the electric arc of the spark plug, which must be sufficient for the ignition, but not generally effective to provoke, **at low temperatures**, a rapid and complete combustion of the air-gasoline mixture in the combustion chambers.

Consequently, the efficiency of the hydrogen enrichment of the air-gasoline mixture can be achieved only by improving the mass production capacity, which remains very low (7.4) for a module. One of the solutions then consists of designing a generator equipped with several modules electrically connected in parallel. Figure 7.4 shows the geometric definition of a generator with $N_{Module}$ identical modules.

### 7.2.1- Hydrogen production capacity of a generator

To increase the hydrogen production capacity, one of the solutions then consists of using a generator equipped with $N_{Module}$ identical modules electrically connected in parallel. Thus, from the expression (7.4), the hydrogen production capacity of the generator can be written as follows

$$C_{PGenerator} = 104\ 466\ .\ 10^{-9}\ .\ N_{Module}\ .\ I_{Module} \quad (7.10)$$

or as a function of the intensity $I_{Generator}$ passing through the generator

$$C_{PGenerator} = 104\ 466\ .\ 10^{-9}\ .\ I_{Generator} \quad (7.11)$$

where

$$I_{Generator} = N_{Module}\ .\ I_{Module} \quad (7.12)$$

Depending on the concentration C of the electrolyte, the following expression is deduced from the equation (7.1)

$$C_{PGénérateur} = N_{Module}\ .\ (1\ 091{,}67\ C + 59\ 355{,}49)\ .\ 10^{-9} \quad (7.13)$$

### 7.2.2- Power supplied by the hydrogen released by a generator

The power $\mathcal{P}_{Generator}$ supplied by $N_{Module}$ identical modules of the generator can be calculated as a function of the modular power $\mathcal{P}_{Module}$ using the expression

$$\mathcal{P}_{Generator} = N_{Module}\ .\ \mathcal{P}_{Module}$$

By using the relation (7.8) and the intensity of the generator (7.12), the power in Watts [W] is

$$\mathcal{P}_{Generator} = 12{,}536\ .\ I_{Generator} \quad (7.14)$$

### 7.2.3- Optimal intensity powering the hydrogen generator

Stoichiometry, from the Greek stoikheion and metron, meaning "element" and then "measure", refers to the study of the ideal proportions of elements that permit a complete, clean and waste-free chemical reaction. Thus, the concentration of fuel in the oxidizer is also a determining factor in determining whether the combustion can take place. The minimum concentration permitting combustion is called the "Lower Explosion Limit (LEL)" and the maximum concentration the "Upper Explosion Limit (UEL)". The area bounded by the LEL and the UEL is the *range of explosiveness*. The oxygen concentration limit can be defined as the highest oxygen content below which the explosion becomes impossible. In this study, on the one hand, the hydrogen generator produces HHO resulting from a stoichiometric mixture of the electrolysis of the water and, on the other hand, the carburetor or the injection system of the engine regulates the air-gasoline mixture at stoichiometry "15-1".

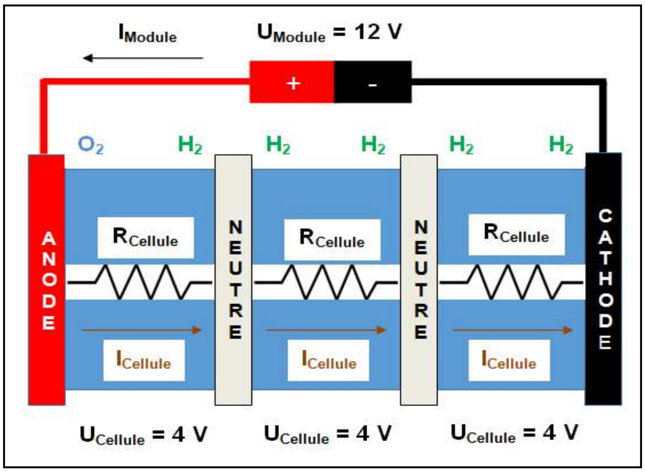


Figure 7.2: Electrochemical definition of a module of the bipolar hydrogen generator 12V

