

Studying and Improving the Efficiency of Water Electrolysis
Using a Proton Exchange Membrane Electrolyser

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ENERGY SYSTEMS AND THE ENVIRONMENT

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2. Introduction

Over the last few years, energy seems to be one of the major problems all over the world. Plenty of researches and projects are taking place in order to find alternative ways to produce energy that will fulfil the needs of each country in a clean and sustainable fashion. Such kind of energy is called renewable energy.

Renewable energy is energy obtained from the continuous flows of energy occurring in the natural environment, such as solar energy, wind, hydro and energy from biomass.

The idea of creating sustainable energy systems has led over the past decade to several hydrogen energy demonstration projects around the world. The method that has plenty of potential to improve the production of hydrogen is electrolysis. The principle of electrolysis has been well known since the early 19th century and today's state of the art electrolyzers are systems of high security and easy use [1].

Water Electrolysis is a very simple process that takes water and passes a supply of electricity through it using immersed electrodes to split into positive hydrogen (H^+) and negative oxygen (O^-) ions. These hydrogen and oxygen ions migrate through the water towards the cathode and anodes respectively, where electron transfers allow for the diatomic H_2 and O_2 molecules to form at high purity.

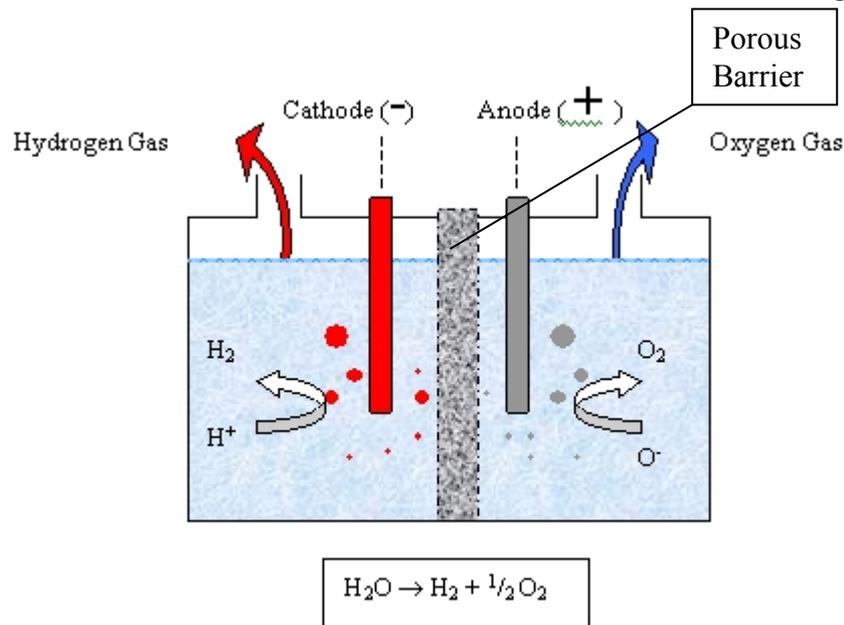


Figure 1: Water Electrolysis

A porous barrier or salt bridge is placed in the tank where the electrolysis process takes place. It must be added to the system in order to allow the current flow. Both the porous barrier and the salt bridge contain an ionic substance in solution. It is used to prevent the quick mixing of various solutions, while permitting the exchange of ions.

Electrolysis of hydrogen is currently around 75% energy efficient and could be theoretically increased to more than 90 % in the future [1]. Therefore this process appears to be an efficient method of producing high purity hydrogen in large quantities with little or no environmental impact. However the electrical energy required in running such a process would have to come from renewable power sources such as wind, photovoltaic, hydroelectric or geothermal generators for it to be truly environmentally friendly and sustainable in the future. The use of nuclear power could also be used to fill any shortfall in renewable power generation, as it has no NO_x or CO_x emissions. Considering a most effective strategy regarding the supply of hydrogen to the consumer, water electrolysis from non fossil fuel power generation is appointed as the preferred method of hydrogen production.

The aim of this thesis is to study the efficiency of electrolysis using a proton exchange membrane electrolyser to produce hydrogen and to construct a theoretical model, from which alternative solutions to achieve better efficiency will be proposed. Experiments were conducted in order to determine the energy efficiency of the electrolyser and validate the model, which is then compared with the theoretical predictions.

3. Literature Review

3.1 Electrolysers

The electrolyser is a device that generates hydrogen and oxygen from water through the application of electricity and consists of a series of porous graphite plates through which water flows while low voltage direct current is applied.

Electrolysers split the water into hydrogen and oxygen gases by the passage of electricity, normally by breaking down compounds into elements or simpler products. An electrolyser has to fulfil requirements such as high efficiency, low cost, large range of operation etc. Physically a practical electrolyser stack will consist of several cells linked in series. Monopolar and bipolar are two types of cell designs. A monopolar design is when the electrodes are either negative or positive with parallel electrical connection of the individual cells as shown in Figure 2.

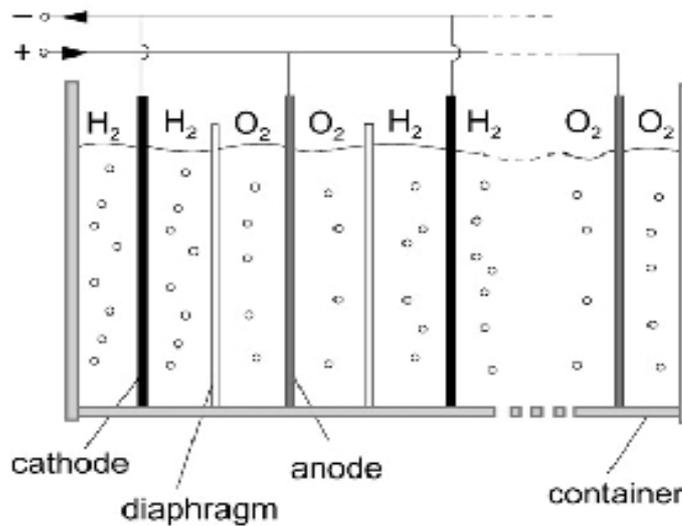


Figure 2: Monopolar Design

In a bipolar design the individual cells are linked in series electrically and geometrically as shown in Figure 3.

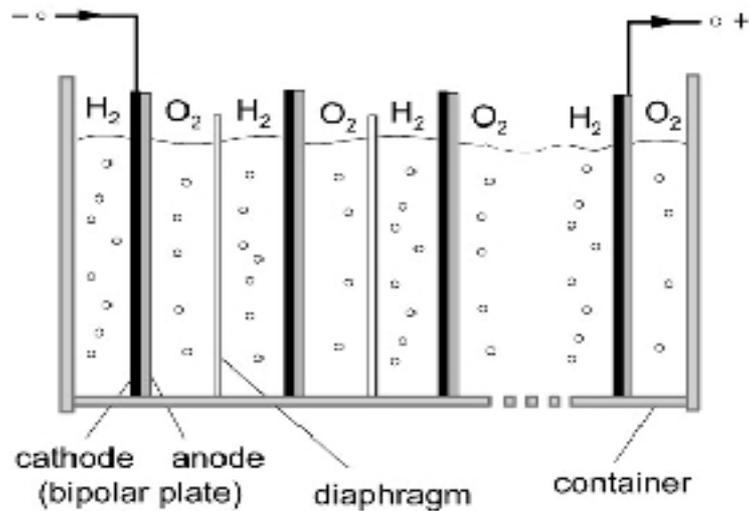


Figure 3: Bipolar Design

An advantage of the bipolar electrolyser stack design is that it is more compact than the monopolar design. This means that the length of the electrical wires is minimised and the losses due to the internal ohmic resistance of the electrolyte is reduced therefore the electrolyser efficiency is increased.

On the other hand, there are also some disadvantages with bipolar cells design. One of these is the corrosion problem that can occur because of parasitic currents. This current is caused by parasitic elements of the electric circuit and it can lead to losses of electrical energy. Furthermore, the compactness and high pressures of the bipolar electrolysers, which results that large quantities of hydrogen and oxygen can be generated in a small unit with small space requirement, involve relatively sophisticated and complex system designs, which means that the manufacturing cost is increased. The relatively simple and sturdy monopolar electrolyser systems are in comparison less costly to manufacture [2].

3.2 Types of Electrolyser

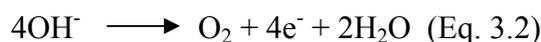
3.2.1 Alkaline Electrolyser

Alkaline water electrolyzers usually use electrolyte that contains aqueous potassium hydroxide (KOH), mostly with solutions of 20 - 30 wt% because of the optimal conductivity and require to use corrosion resistant stainless steel to withstand the chemical attack. The typical operating temperatures and pressures of these electrolyzers are 70 – 100 °C and 1 – 30 bar respectively. The chemical reactions that take place in the operation of the alkaline electrolyser are mentioned below.

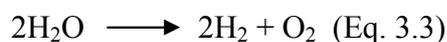
For the anode reaction it is:



For the cathode reaction it is:



And finally the overall reaction is:



3.2.2 Proton Exchange Membrane Electrolyser

The electrolyzers that are based on Polymer – Electrolyte Membrane (PEM) separators are mostly used for industrial purposes because they can achieve high efficiencies. These devices anticipate the imminent development of a renewable energy economy based on electricity and H₂ fuel as complementary energy vectors.

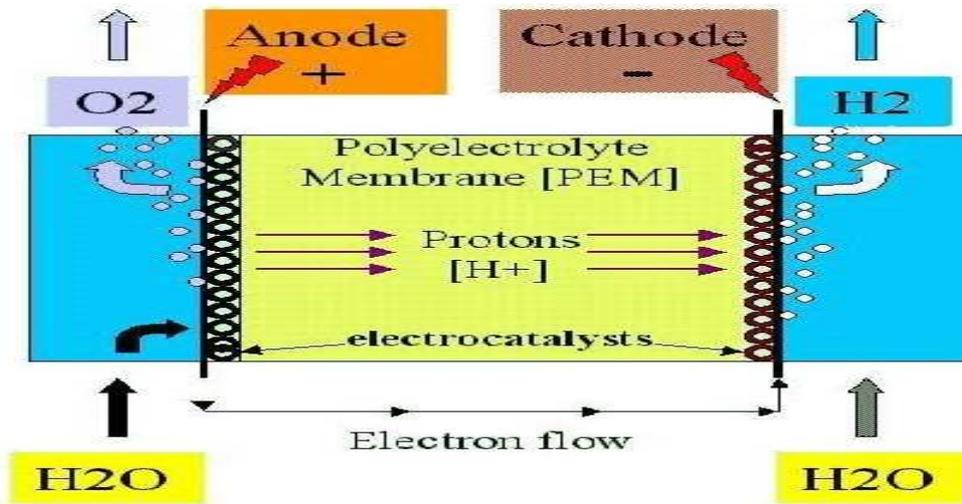


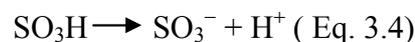
Figure 4: Schematic Diagram of a Proton Exchange Membrane Electrolyser

3.3 Polymer Electrolyte Membrane Electrolyser Operation Functions

A PEM electrolyser is shown in Figure 4. Its efficiency is a function primarily of membrane and electro catalyst performance. This becomes crucial under high-current operation, which is necessary for industrial-scale application.

3.3.1 Membrane

The membrane consists of a solid fluoropolymer which has been chemically altered in part to contain sulphonic acid groups, SO_3H , which easily release their hydrogen as positively-charged atoms or protons $[\text{H}^+]$ [3]:



These ionic or charged forms allow water to penetrate into the membrane structure but not the product gases, molecular hydrogen $[\text{H}_2]$ and oxygen $[\text{O}_2]$. The resulting hydrated proton, H_3O^+ , is free to move whereas the sulphonate ion $[\text{SO}_3^-]$ remains fixed to the polymer side-chain. Thus, when an electric field is applied across the membrane the hydrated protons are attracted to the negatively charged electrode, known as the cathode. Since a moving charge is identical with electric current, the membrane acts as a conductor of electricity. It is said to be a protonic conductor. A

typical membrane material that is used is called “nafion”. Nafion is a perfluorinated polymer that contains small proportions of sulfonic or carboxylic ionic functional groups. Its general chemical structure can be seen below in Figure 5, where X is either a sulfonic or carboxylic functional group and M is either a metal cation in the neutralized form or an H⁺ in the acid form.