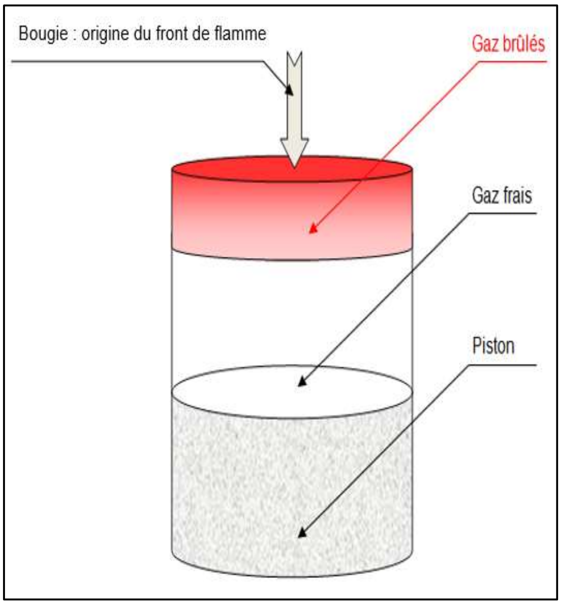


Figure 7.3: Diagram of propagation of the flame front in a cylinder

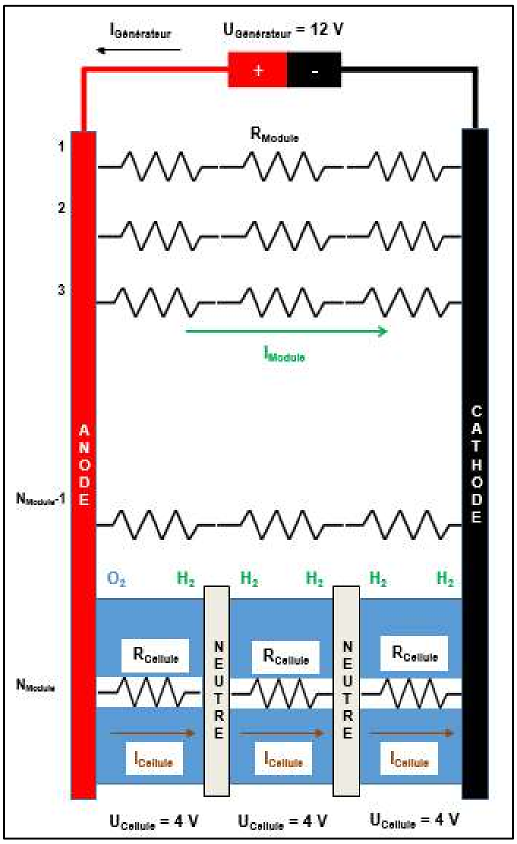


Figure 7.4: Geometric definition of a hydrogen generator composed of identical modules connected in parallel

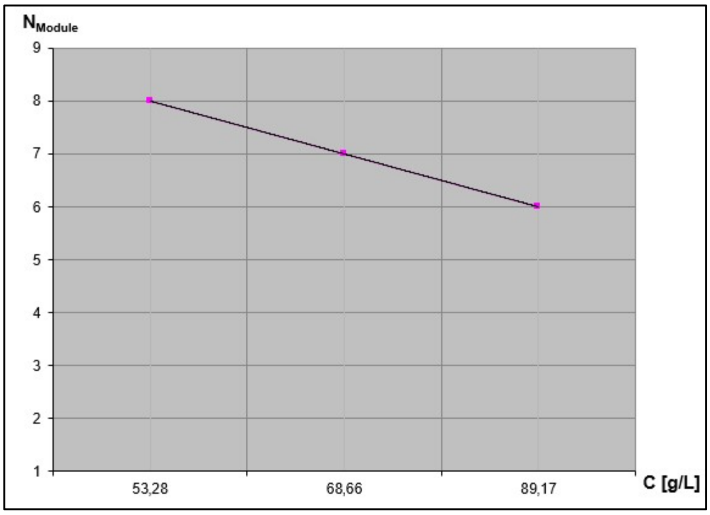


Figure 7.5: Design solutions for a hydrogen generator powered by 9 A and delivering ignition energy of 33.84 mJ

Thus, three conditions must be met for combustion:

- the presence of one or several fuels with a concentration in their range of explosiveness: hydrogen and/or gasoline. The latter, of chemical formula $C_7H_{16}$, has a mass composition of 84 % carbon and 16 % hydrogen;
- the presence of an oxidant: oxygen with a concentration higher than its limiting concentration;
- ignition energy: electric arc of the spark of a spark plug, hot spot created by the ignition of hydrogen in the combustion chamber, exceeding the minimum ignition energy of the air-gasoline mixture to initiate the combustion of this mixture.

The optimization of a generator then begins with the determination of the minimum energy to be supplied by the hydrogen for an ignition delay of the air-gasoline mixture. This delay is generally between

$$0{,}3 \text{ ms} < T_{Inflammation} < 0{,}5 \text{ ms} \qquad (7.15)$$

at the start of the combustion. To be efficient, this energy is the minimum energy delivered by the electric arc of the spark of a spark plug [8]

$$(E_{Spark\ plug})_{Min} = 10 \text{ mJ} \qquad (7.16)$$

Starting from relations (7.14) to (7.16), it is then possible to deduce the minimum intensity passing through the hydrogen generator

$$(I_{Generator})_{Min} = \frac{(E_{Spark\ plug})_{Min}}{12{,}536\ .\ (T_{Inflammation})_{Min}}$$

hence

$$(I_{Generator})_{Min} = 2{,}66 \text{ A} \qquad (7.17)$$

Furthermore, the **maximum permissible intensity** passing through the generator is set according to the power of the alternator of the vehicle. By devoting 30 % of the load current of an alternator of 30 A to power the generator,

$$(I_{Generator})_{Max} = 9 \text{ A} \qquad (7.18)$$

Since the objective is to deliver the maximum permissible power of the generator, the optimal intensity powering the generator is deduced from relations (7.14) and (7.18)

$$\mathbf{I_{Optimal} = (I_{Generator})_{Max} = 9\ A} \qquad \mathbf{(7.19)}$$

### 7.2.4- Optimal configuration of a hydrogen generator

The expression of the intensity of the hydrogen generator can be deduced from relations (7.1) and (7.12). The number of modules $N_{Module}$ and the mass concentration C of the electrolyte give

$$I_{Generator} = N_{Module}\ .\ [0{,}01045\ C + 0{,}56818] \qquad (7.20)$$

From this last relation and the constraints (6.4), (7.17) and (7.19), the different solutions relating to the design of a hydrogen generator are given by the following system of equations:

$$\mathbf{I_{Optimal} = N_{Module} \, . \, [0{,}01045\ C + 0{,}56818] = 9\ A} \qquad \mathbf{(7.21)}$$

$$\mathbf{48\ g/L \leq C < 96\ g/L}$$

By powering the hydrogen generator with the optimum intensity of 9 A (7.19), three pairs of solutions (C = 53,28 ; $N_{Module}$ = 8), (C = 68,66 ; $N_{Module}$ = 7) and (C = 89,17 ; $N_{Module}$ = 6) of the system of equations (7.21) determining the mass concentration C of the electrolyte and the number of modules $N_{Module}$, can be seen on the figure 7.5. Considering an ignition delay of 0,3 ms (7.15), the ignition energy delivered by hydrogen for the combustion of the air-gasoline mixture is estimated using the power in (7.14) and has a value of

$$E_{Hydrogen} = 33{,}84\ mJ \qquad (7.22)$$

It is three times greater than the electric arc of the spark plug (7.16),

$$\mathbf{E_{Hydrogen} > 3\ (E_{Spark\ plug})_{Min}} \qquad \mathbf{(7.23)}$$

and this energy makes it possible to improve the ignition of the air-gasoline mixture triggered by this arc.

Since the cost of the electrolyte is negligible compared to the cost of the stainless steel plates (see figures 6.3 and 6.4), the minimum mass criterion of the generator is adopted while imposing the optimum intensity. In other words, sit results in the design of a hydrogen generator with a reduced number of modules, while providing, with the spark plug, an additional maximum admissible energy intended to quickly ignite the air-gasoline mixture. The objective is to obtain a complete and efficient combustion during the operation of the engine.