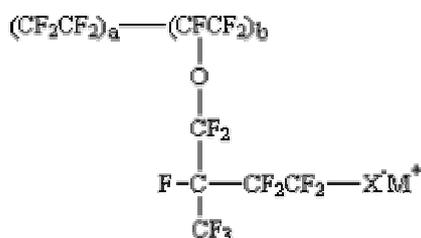


Figure 5: Nafion Perfluorinated Ionomer

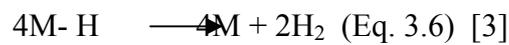
It has several advantages over conventional electrolyses, which normally use an aqueous caustic solution for workable conductivity. Because “nafion” is a solid, its acidity is self-contained and so chemical corrosion of the electrolyser housing is much less problematic. Furthermore as it is an excellent gas separator, allowing water to permeate almost to the exclusion of H₂ and O₂, it can be made very thin, typically only 100 microns, or one tenth of a millimetre. This also improves its conductivity so that the electrolyser can operate efficiently even at high currents.

However, the membrane also has some disadvantages. Unlike conventional polymers which are water-repellent, it must also be kept humidified constantly otherwise its conductivity deteriorates and it is a very expensive material. To be kept constantly humidified is never a serious problem in an electrolyser because of continual contact with water, but the PEM fuel cell requires intensive water management for stable, continuous operation.

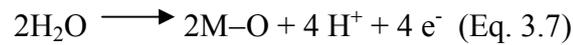
3.3.2 *Electro catalysts*

A voltage of about 1.5V is supplied to the metal plate electrodes and a unidirectional DC electric current is caused to flow. An electrochemical cell is a device that uses a spontaneous chemical reaction to produce an electric current. It consists of two half-cells, each with a conducting electrode in contact with an electrolyte solution and separated by a porous barrier or salt bridge. The electrode at

which the oxidation occurs is called the anode and the electrode in which reduction occurs is called the cathode. The electrons produced flow through the external circuit to the cathode. The circuit is completed by cations moving to the cathode and anions moving to the anode by ionic conduction. Protons are drawn to the cathode and are discharged as H atoms by combination with electrons at the metal cathode surface. Pairs of adsorbed H atoms then combine to make molecules of H₂ gas, which escape freeing the electrode surface for more proton discharge:



At the positive electrode or anode, electrons are lost by incoming water molecules creating O atoms and protons. The electrons are shunted to the cathode, protons enter the membrane, and two O atoms combine to release O₂ gas:



Although the overall process or mechanism is complex, its sum or balance is simply equivalent to producing two molecules of hydrogen and one molecule of oxygen from two molecules of water:



Since chemical (H₂) energy is being created, a minimum energy must be input to drive the process according to the laws of thermodynamics. In terms of electrical energy, this corresponds to a voltage greater than 1.23V. In reality, the working voltage necessary to sustain water electrolysis is always greater than this. The extra voltage, generally known as the over voltage, represents a waste of energy or loss of efficiency. It has two main causes, one of which is the internal voltage drop loss due to the finite electrical resistance of the electrolyte, or membrane in this case. The second is kinetic in origin, i.e., to do with the overall speed of the process at the electrode surface [3].

A solid catalyst speeds up chemical reactions due to its surface action. As a simple example, two H atoms held loosely on a surface are much more likely to collide and make H₂ gas than if they are dispersed in a liquid with billions of water molecules in-between. This is a spatial or localized concentration effect. The case of O₂ evolution is much more complex. Two water molecules must be broken into their constituent atoms; then the two O atoms must combine. The electro catalyst at the anode is a special catalyst, which facilitates this process by withdrawing electrons from the water such that the H atoms are ejected as protons, which enter the membrane. Water is said to be activated by charge-transfer. The OH or O atoms are very reactive in their free state. However, when fixed at the surface by chemical bonds, they are much more stable. When more water encounters the surface, its protons are ejected in turn and O atoms are accumulated. These are then able to combine easily by surface diffusion just as described for hydrogen. It is said that the surface provides a low-energy pathway, which is intrinsically much faster because the speed of the reaction is related exponentially to the energy difference.

It is easy to visualize that if the cathode and anode surfaces, respectively, attract H or O atoms too strongly, the surfaces will become completely covered with these intermediates and the catalytic process stops. On the other hand, if protons or water are not attracted strongly enough, the process never gets going. Only when there is a moderate strength of binding of reactants and intermediates at the electrode surfaces will the right balance be obtained. This is the key factor in determining if a solid catalyst will work efficiently. It is also obvious that the larger the catalyst surface area available, the more H₂ and O₂ will be produced in a given time, i.e., a higher current will flow in the electrolyser.

Platinum is long known to be the best catalyst for water electrolysis due to its moderate strength of adsorption of the intermediates of relevance. It has the lowest over-voltage of all metals. However due to its cost, and the preferred operation of the electrolyser at high current, ingenious ways have been devised to deposit ultra-fine Pt particles either on the electrode support plate, or directly onto the membrane, which is then clamped for good electrical continuity. A current of 1-3 Amperes per square centimetre can be obtained from as little as 3 milligrams of Pt spread over the same area [3].

4. Efficiency losses

Almost for every device that produces energy, the main aim is how to achieve high efficiency in order to get the maximum output. The same applies for electrolysis and more specifically to the proton exchange membrane electrolyser. In this case, the losses that create a drawback in achieving high efficiencies are mentioned below.

4.1 Activation losses

Activation loss relates to the rate of the reactions that take place on the surface of the electrodes. During the chemical reactions in the electrodes, a proportion of the generated voltage is lost. This is called the activation loss due to the activation energy required at both the anode and the cathode. A great advantage of the proton exchange membrane (PEM) is that the activation loss of the hydrogen (anode) is much smaller than the activation loss of the oxygen (cathode) [4]. The chemical processes that contribute to such losses are highly complicated. These processes affect the absorption of reactant molecules, the transfer of electrons through the layers and the material of the membrane, and the nature of the electrode surface itself. This voltage loss is proportional to the logarithmic of the current and it is expressed as:

$$V_{activation} = \frac{R \cdot T}{2 \cdot a \cdot F} \cdot \ln \frac{I}{I_o} \quad (\text{Eq. 4.1})$$

where R is the gas constant and it is equal to 8.3145 J/K·mol, T is the temperature in °K and F is the Faraday's constant and its value is 96484 C/mol, a is the charge transfer coefficient, which is the proportion of the electrical energy applied that is harnessed in changing the rate of an electrochemical reaction and its value is between 0 and 1 depending on the reaction and the electrode material. I is the current used in Amperes and I_o is the exchange current, the current that goes back and forth at the electrodes. For a typical electrolyser operating at ambient conditions the exchange current can take a value of 100 mA [5]. Activation loss is mostly dependent upon temperature. In Figure 6 it is shown the amount of activation loss varying with

different values of current. It is obvious that the highest differences occur at low currents while in higher current the difference could be negligible.

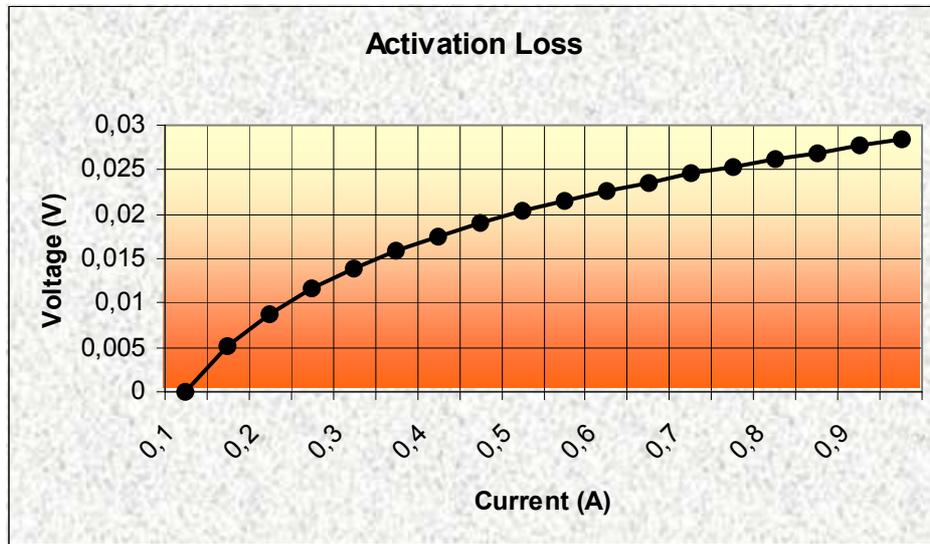


Figure 6: Activation Loss

4.2 Ohmic losses

The ohmic losses are due to the resistance of the wiring and the resistance of the imperfect electrodes. The slope of the cell voltage in the middle section of the polarisation curve, which is shown in Figure 7, is due to the ohmic loss. The loss in the fuel cell is approximately linear after the activation loss levels out and before the concentration loss becomes significant. The ohmic loss of the PEM is slightly non-linear and variable due to the characteristics of the conduction at different conditions [4]. In most cases, the ohmic loss can be considered to have the relationship of $I \cdot R$, where R is constant. So, the equation that can relate to the ohmic loss is:

$$V_{ohmic} = I \cdot R_i \text{ (Eq. 4.2)}$$

According to the experimental values of current and voltage the resistance of the electrolyser is calculated for each value and the curve of ohmic loss is shown in Figure 7. The value of the resistance is calculated in chapter 8 using equation 8.1 shown in the thesis later on and it is

$$R_i = \frac{V_2 - V_1}{I_2 - I_1} = \frac{1.8 - 1.6}{0.82 - 0.188} = 0.316\Omega \text{ (Eq. 8.1)}$$

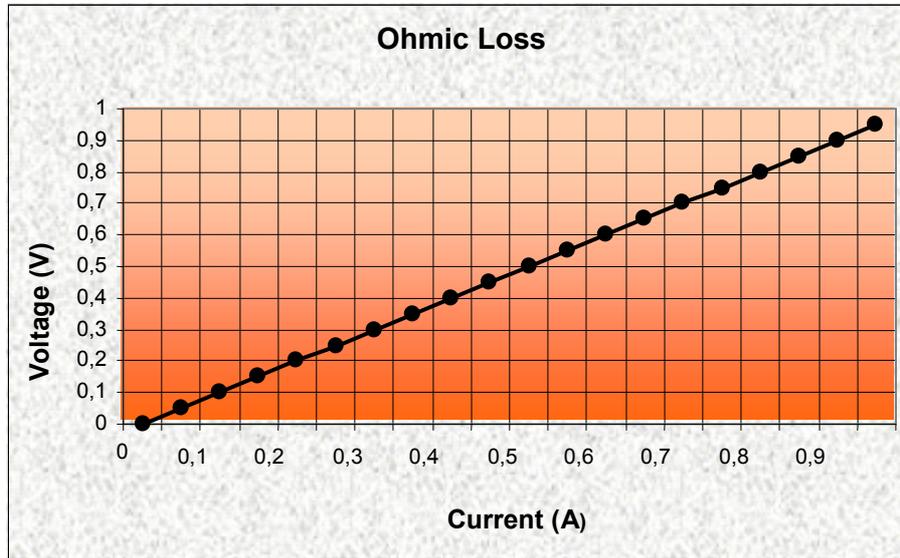


Figure 7: Ohmic Loss

4.3 Concentration losses

Concentration loss relates to the reduction of the reactant's concentration in the gas channels. The fuel and the oxidant are used at the surface of the electrodes and then the incoming gas must take the place of the used reactant. The concentration of the fuel is therefore reduced. The concentration loss can be neglected in some cases, but it is significant at higher currents and when the fuel and oxidant are used at higher rates and the concentration in the gas channel is at a minimum. The concentration loss is expressed as:

$$V_{concentration} = \frac{R \cdot T}{2 \cdot F} \cdot \ln\left(1 - \left(\frac{I}{I_L}\right)\right) \text{ (Eq. 4.3) [15]}$$

R is the gas constant and it is equal to 8.3145 J/K·mol, T is the temperature in °K and for figures 6,7,8 it has the value of 25 °C, F is the Faraday's constant and its value is 96484 C/mol, I is the current used in Amperes and the current I_L , which is

called the limiting current in A, is the point where the gas used is at a rate equal to the maximum power supply. The value of I_L is 1A and it is the maximum value of current that this specific electrolyser can use. The value of I_L in this case cannot be different because equation 4.3 will not be valid. Therefore Figure 8 shows the curve of concentration loss varying with current. At low currents, concentration loss is negligible but it starts being really important at higher currents.