**For a supply current of 9 A, the optimal solution consists of designing a six-module hydrogen generator and using an electrolyte with a mass concentration of 89,17 g/L of sodium bicarbonate ($NaHCO_3$) in water at 20 °C (see figure 7.5).**

## 8- CONCLUSION AND PERSPECTIVES

The first water-powered car was in circulation in the United States in 1929. Elsewhere, there were several inventions of the same type, but there is no trace of this with certainty. Indeed, there is no precise solution published in the literature on the enrichment of fuel by hydrogen. The invention of water-powered cars leaves only few scientific writings. This is a taboo subject: everyone is aware of the work on hydrogen, side lined because of the financial impacts associated with oil substitution.

In operational vehicles in Madagascar, there are often old engines designed to be fueled with high octane leaded super or the most modern and with a high performance fueled with unleaded super 98. But, for various reasons, unleaded gasoline 95 is the only imported. This is a situation which requires technological innovations by automotive technicians to overcome the problems of energy saving and environmental constraints.

Faced with the constant increase in the price of petroleum fuels, the gasoline bill at the end of the month becomes more and more large. In addition, the air pollution created by exhaust emissions from vehicles of all kinds remains unbearable in large cities. The hydrogen generator makes it possible to remedy these two problems by proposing an efficient solution at a lower cost.

First, it should be understood that hydrogen is not used as the main fuel since the available electric power of the vehicle to power the hydrogen generator is limited and relatively low compared to the mechanical energy to be developed by the engine. Otherwise, it would be interesting to use an electric motor by virtue of the principle of conservation of energies ($W_{Electric} = W_{Mechanics}$). Thus, the objective is to improve the ignition triggered by the electric arc of the spark of the spark plug in the combustion chamber of a gasoline engine using HHO gases. Scientific tests carried out by NASA have shown that the addition of hydrogen to the air-gasoline mixture improves the combustion of gases. By injecting a small amount of HHO gas into the air intake of the engine, combustion becomes rapid and complete. This explains the reduction in fuel consumption of the vehicle. In addition, as the fuel is fully consumed, emissions of major pollutants such as carbon monoxide and carbon dioxide are drastically reduced by 80 %.

The effectiveness of injecting HHO gas as auxiliary fuel into gasoline engines is no longer scientifically doubted. This technique offers several benefits:

- hydrogen is a light gas and occupies more volume in the combustion chamber than gasoline vapors. The supercharging in HHO gas is strongly recommended to increase the power of the engine;
- the propagation of an initially slow hydrogen flame can reach a very high speed in confined explosion. Thus, high flame acceleration can be achieved over a very short distance. This makes it possible to obtain rapid inflammation of air-gasoline mixtures, even if the latter are poor;
- the low ignition energy of HHO gases, 3 μJ in pure oxygen and 17 μJ in the air, and the self-ignition of hydrogen at 585 °C means the ignition of the air-gasoline mixture by the energy of the spark of more than 10 mJ of a spark plug below the ignition temperature of 380 °C of conventional gasoline engines, which gives a rapid and complete combustion of this mixture from low temperatures;
- the result is an average fuel economy of 25 % on a passenger vehicle and a reduction in the emission of pollutants. **The hydrogen generator is then a fuel saver**.

However, the abnormal rise in engine temperature must be constantly checked. This is due to technical faults: incorrect adjustment of the air-gasoline mixture, lack of liquid or engine cooling system malfunction, etc. Indeed, the presence of hot gases in the combustion chamber or high temperatures on the walls of the cylinder, the piston and the cylinder head can prematurely trigger the ignition of hydrogen during the compression stroke of the piston of the engine, just before the ignition of the spark plug. This leads to the appearance of knocks and flame returns and then requires a possible correction of the angle of advance at the ignition of the engine. It is also necessary to provide an air-to-air intercooler, when using turbochargers.

In this article, obtaining some modest results from electrochemical tests allowed to develop, from a mechanistic view, an energy approach intended to design an optimal hydrogen generator. The results obtained open the way to many applications, among others:

- checking the efficiency of fuel enrichment by hydrogen in a gasoline engine;
- extending the work to include diesel engines;
- confirmation of the results obtained by chemical thermodynamic approaches;
- the preservation of the vehicle battery by the design of a regulator, varying the intensity passing through the hydrogen generator as a function of the alternator load current and the engine speed;
- the specification of safety rules in the production of hydrogen: HHO gas leaks, limitation of the flow of HHO gases produced, risks of explosion, prevention of phenomena associated with hydrogen, dimensioning of various electrical and mechanical equipment, etc.