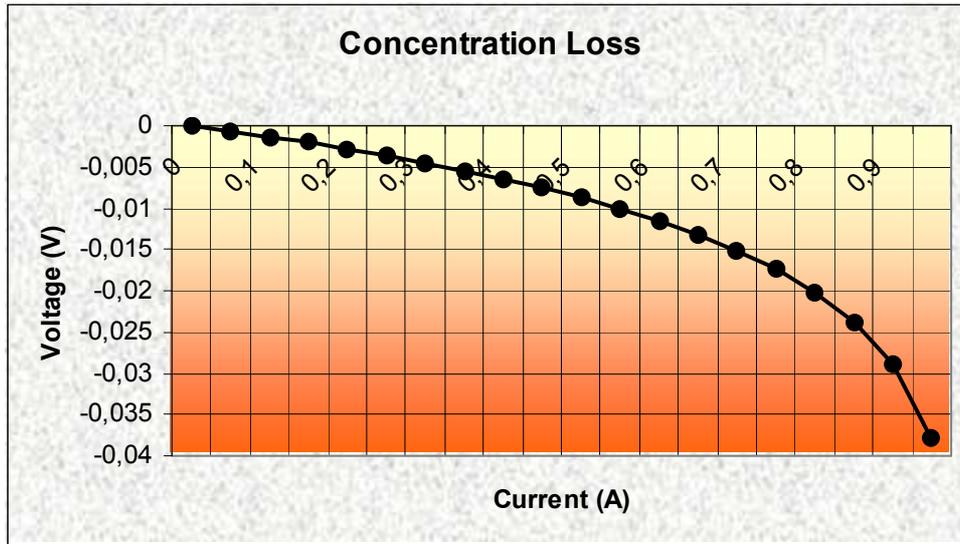


Figure 8: Concentration Loss

4.4 Internal current losses

The internal current loss is due to the wasted fuel and oxidant that passes through the membrane and does not produce any useful work [6]. In addition, the electron conduction in the membrane can lead to such losses. These affect the performance mostly at open circuit but can be negligible at higher currents. An internal current loss means that excess chemical activity is frequently occurring.

All the losses described above include internal current losses. The current used for all the voltage loss equations includes a proportion of internal current loss. This means that the external current I plus the internal current I_n equals to the amount of current used in the previous formulas.

Therefore the losses become:

$$V_{activation} = \frac{R \cdot T}{2 \cdot a \cdot F} \cdot \ln \frac{I + I_n}{I_o} \quad (\text{Eq. 4.4})$$

$$V_{ohmic} = (I + I_n) \cdot R_i \quad (\text{Eq. 4.5})$$

$$V_{concentration} = \frac{R \cdot T}{2 \cdot F} \cdot \ln \left(1 - \left(\frac{I + I_n}{I_L} \right) \right) \quad (\text{Eq. 4.6})$$

As mentioned before, the internal current can be negligible at high currents since the ratio of I_n/I is very small. Activation loss is the one that is affected the most by internal current loss due to the low currents.

In ohmic loss the affection of the internal current loss depends on the rate of current used. In general, the current that is used is relatively high so the effects of such losses are negligible.

As for the concentration loss, the current used is very high in order for this loss to become considerable. Therefore, the internal current loss is not significant and can be excluded from the concentration equation. [4]

Therefore, the overall voltage of the electrolyser can be defined as:

$$V_{in} - V_{activation} - V_{ohmic} - V_{concentration} = V_{out} \quad (\text{Eq. 4.7})$$

The polarisation curve of losses is shown in the graph below:

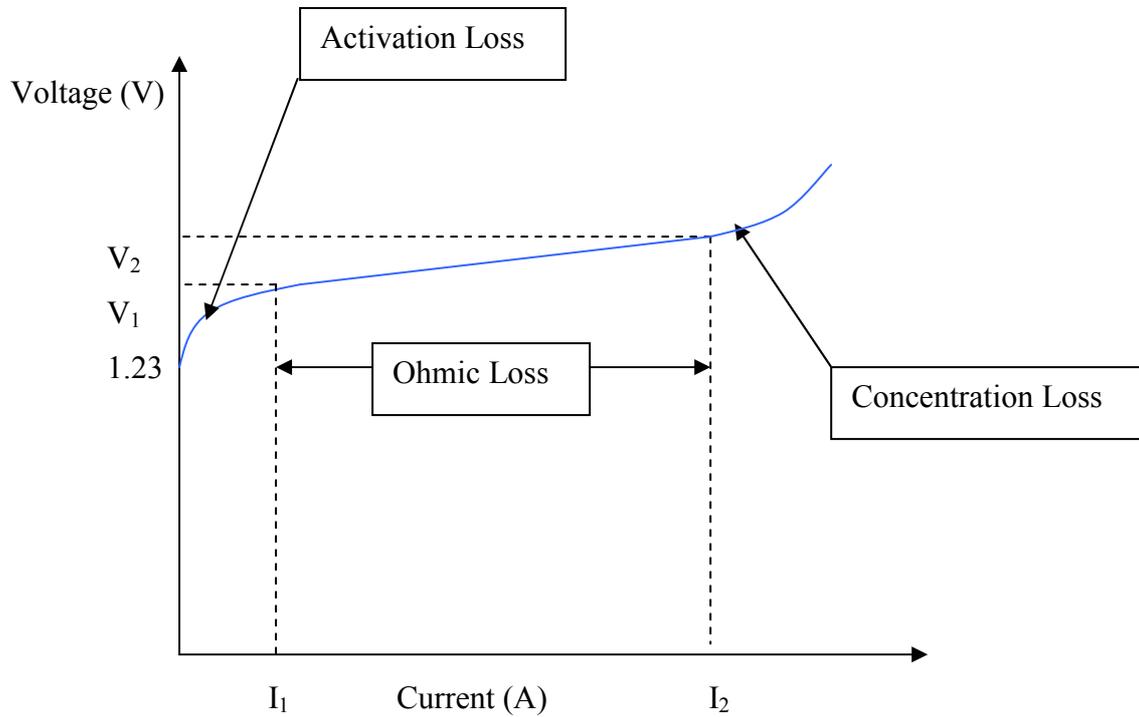


Figure 9: Polarisation Curve

I_1 is the value of the current where the activation loss is no longer the main factor of losses and where ohmic losses become significant. For the specific electrolyser I_1 is approximately 0.3 A. I_2 is the current where concentration loss becomes significant and as it is shown in the characteristic curve of V-I later in Figure 14 the value is approximately 0.6A. These values are specified by the dimensions of and the physical parameters of the cell and they vary between different types of cells.

So the theoretical efficiency of the electrolyser is:

$$\eta = \frac{P_{out}}{P_{in}} \text{ (Eq. 4.8)}$$

Assuming a temperature of 20 °C (293 °K) and normal pressure, the energy efficiency against the Voltage input graph of the proton exchange membrane electrolyser is shown in Figure 10. This graph is created using the equations (4.1), (4.2), (4.3) and (4.8) for the range of values the current could have (0.1 A to 0.95 A).

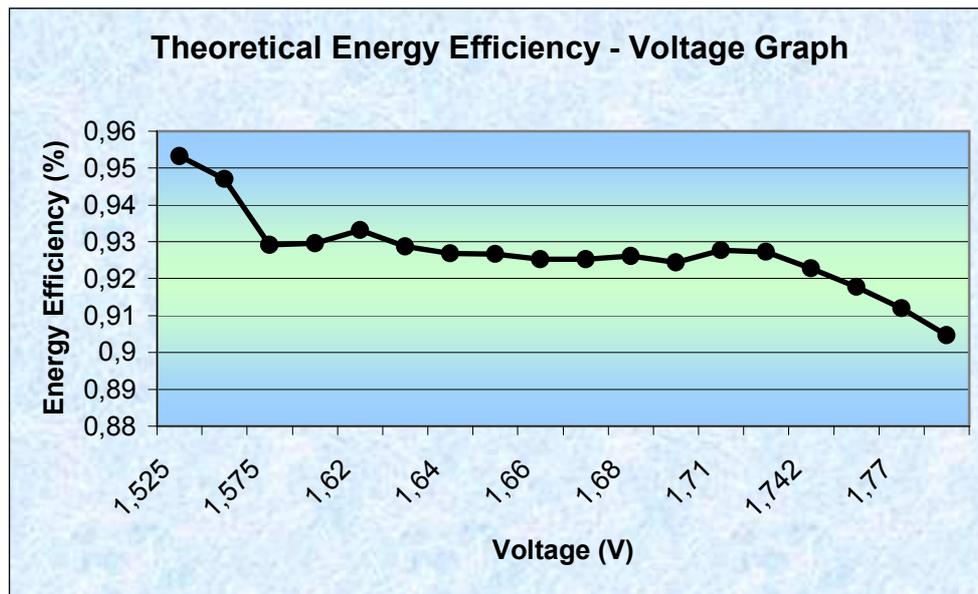


Figure 10: Theoretical Energy Efficiency – Voltage Graph

The energy efficiency of the proton exchange membrane electrolyser varies between 95.3% and 90.4%. Figure 10 above shows the theoretical energy efficiency of a proton exchange membrane electrolyser. Although the losses such as activation and concentration losses are significant at low and high currents respectively, in this model they were assumed to apply for the whole range of values current could get since this also applies in reality. The values of current used in this model were from 0.1 to 0.95 Amperes. In reality, the efficiency of the electrolyser is difficult to achieve a value of 95.3 % not only because these losses have different significant role at each point but also the environment where the electrolyser operates is a very important factor for achieving high efficiencies. Therefore in reality, the efficiency of the electrolyser is expected to be lower that shown in Figure 10.

Faraday's efficiency is also quite important for the electrolysers. It expresses how much of the current is converted in the desired reaction and it is the ratio of the experimental volume of hydrogen and the theoretical volume of hydrogen.

$$\eta_{Faraday} = \frac{V_{H2experimental}}{V_{H2theoretical}} \quad (\text{Eq. 4.9})$$

The experimental volume of hydrogen can be obtained from the experimental data. The theoretical volume must be calculated using the formula:

$$V_{H2theoretical} = \frac{I \cdot t \cdot V_m}{a \cdot F} \quad (\text{Eq. 4.10})$$

Where I is the current in Amperes and it is measured in the experiment, t is the time measured during the experiment, V_m is the molar volume of hydrogen in l/mol, a is the number of electrons that are exchanged in order to release one particle at the electrode and F is the Faraday's constant and it is equal to 96484 C/mol.

The energy efficiency of the electrolyser is the ratio between the energy content of the hydrogen generated and the amount of electrical energy required.

$$\eta_{Energy} = \frac{H_{H2} \cdot V_{H2experimental}}{U \cdot I \cdot t} \quad (\text{Eq. 4.11})$$

The term H_{H2} is the calorific value of hydrogen in kJ/mol, V_{H2} is the experimental volume of hydrogen measured in mol, U is the voltage, I is the current and t the time in seconds.

Both Faraday's efficiency and energy efficiency apply only to experimental data. The difference between them is that Faraday's efficiency expresses the difference between the theoretical volume and the experimental volume of hydrogen. How much is produced in the experiment and how much it should be produced theoretically. Energy efficiency of the electrolyser expresses how efficient is the electrolyser at different values of voltage and current and helps to establish the point where the electrolyser produces the most.

4.5 Sensitivity Analysis

A sensitivity analysis was performed of this model in order to verify the behaviour of temperature that exist in the formulas above and since its condition is uncertain. This would help to provide information concerning the behaviour of each parameter under different conditions. Sensitivity analysis was only performed in activation and concentration loss. For ohmic loss, the resistance could be calculated from the readings of voltage and current since it was considered to be constant.

4.5.1 Activation Loss

The following sensitivity analysis provides a good assessment of the temperature as it increases for different values of current. The tables and the graphs below show the values of temperature, current and the final value of activation loss. The initial value for temperature is 274 °K and reaches up to 323 °K. The current starts from 0.1 Amperes and reaches the value of 1 Ampere in steps of 0.1 Amperes. For each value a graph is provided to show the effect of temperature on activation loss. The temperature for such type of electrolyser can vary from 1 °C up to 50 °C. In case temperature exceeds these limits it can be dangerous since it can destroy the electrolyser.

V_{activation} (V)	T (°K)	I (mA)
0.0081833	274	200
0.0082131	275	200
0.008243	276	200
0.0082729	277	200
0.0083027	278	200
0.0083326	279	200
0.0083625	280	200
0.0083923	281	200
0.0084222	282	200
0.0084521	283	200
0.0084819	284	200
0.0085118	285	200
0.0085417	286	200
0.0085715	287	200
0.0086014	288	200
0.0086313	289	200
0.0086611	290	200
0.008691	291	200

0.0087209	292	200
0.0087507	293	200
0.0087806	294	200
0.0088105	295	200
0.0088403	296	200
0.0088702	297	200
0.0089001	298	200
0.0089299	299	200
0.0089598	300	200
0.0089897	301	200
0.0090195	302	200
0.0090494	303	200
0.0090792	304	200
0.0091091	305	200
0.009139	306	200
0.0091688	307	200
0.0091987	308	200
0.0092286	309	200
0.0092584	310	200
0.0092883	311	200
0.0093182	312	200
0.009348	313	200
0.0093779	314	200
0.0094078	315	200
0.0094376	316	200
0.0094675	317	200
0.0094974	318	200
0.0095272	319	200
0.0095571	320	200
0.009587	321	200
0.0096168	322	200
0.0096467	323	200

Table 1

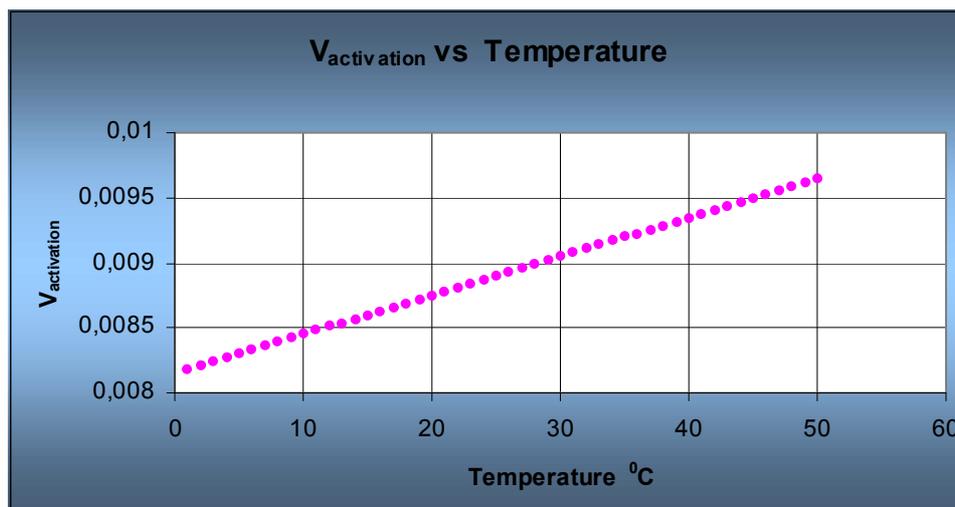


Figure 11: Sensitivity Analysis of Activation Loss varying with Temperature at
I = 0.2 Amperes

Table 1 shows the values of activation loss varying along with temperature at a current of 0.2 Amperes. This is a starting value for the sensitivity analysis since the factor “ $\ln \frac{I}{I_o} > 0$ “. The graph is produced using Excel and it shows a straight line having an initial value of activation loss 0.0081833 V at 1 °C and reaches a final value of 0.0096467 V at 50 °C. Therefore as temperature increases it results in higher values of activation loss.

The same procedure is followed for the remaining values of current up to 1 Ampere and for easy comparison only the graphs are included.

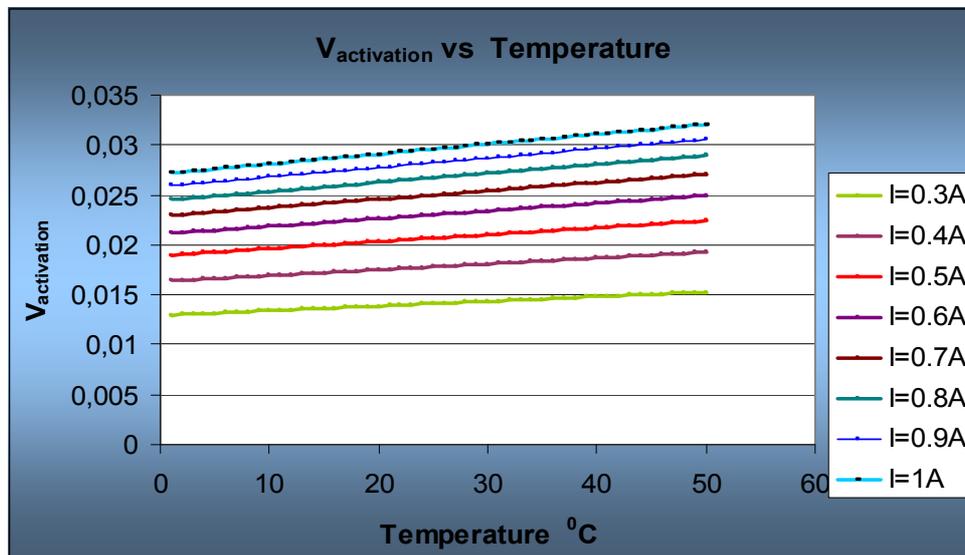


Figure 12: Sensitivity Analysis of Activation Loss varying with Temperature for values of I = 0.3 Amperes to I = 1 Ampere

The graph above represents the variation of temperature along with different values of current. Activation loss was modelled for every value of current the electrolyser can operate. As the current increases the loss increases too. The difference is that the increments of activation loss are smaller when working at low currents therefore it would be better if the operating conditions of the electrolyser would remain at low temperatures. This would allow using higher values of current and increasing the production rate of hydrogen.

In Figure 13 is presented the variation of activation loss along with different values of current at a constant temperature of 25 °C. The initial value of activation

loss is 0 V at 0.1 Amperes and reaches up to 0.029 V at 1 Ampere. It is obvious that the biggest amount of losses occur at low currents while at higher currents the increase of activation loss is not much significant. Therefore, electrolyzers work at a constant temperature, which is defined along with its behaviour with the rest of the losses in order to achieve the minimum loss of hydrogen under specific working conditions.

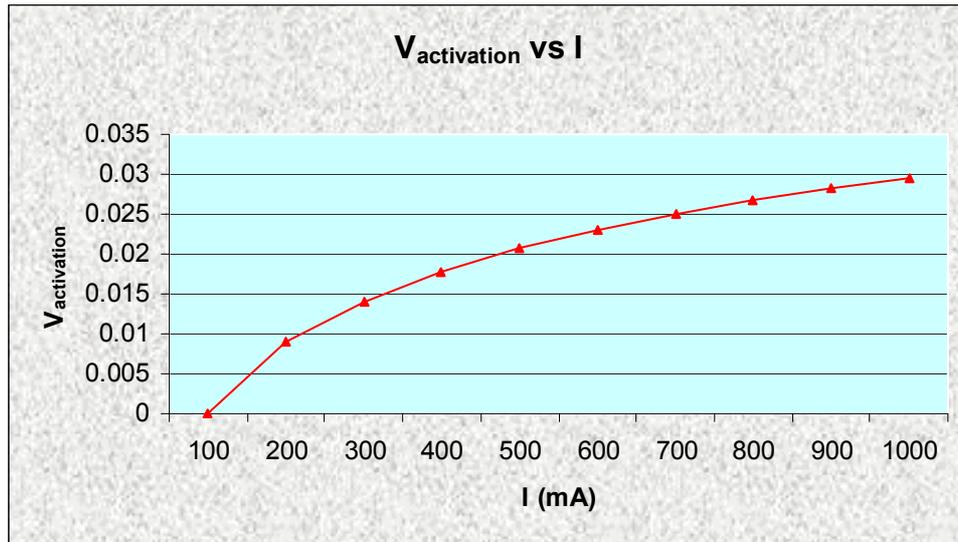


Figure 13: Sensitivity Analysis of Activation Loss varying with Current at a Temperature of 25 °C.

The graph shows that the activation loss is proportional to the temperature and as the temperature increases the activation loss increases too. In reality, the electrolyzers work at a constant temperature which is defined along with its behaviour with the rest of the losses in order to achieve the minimum loss of hydrogen under specific working conditions.

Another parameter that could affect activation loss is the exchange current. The initial value of I_0 is 0 A and it increases with increments of 0.005 A. The purpose of this sensitivity analysis is to examine the influence of exchange current to activation loss. The following table shows the measurements of Voltage and current taken from an experiment.

<i>Voltage (V)</i>	<i>Current (mA)</i>
0	0
0.7	0
1.0	21
1.5	58
1.6	254
1.7	674
1.8	983
1.9	1000

Table 2

The characteristic curve of V-I is shown in figure 14 below. The influence of exchange current to activation loss is shown with the pink line. The value of exchange current starts at 0 A and reaches up to 0.2 A for this session.

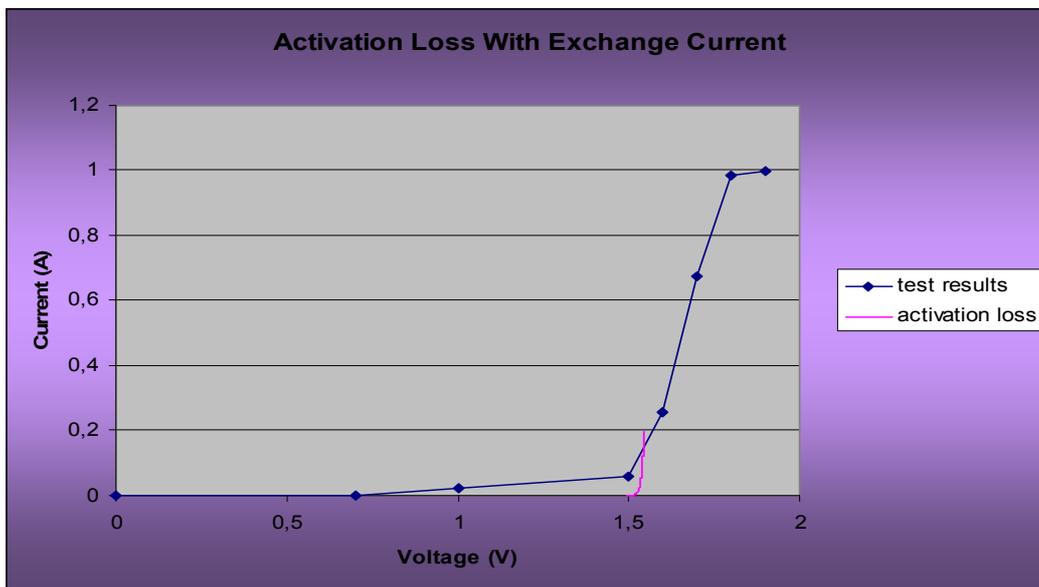


Figure 14: Activation Loss with exchange current values from 0 to 0.2 A

According to the selected value of exchange current activation loss is presented as a straight vertical line. This shows that activation loss is significant at low values of current where the exchange current has values in order for the

parameter “ $\ln \frac{I}{I_o}$ ” to be physically valid. Activation loss occurs only at low currents and therefore the exchange current can take limited values so it is almost impossible to have a significant amount of exchange current at high values.

Temperature also for this session is considered to be 25 °C. By using lower temperature, the pink line showing activation loss is moving left resulting to a decrease of activation loss and vice versa when the temperature is increasing.

Electrolysers usually operate at high currents in order to maximise the production of hydrogen. The exchange current and temperature are the main factors that mostly affect activation loss and it is preferred to stay at low levels so activation loss will not be significant in order to affect the rate of hydrogen production at such values.

4.5.2 Ohmic Loss

For ohmic loss the parameter that could affect it is the internal resistance. The value of internal resistance used in this case is 0.316Ω. Using the values from table 2 and the characteristic curve of V-I the loss due to the internal resistance is shown with the yellow line.