Besides, HHO gases today have many uses, which are certainly not all known. The areas where they can intervene are:

- aerospace in the context of rocket launches, for example;
- welding and cutting of metals by torch;
- the manufacture of glass and precious stones, etc.

Finally, this article aims to show in a simple way a solution of partial substitution of the black gold by the blue gold. It makes it possible to satisfy the energy needs of the population of Madagascar in the long term by the design, manufacture and use of a fuel saver within the budget of the Malagasy people.

## BIBLIOGRAPHICAL REFERENCES

[1] ANDRIAMAMPIANINA José
**Optimisation des assemblages de plaques minces par boulons ajustés sans jeu (assemblages aéronautiques).**
Doctorat de l’Institut National des Sciences Appliquées de Toulouse. Spécialité : Génie Mécanique. Institut National des Sciences Appliquées de Toulouse. Laboratoire de Génie Mécanique de Toulouse. École Nationale Supérieure d’Ingénieurs en Construction Aéronautique. 1991.

[2] ANDRIAMAMPIANINA José
**Conception optimale des citernes de navires méthaniers et des assemblages aéronautiques.**
Habilitation à Diriger des Recherches en Physique. Spécialité : Mécanique et Physique des Suspensions. Université d’Antananarivo. BUREAU VERITAS France. Institut Clément ADER. INSA de Toulouse. Institut Supérieur de Technologie d’Antananarivo. 2012.

[3] ANDRIAMAMPIANINA José
**Conception et réalisation de la pico centrale hydroélectrique d’Andretsemboka d’une puissance de 7,5 kW**
*Bulletin de l’Académie Nationale des Arts, des Lettres et des Sciences.* Tome XCIII/2. Juillet – Décembre 2013. ISSN 1728-4317.

[4] ANDRIAMAMPIANINA José
**Focus sur le changement climatique et les énergies renouvelables à Madagascar**
Académie Nationale des Arts, des Lettres et des Sciences. 28 janvier 2016

[5] ANDRIAMIADANARIVO Heritiana Mathieu
**Étude paramétrique et conception d’un générateur d’hydrogène de type « dry cell » pour voiture. Cas de l’électrolyte $NaHCO_3$.**
Mémoire d’Ingénieur dans le Parcours « Génie Industriel en maintenance et production ». Institut Supérieur de Technologie d’Antananarivo. 2016.

[6] ASSOCIATION FRANCAISE POUR L’HYDROGENE ET LES PILES A COMBUSTBLES
**Situation mondiale de l’énergie**
Mémento de l’hydrogène. Fiche 2.1. Révision : 14 mars 2013. Source : AFHYPAC – Th.A.

[7] AUDICHON Thomas
**Synthèse et caractérisation de matériaux électro catalytiques : activation anodique de l'eau dans un électrolyseur PEM.**
Thèse de Doctorat de l'Université de Poitiers. Secteur de recherche : Chimie théorique, physique analytique. Novembre 2014.

[8] BERU – FEDERAL MOGUL
**Tout sur les bobines d’allumage**
Information technique N°7. 02-09-2013.

[9] HOUSSEMAN John – CERENI D. J.
**On-Board Hydrogen Generator for a Partial Hydrogen Injection Internal Combustion Engine**
Jet Propulsion Laboratory du California Institute of Technology. 1974. 470600.

[10] IMMONGAULT Régis
**Accessibilité énergétique**
Congrès mondial de l'énergie. 2010. Concertation ministérielle francophone. Montréal, 12-16 septembre 2010.

[11] PROUST C.
**Quantifier les effets d'explosion de l'hydrogène**
INERIS. 2013.

[12] PRIGENT M.
**On-board hydrogen generation for fuel cell powered electric cars. A review of various available techniques.**
***Production d'hydrogène embarquée pour véhicules électriques à piles. Aperçu des différentes techniques envisageables.***
Institut Français du Pétrole - Revue de l'Institut Français du Pétrole - Vol. 52 - N° 3 - Mai-juin 1997.