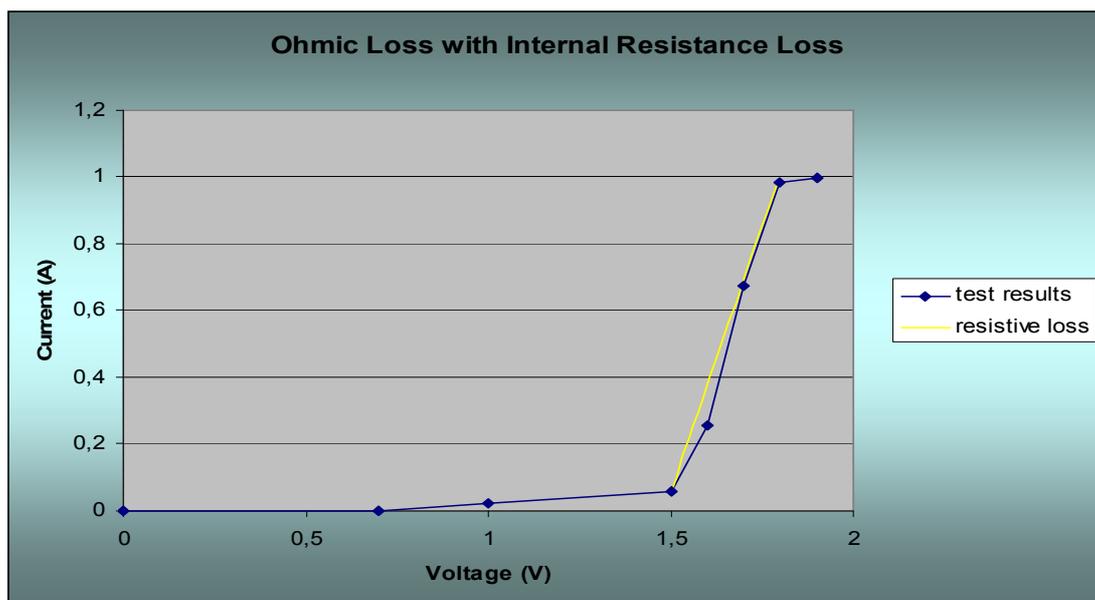


Figure 15: Ohmic Loss with Internal Resistance Loss

The values of the internal resistance in Figure 15 above are shown in table 3 below.

Voltage (V)	Current (A)	V_r Loss
1,5	0,058	1,500328
1,6	0,254	1,562264
1,7	0,674	1,694984
1,8	0,983	1,792628

Table 3

Supposing that the internal resistance could take values from 0.1Ω to 0.3Ω in increments of 0.02Ω the variation of such losses is shown below.

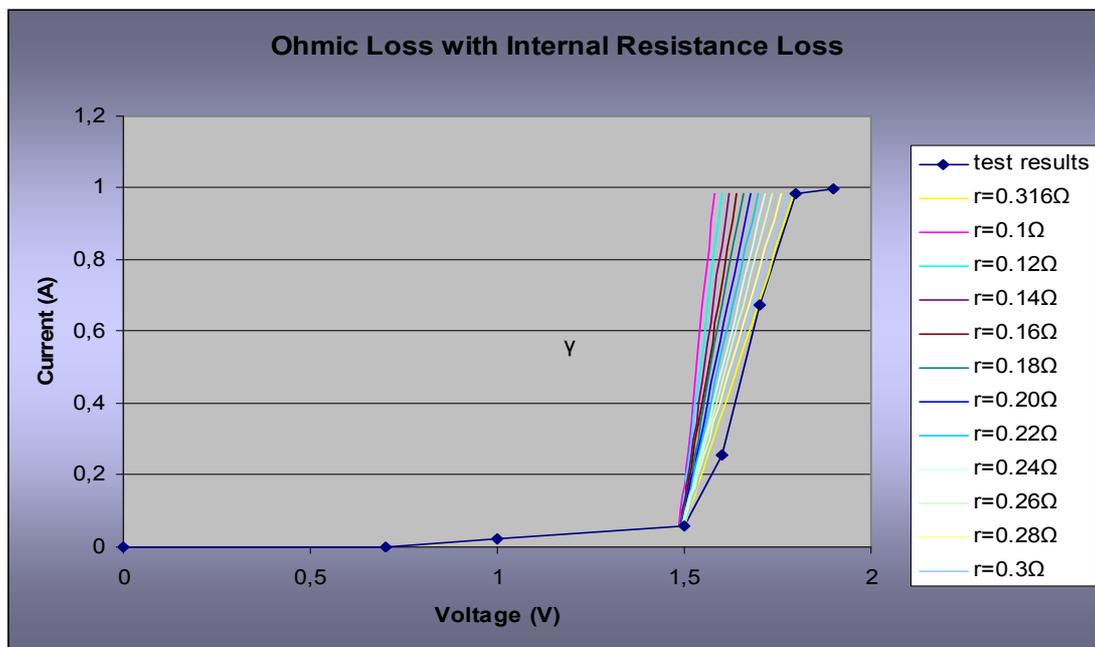


Figure 16: Ohmic Loss with Internal Resistance losses for values of $r=0.1\Omega$ to $r=0.316\Omega$.

The internal resistance loss is quite significant according to the analysis shown in figure 16. As the current increases, the loss due to the internal resistance increases too. Several values of internal resistance were plotted in order to investigate the influence of ohmic loss. It is obvious that when the resistance has a low value, the graph is more vertical to X axis and therefore the loss due to the internal resistance is low. Also, according to the results provided in table 3, ohmic loss is considered to be

the most significant out of all three losses. Therefore it is obvious that the rate of hydrogen production is mostly depended upon the loss due to resistance.

4.5.3 Concentration Loss

For the concentration loss, the only parameter that could be considered uncertain is the temperature. As in activation loss, a condition should be fulfilled such as $I_L > I$ in order for the formula to be valid. The value of I_L is always bigger than the value of the current since I_L equals to the maximum supply rate and in this case it is equal to 1 Ampere [1], since the electrolyser cannot operate above this value as mentioned in the characteristics, so the factor $\ln(1-(I/I_L))$ is always valid. Therefore concentration loss is mostly dependent upon temperature. The same procedure is followed as in activation loss. Table 4 shows the values of concentration loss when temperature varies from 1°C to 50 °C at a current equal to 0.2 Amperes. The graph is a straight line, presented in Figure 17, and this proves that as temperature and concentration loss are proportional.

V_{concentration} (V)	T (°K)	I (mA)
0.002634	274	200
0.002644	275	200
0.002654	276	200
0.002663	277	200
0.002673	278	200
0.002682	279	200
0.002692	280	200
0.002702	281	200
0.002711	282	200
0.002721	283	200
0.002731	284	200
0.00274	285	200
0.00275	286	200
0.002759	287	200
0.002769	288	200
0.002779	289	200
0.002788	290	200
0.002798	291	200
0.002807	292	200
0.002817	293	200
0.002827	294	200
0.002836	295	200
0.002846	296	200
0.002856	297	200
0.002865	298	200

0.002875	299	200
0.002884	300	200
0.002894	301	200
0.002904	302	200
0.002913	303	200
0.002923	304	200
0.002932	305	200
0.002942	306	200
0.002952	307	200
0.002961	308	200
0.002971	309	200
0.002981	310	200
0.00299	311	200
0.003	312	200
0.003009	313	200
0.003019	314	200
0.003029	315	200
0.003038	316	200
0.003048	317	200
0.003057	318	200
0.003067	319	200
0.003077	320	200
0.003086	321	200
0.003096	322	200
0.003105	323	200

Table 4

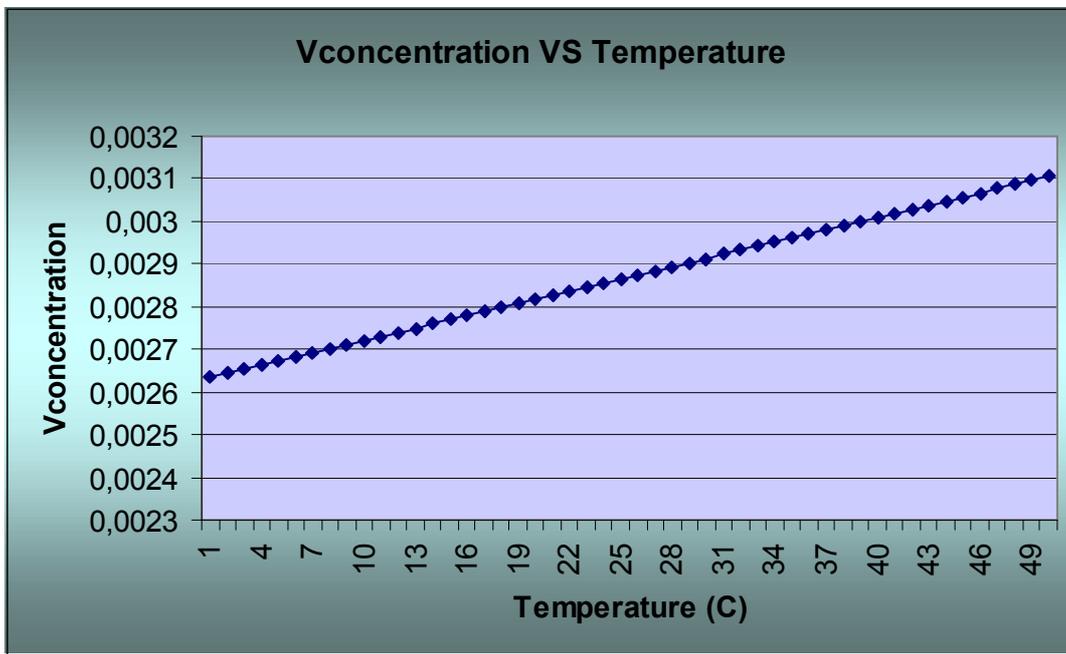


Figure 17: Sensitivity Analysis of Concentration Loss varying with Temperature at
I = 0.2 Amperes

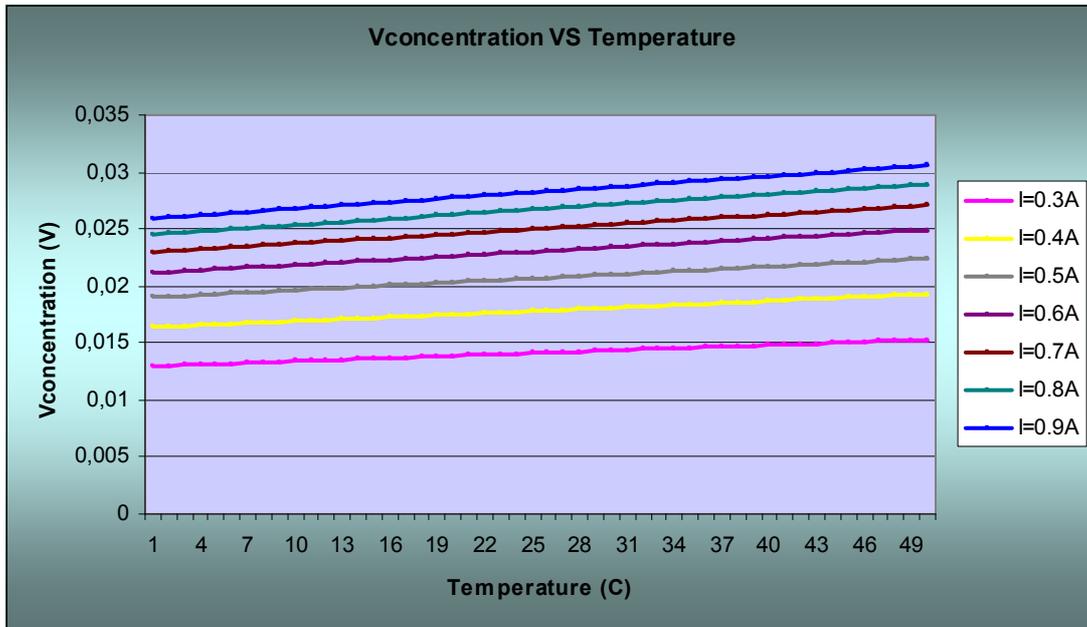


Figure 18 Sensitivity Analysis of Concentration Loss varying with Temperature for values of $I = 0.3$ Amperes to $I = 0.9$ Ampere

The figures above represent the variation of concentration loss with temperature at different values of current from 0.2 to 0.9 Amperes. As the value of current increases, concentration loss increases too resulting in greater loss of hydrogen.

Figure 19 shows the variation of concentration loss along with current at a working temperature of 25 °C. It is obvious that as the current increases the loss of hydrogen due to concentration is bigger.

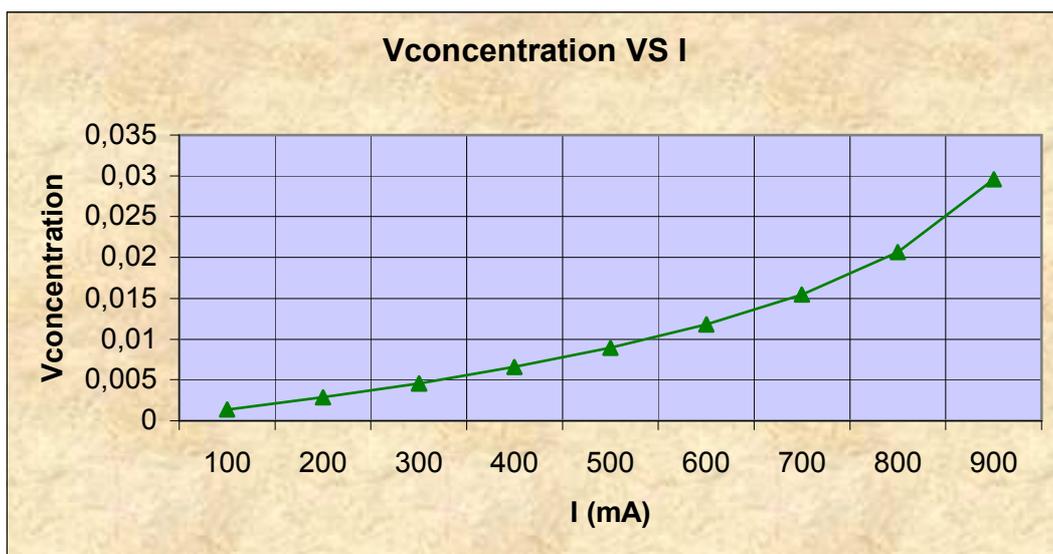


Figure 19: Sensitivity Analysis of Concentration Loss varying with Current at a Temperature of 25 °C.

5. Experimental Tests: PEM Electrolyser and Instrumentation

In order to examine the efficiency of electrolysis, a proton exchange membrane electrolyser has been used to carry out different types of experiments. A figure of the exact equipment is shown below.

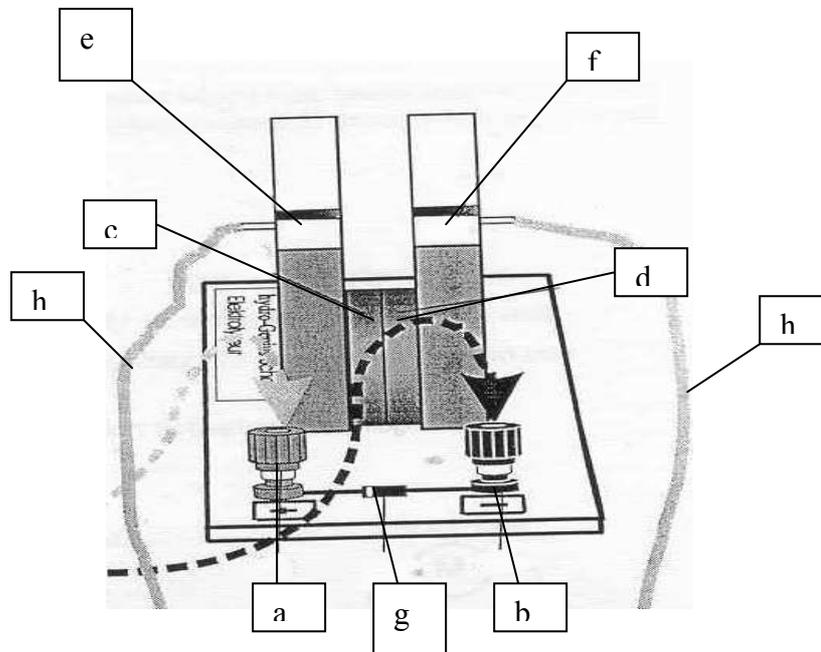


Figure 20: Proton Exchange Membrane Electrolyser

The electrolyser comprises of a positive terminal (a) and a negative terminal (b) where the power supply must be connected. The most important parts of the electrolyser are parts (c) and (d). Part (c) is the half-cell that is used for oxygen generation and part (d) is the other half that is used for hydrogen generation. In the middle is a proton exchange membrane that is used for the separation of water to its elements – Hydrogen (H_2) and Oxygen (O_2). Two separate tubes are attached to each cell, one for Hydrogen and one for Oxygen, and are called gas storage units (e) and (f). They are connected to the cells via two very small tubes, which are vertical to both the cell and the storage units, and they have a small scale from 0 to 10 millilitres to measure the amount of gas produced. On the upper side of the storage units there are two plastic tubes (h) – one in each unit – mounted on a very small vertical tube, which is exactly the same as the one in Figure 20. Tubing stoppers (k), like these shown in figure 21, are used with the purpose of not allowing the gas to escape from the storage unit.

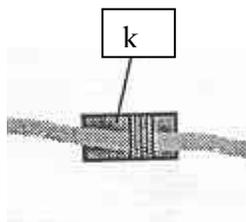


Figure 21: Tube Stoppers

In addition to the whole equipment a protective diode (g) is mounted along the wire that connects the positive and the negative terminal.

Proton Exchange Membrane Electrolyser Parts List	
a	Positive Terminal
b	Negative Terminal
c	Half-cell for Oxygen Generation
d	Half-cell for Hydrogen Generation
e	Gas Storage Unit for Oxygen
f	Gas Storage Unit for Hydrogen
g	Protective Diode
h	Plastic Tubes
k	Tubing Stoppers

Table 5

All the parts of the equipment are attached to a plastic, transparent, stiff base as shown in figure 20. The tubes and the cells are also made out of the same material except the plastic tubes that are connected to the upper part of the storage units and are very flexible.

After assuring that none of the parts of the electrolyser were missing, some other devices were necessary in order to start the experiments. A power supply unit (Figure 22) that could be able to provide low current, a resistor and two multimeters (Figure 23) to monitor the amount of current and voltage supplied to the electrolyser.



Figure 22: Power Supply Unit



Figure 23: Multimeter

6. METHODOLOGY

The units were assembled together as shown in the figure below.

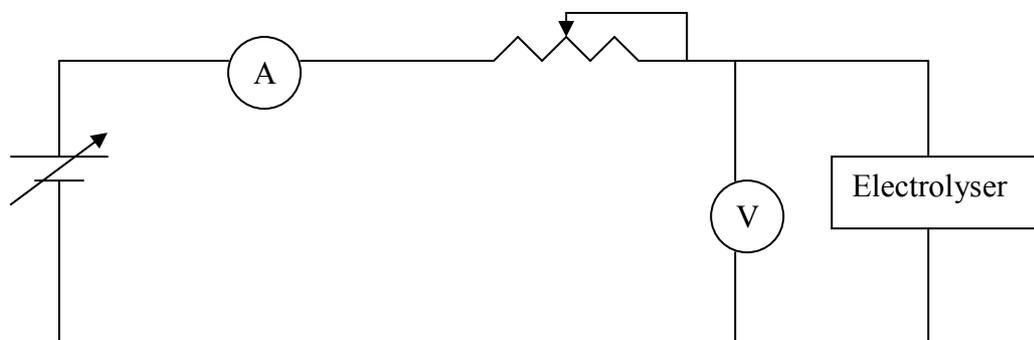


Figure 24: Electrical Circuit

The power supply unit is connected to the first multimeter, which will be used to measure the current in milliamperes, to the resistor, which is set to avoid high currents and connects to the electrolyser. The second multimeter is used to measure the voltage in volts and is connected parallel to the electrolyser. The polarity was double-checked to assure that the positive terminal of the power supply unit is connected to the positive terminal of the electrolyser and the negative terminal of the power supply unit to the negative terminal of the electrolyser.

After completing all the connections, distilled water was poured into the storage cylinders shown in figure 25.

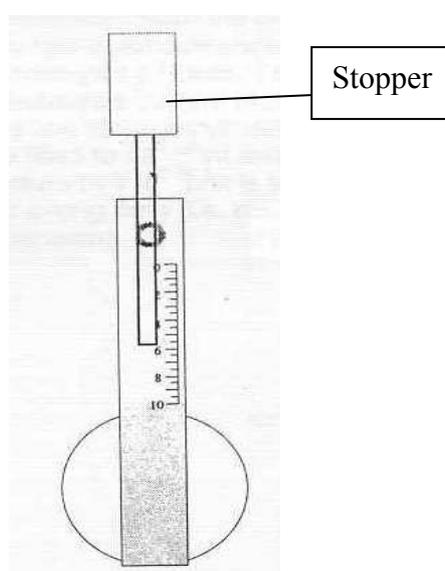


Figure 25: Storage Cylinders

The minimum amount of water should be at least up to the 10 ml mark. In case the level of liquid on the oxygen side falls below the 10 ml mark it must be refilled. On the hydrogen side the level of liquid can be reduced to the 10 ml mark when necessary by pouring off the surplus water. The proton exchange membrane electrolyser must only be filled with distilled water. Any other liquids that contain electrolyte will destroy the electrolyser. The stopper must be inserted in the storage cylinder with the short overflow pipe into the lower gas storage cylinder.

There are two different modes of operation for the electrolyser. First is storage mode, where both storage cylinders must be filled with distilled water up to the 0 ml mark before starting the experiments.

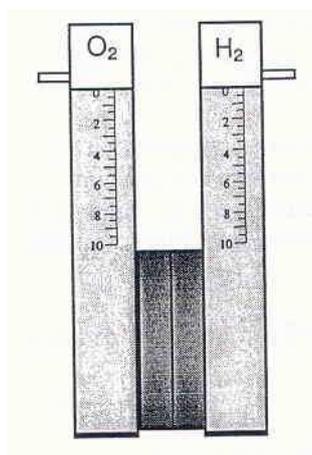


Figure 26: Storage Mode

For the continuous mode the hydrogen gas storage cylinder should be filled only up to the 10 ml mark in comparison with the oxygen gas storage cylinder, which must be filled with distilled water up to the 0 ml mark since as small amount of water is transported from the oxygen side to the hydrogen side during electrolysis. By the time the water level in the hydrogen storage cylinder reaches the 0 ml mark, the surplus water must be siphoned off after removing the stopper.

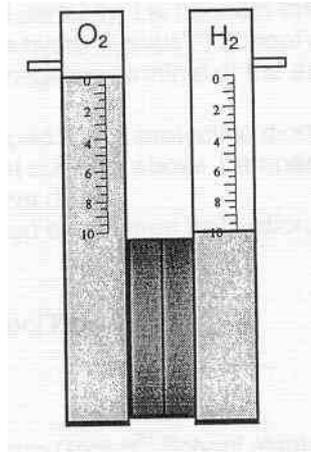


Figure 27: Continuous Mode

The technical data of this specific proton exchange membrane electrolyser are shown in table 6. The consumption of distilled water is quite low since it is 1 ml for every ten hours of continuous operation at a current of 300 mA. The amount of water carried from oxygen gas storage unit to hydrogen gas storage unit is 1ml per hour at 500 mA. The normal voltage that is used has a range from 1.4 to 1.9 Volts and the current from 0 to 1000 mA. Finally, the maximum hydrogen production is 7ml per minute [7].

Proton Exchange Membrane Electrolyser	
Consumption of distilled water	1 ml/10 h at 300 mA electrolysis current
Amount of water carried from oxygen gas storage unit to hydrogen gas storage unit	1 ml/h at 500 mA electrolysis current
Normal Voltage	1.4 – 1.9 Volts
Current	0 – 1000 mA
Maximum Hydrogen Production	7 ml/minute

Table 6

In order for the distilled water to begin splitting a minimum of 1.23 Volts must be applied since the potential difference is temperature dependent and this is the theoretical value at ambient temperature. Also, the current must not exceed 1000 mA as this will result in the destruction of the electrolyser. For safety reasons a capacitor is mounted on the equipment to avoid current overflow. The equipment should operate under normal temperature conditions [8].

7. EXPERIMENT

The aim of this project was to examine the efficiency of electrolysis and therefore to suggest how it can be improved. One of the basic stages was to do a number of experiments that would help examine how the efficiency is balancing and to validate a model that will be used to investigate the effects that influence the efficiency. Experimental data is quite useful in such projects as it usually varies with theory and hence proposals could be made in order to improve the operation modes.

For this specific project, eight types of experiments were chosen to help investigate the efficiency of the proton exchange membrane electrolyser and these are listed below.

Experiment 1:

The first experiment was performed to examine how the current varies and what stage it reaches by applying several amounts of voltage. As it was mentioned above, the maximum voltage applied to the electrolyser is 1.9 Volts and the current must not exceed 1000 mA otherwise this will result in the damage of the electrolyser. So, the table with the different amounts of voltage applied is shown below and according to the experimental results that will be obtained the characteristic curve of V-I will be drawn. In addition the characteristic curve of V-I will be used in order to examine all the parameters that affect the electrolyser efficiency as it is previously presented in section 4.