[13] RAKOTOARISON Mihary Simon
**Conception et réalisation d'un prototype de générateur d'hydrogène alimentant un moteur a explosion interne. Approche thermodynamique.**
Mémoire d'Ingénieur dans le Parcours « Génie Industriel en maintenance et production ». Institut Supérieur de Technologie d'Antananarivo. 2014.

[14] RAMAMONJISOA Ranjanalitiana
**Conception optimale d'un générateur d'hydrogène de type « dry cell » pour voiture. Cas de l'électrolyte KOH.**
Mémoire d'Ingénieur dans le Parcours « Génie Industriel en maintenance et production ». Institut Supérieur de Technologie d'Antananarivo. 2016.

[15] UNITED STATES DEPARTMENT OF TRANSPORTATION - FEDERAL MOTOR CARRIER SAFETY ADMINISTRATION
**Guidelines for use of hydrogen fuel in commercial vehicles**
Final Report "FMCSA-RRT-07-020". November 2007.

[16] SACHS C, MACK-GARDNERA.
**Safety Aspects of Hydrogen Fuel Cell Vehicles**
Detlef Stolten, Thomas Grube (Eds.): 18th World Hydrogen Energy Conference 2010 - WHEC 2010.
Parallel Sessions Book 5: Strategic Analyses / Safety Issues / Existing and Emerging Markets. Proceedings of the WHEC, May 16.-21. 2010, Essen. Schriften des Forschungszentrums Jülich / Energy & Environment, Vol. 78-5. Institute of Energy Research - Fuel Cells (IEF-3). Forschungszentrum Jülich GmbH, Zentralbibliothek, Verlag, 2010. ISBN: 978-3-89336-655-2.

## WEBOGRAPHICAL REFERENCES

[1'] http://www.omh.mg/

[2'] https://www.google.com/search?q=Cours+record+du+baril+du+p%C3%A9trole&client=firefoxb&source=lnms&tbm=isch&sa=X&ved=0ahUKEwia8_iplf3QAhUXM1AKHYy8CHoQ_AUICigD&biw=1354&bih=637#imgrc=2Rp55BmUvBMEeM%3A

[3'] http://www.themavision.fr/jcms/rw_259408/la-hausse-du-prix-des-matieres-premieres-met-durablement-la-filiere-sous-contrainte

[4'] https://fr.wikipedia.org/wiki/Enrichissement_du_carburant_par_hydrog%C3%A8ne

[5'] https://fr.wikipedia.org/wiki/Hydrog%C3%A8ne

[6'] https://www.google.com/search?q=v%C3%A9hicule+hydrog%C3%A8ne&client=firefox-b&biw=1354&bih=637&source=lnms&tbm=isch&sa=X&sqi=2&ved=0ahUKEwji9ufJ4YXRAhVVYFAKHWIbBJQQ_AUIBygC#imgrc=6H1mcFI4RmCbVM%3A

[7'] https://fr.wikipedia.org/wiki/V%C3%A9hicule_%C3%A0_hydrog%C3%A8ne

[8'] https://fr.wikipedia.org/wiki/%C3%89lectrochimie

[9'] https://fr.wikipedia.org/wiki/%C3%89lectrolyse_de_l'eau

[10'] https://fr.wikipedia.org/wiki/Lois_de_Faraday_(%C3%A9lectrochimie)

[11'] http://edu.ge.ch/chavanne/cours/cours/baudc/2df/lelectrolyse/lelectrolyse%20-%20theorie.pdf

[12'] https://fr.wikipedia.org/wiki/Mole_(unit%C3%A9)

[13’] http://www.larousse.fr/encyclopedie/divers/%C3%A9lectrolyse/46246

[14’] http://crombette.altervista.org/fr_gaz_de_brown.htm

[15’] http://kghho.fr/category/hho/

[16’] http://www.generateurhho.com/conseils-technique-truc-astuces/les-differents-electrolytes

[17’] https://fr.wikipedia.org/wiki/Bicarbonate_de_sodium

[18’] https://fr.wikipedia.org/wiki/Dihydrog%C3%A8ne

[19’] https://fr.wikipedia.org/wiki/Masse_molaire

[20’] http://trissiti.blogspot.com/