Voltage (Volts)	Current (mA)
0	
0.7	
1.0	
1.5	
1.6	
1.7	
1.8	
1.9	

Table 7

Experiment 2:

On this experiment, different amount of currents were applied for thirty seconds and then the volume of hydrogen produced in each current was measured. The results from this experiment will show if the electrolyser produces the same amount of hydrogen when the same values of current are used and what is the loss of hydrogen volume each time using the same settings.

Current (mA)	Time (seconds)	Volume H ₂ (ml)
0	30	
50	30	
100	30	
150	30	
200	30	
250	30	
300	30	
350	30	
400	30	
450	30	
500	30	

Table 8

Experiment 3:

In this experiment a constant voltage is applied and every thirty seconds measurements are taken for the volume of hydrogen produced. Again, as in experiment 2, the loss of hydrogen volume will be investigated by applying the same operating conditions numerous times.

Voltage (Volts)	Time (seconds)	Volume H ₂ (ml)
1.5	0	
1.5	30	
1.5	60	
1.5	90	
1.5	120	
1.5	150	
1.5	180	
1.5	210	

Table 9

Experiment 4:

Again, this experiment has the same procedure as experiment 3 but intervals of voltage are used instead of current.

Voltage (Volts)	Time (seconds)	Volume H ₂ (ml)
0	30	
0.5	30	
1.0	30	
1.2	30	
1.3	30	
1.4	30	
1.5	30	
1.6	30	
1.7	30	
1.8	30	
1.9	30	

Table 10

Experiment 5:

Experiment 5 was considered to be one of the most interesting. By applying a constant current for a specific amount of time, the aim was to take multiple measurements of the volume of hydrogen produced by the electrolyser. This would help to work out the efficiency of the electrolyser and find out the amount of energy produced. In this experiment there is repeatability in comparison with experiment 2 where the electrolyser operates constantly and different data is retrieved. With this experiment it is possible to calculate both Faradaic and energy efficiency. The above tests were done more to investigate the operation of the electrolyser and to examine if the data that would be retrieved from it is appropriate to calculate the Faradaic and energy efficiencies.

(i)

Current (mA)	Voltage (Volts)	Time (seconds)	V _{H2} (ml)
300	Reading from device	60	

(ii)

Current (mA)	Voltage (Volts)	Time (seconds)	V _{H2} (ml)
300	Reading from device	60	

(iii)

Current (mA)	Voltage (Volts)	Time (seconds)	V _{H2} (ml)
300	Reading from device	60	

Table 11

8. Experimental Results and Analysis

Experiment 1:

This experiment was carried out before every session in order to monitor how the current increases with respect to different voltage applied. In this point it is much of use to mention that the proton exchange membrane electrolyser was equipped with a small capacitor, which would give slightly different results when it was charged or discharged. For each session, the characteristic curve of voltage against current was produced.

For all Sessions	Session 1	Session 2	Session 3	Session 4	Session 5	Session 6	Session 7
<i>Voltage (V)</i>	<i>Current (mA)</i>						
0	0	0	0	0	0	0	0
0.7	0	0	0	0	0	0	0
1.0	25	31	29	27	0	25	21
1.5	48	52	52	51	21	161	58
1.6	176	199	215	184	188	281	254
1.7	555	579	645	476	488	664	674
1.8	960	980	981	789	820	974	983
1.9	1000	1000	1000	1000	1000	1000	1000

Table 12

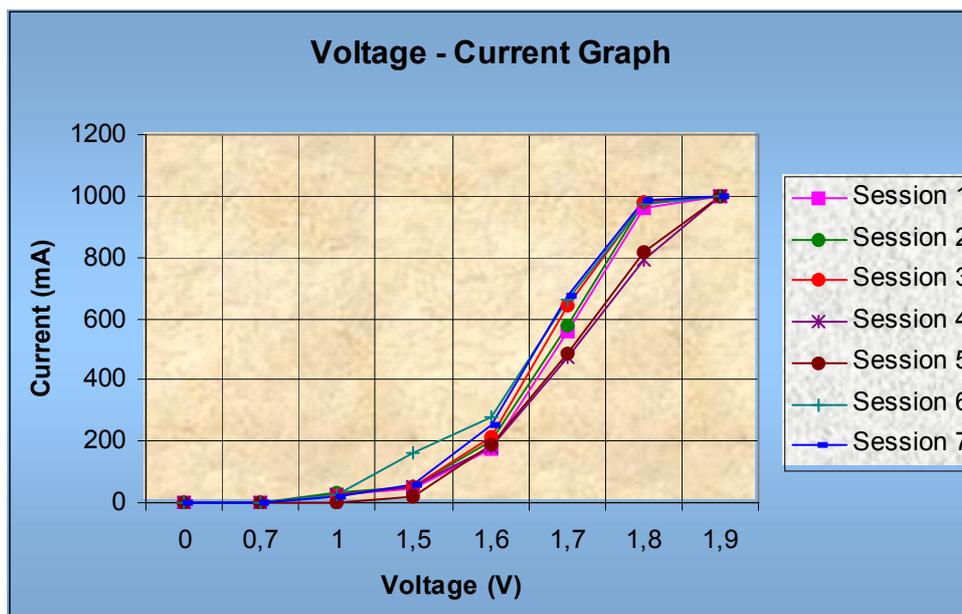


Figure 28: Voltage - Current Graph

The graph above represents the current variation along different amounts of voltage. This type of graph was provided – voltage against current and current against voltage – in order to have a complete idea about their behaviour under different operating conditions. By observing it is obvious that the numbers on each session differ by small increments and the characteristic curves are almost the same on every session. The reason of this small difference is the capacitor that is mounted in the electrolyser. The capacitor was discharged on sessions one, four and six the device was not in operation mode for at least twenty-four hours. However the difference is not incredibly important and thus could be considered negligible.

The voltage – current graph shows that for the proton exchange membrane electrolyser the current only starts to flow at a certain voltage and then it rises continuously. Note that this depends on the type of electrolyser and that different types will produce different curves.

By applying a small voltage could not set off an electrolysis current, because the applied voltage must be at least as large as the theoretical cell voltage in order for a current to be able to flow, which could lead to the release of hydrogen at the cathode and oxygen at the anode. This happens because the electrodes initially absorb the gases and a galvanic cell develops. This galvanic cell has a certain cell voltage, which is called polarisation voltage, and sets of an internal current that travels to the

opposite direction to the electrolysis current. The more voltage is increased, the electrodes are absorbing more gas until it reaches a certain point where the gas pressure at the electrodes reaches the level of external air pressure and gas bubbles begin to rise at the electrodes.

By keep increasing the voltage it leads to continuous gas development and that is the point where the electrolysis current is rising dramatically. The minimum voltage at which the water begins to split is called the decomposition voltage and under standard conditions it amounts to 1.23 volts. Also, from the experimental data retrieved the value of the resistance can be calculated. By choosing two values of Voltage and the corresponded values of current it can be calculated using the equation below:

$$R_i = \frac{V_2 - V_1}{I_2 - I_1} = \frac{1.8 - 1.6}{0.82 - 0.188} = 0.316\Omega \text{ (Eq. 8.1)}$$

In the experiments above is shown that the water starts to split at higher voltage than 1.23 volts and this difference between the theoretical decomposition and the voltage decomposition is called overpotential.

The overpotential depends on the electrode material, the consistency of the electrode surfaces, the type and concentration of the electrolyte, the current strength per electrode surface and the temperature.

In practice, the aim is to keep the overpotential at low level because it is not economically efficient. The factors that could help to achieve this are to use good active electrodes and electrolyte materials such as electrical resistance, electrode's dimension diffusion and operating temperature.

Experiment 2:

On experiment 2, the time to measure the volume has been kept constant and the current was varying between an initial and a final price in equal intervals. The time given for each measurement was thirty seconds. The purpose of this experiment was to examine if by applying the same amount of current for the same amount of time would produce the same amount of hydrogen volume.

Sessions 1,2 and3:

The initial value of current was 0 mA and the final 500 mA. The increase was done in increments of 50 mA and the time to measure the volume of hydrogen produced was set to 30 seconds.

For All Sessions		Session 1	Session 2	Session 3
<i>Current (mA)</i>	<i>Time (seconds)</i>	<i>Volume H₂ (ml)</i>	<i>Volume H₂ (ml)</i>	<i>Volume H₂ (ml)</i>
0	30	0	0	0
50	30	0.15	0.1	0.17
100	30	0.5	0.25	0.6
150	30	0.8	0.7	0.7
200	30	1	0.8	1
250	30	1.2	1	1.1
300	30	1.4	1.25	1.2
350	30	1.5	1.5	1.3
400	30	1.6	1.6	1.6
450	30	1.8	1.8	1.8
500	30	2.9	2.2	2.1

Table 13

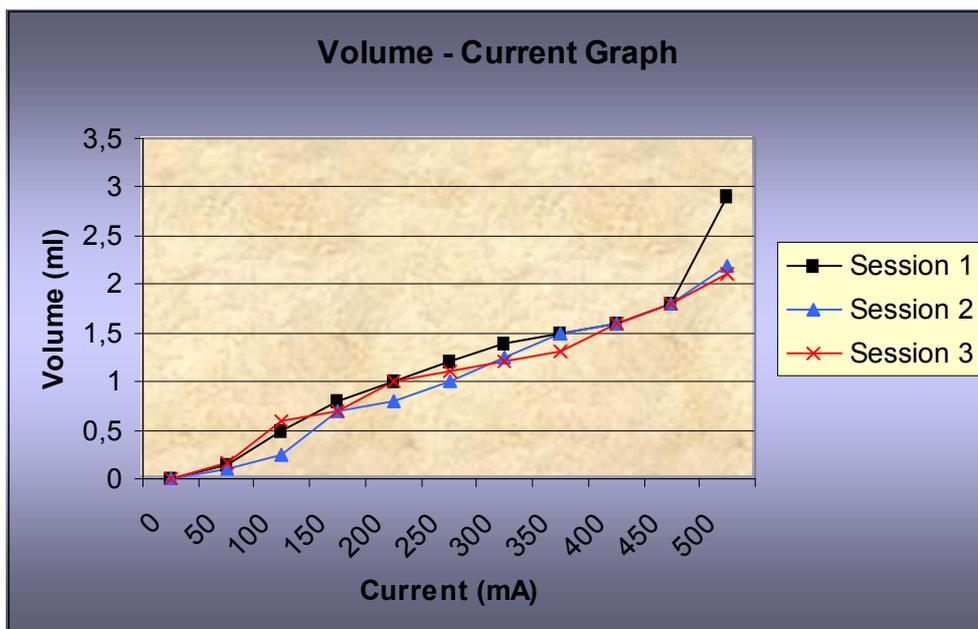


Figure 29: Volume – Current Graph for Sessions 1 to 3

Sessions 4 and 5:

In session four and five, the increments of current have been changed from 50 mA to 100 mA and the final value of the current was 900 mA. The time was kept to its standard thirty seconds. The reason of changing the current values was to inspect the increase in the volume of hydrogen and to compare it with other values.

For All Sessions		Session 4	Session 5
Current (mA)	Time (seconds)	Volume H ₂ (ml)	Volume H ₂ (ml)
0	30	0	0
100	30	0.4	0.5
200	30	0.6	0.7
300	30	1.4	1.2
400	30	1.8	1.5
500	30	2.4	2.9
600	30	2.9	3.0
700	30	3.0	3.1
800	30	3.4	3.2
900	30	3.6	3.6

Table 14

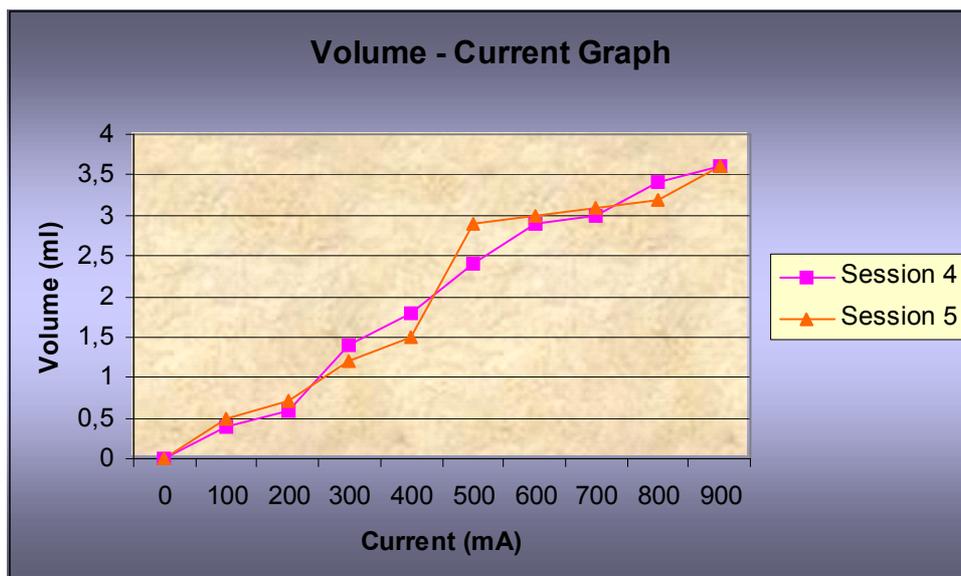


Figure 30: Volume – Current Graph for Sessions 4 and 5

Sessions 6 and 7:

In these last two sessions the current's initial value was 0 mA, the second value was 50 mA and after that it was increased in increments of 100 mA until it reaches its final value, which is 950 mA.

For All Sessions		Session 6	Session 7
<i>Current (mA)</i>	<i>Time (seconds)</i>	<i>Volume H₂ (ml)</i>	<i>Volume H₂ (ml)</i>
0	30	0	0
50	30	0.15	0.1
150	30	0.6	0.6
250	30	0.75	1
350	30	1.2	1.3
450	30	1.7	1.7
550	30	2.2	2.2
650	30	2.6	2.9
750	30	3.2	3.1
850	30	3.5	3.6
950	30	4.0	3.9

Table 15

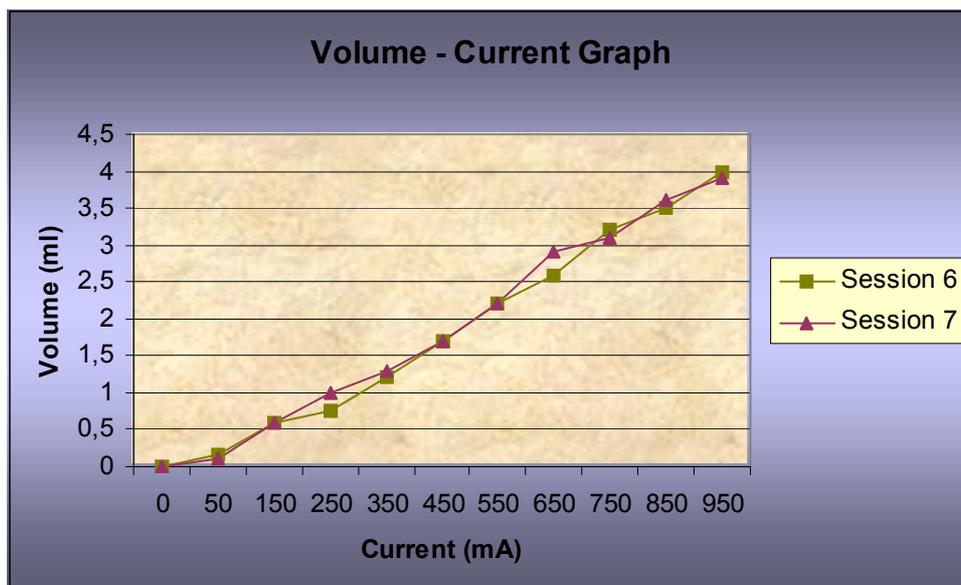


Figure 31: Volume – Current Graph for Sessions 6 and 7

Again, in the first three sessions of this experiment the amount of hydrogen produced by each different amount of current varies slightly between each single session. The characteristic curve of volume against the different types of current is following approximately the same route going upwards and downwards in the same prices. The difference in this is that in some cases it may go up for 0.5 ml of hydrogen and in the next experiment it may undergo the same path but for 0.7 ml.

In sessions four and five it is interesting to observe that both experiments had the same output of hydrogen in the final value of current, which was 3.6 ml. Moreover, the curve increases dramatically in the production of hydrogen between the price of 400 mA and 500 mA

Finally in the last two sessions, the curves have almost the same slope. The only points where great changes occur are in the beginning of the curve where the current is actually low.

Experiment 3:

Experiment four followed exactly the same procedure as experiments two and three with the only difference that voltage was used instead of current.

Sessions 1 and 2:

In the first two sessions the voltage applied to the proton exchange membrane electrolyser was 1.5 Volts and it was constant for 210 seconds.

For All Sessions		Session 1	Session 2
<i>Voltage (Volts)</i>	<i>Time (seconds)</i>	<i>Volume H₂ (ml)</i>	<i>Volume H₂ (ml)</i>
1.5	0	0	0
1.5	30	0.5	0.6
1.5	60	1.4	1
1.5	90	2.1	1.8
1.5	120	3	2.6
1.5	150	3.5	3.1
1.5	180	4.1	3.6
1.5	210	4.9	4.3

Table 16

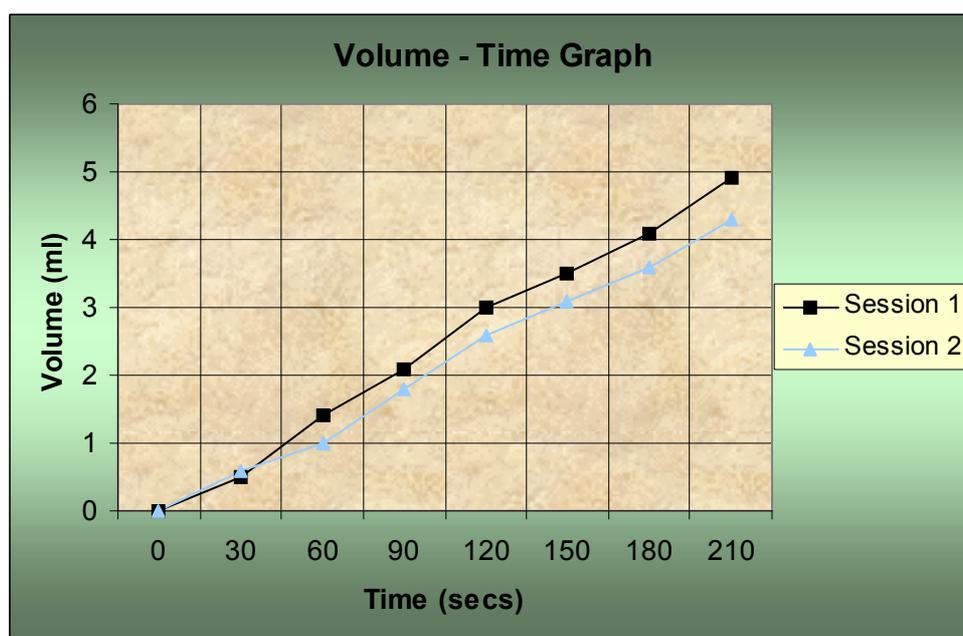


Figure 32: Volume – Time Graph for Sessions 1 and 2

Sessions 3 and 4:

In sessions three and four the voltage was raised and was set to 1.600 Volts.

For All Sessions	Session 3	Session 4
<i>Voltage (Volts)</i>	<i>Time (seconds)</i>	<i>Volume H₂ (ml)</i>
1.6	0	0
1.6	30	0.7
1.6	60	1.6
1.6	90	2.4
1.6	120	3.1
1.6	150	4
1.6	180	4.6
1.6	210	5.5

Table 17

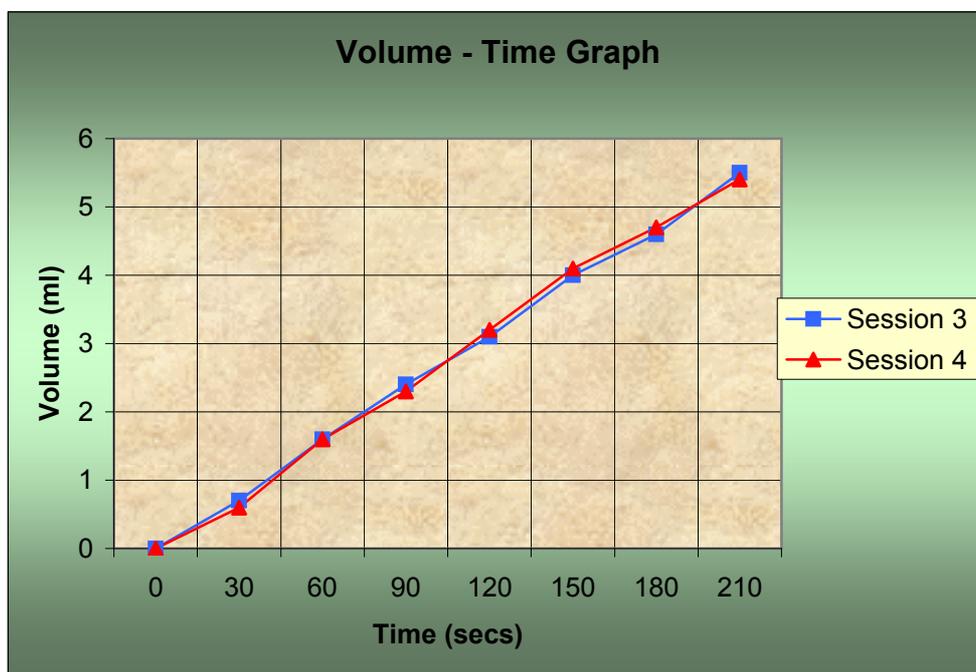


Figure 33: Volume – Time Graph for Sessions 3 and 4

Session 5:

For this session, the voltage was raised up to 1.650 Volts, which results to a current of 413 mA.

Voltage (Volts)	Time (seconds)	Volume H ₂ (ml)
1.65	0	0
1.65	30	1.6
1.65	60	3.2
1.65	90	4.8
1.65	120	6.5
1.65	150	8.1
1.65	180	9.8
1.65	210	11.8

Table 18

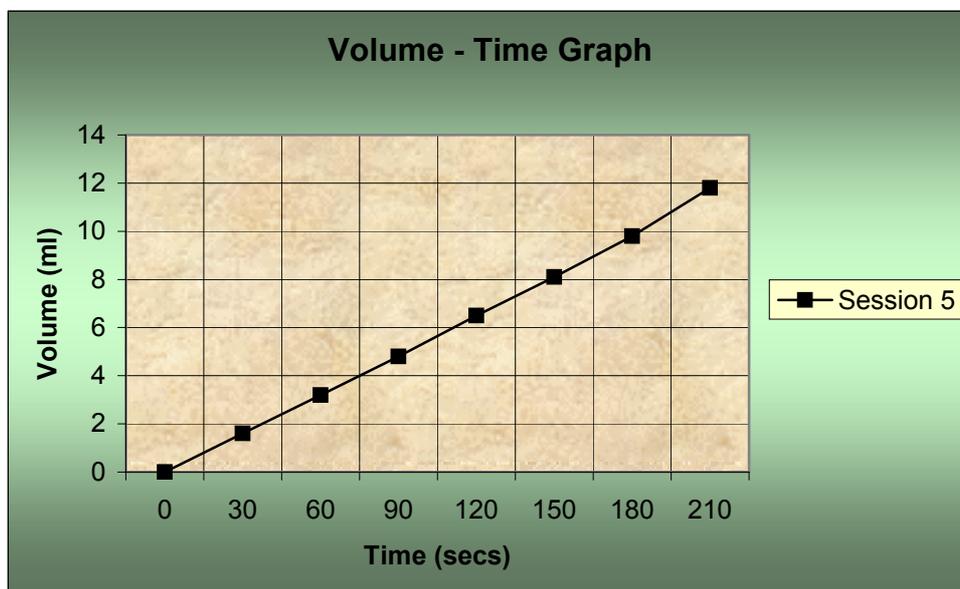


Figure 34: Volume – Time Graph for Session 5

Sessions 6:

For the last two sessions, the voltage was set to 1.7 V and 1.75 respectively, which give a current of 439 mA and 899 mA.

Voltage (Volts)	Time (seconds)	Volume H ₂ (ml)
1.7	0	0
1.7	30	1.6
1.7	60	3.6
1.7	90	5.1
1.7	120	6.6
1.7	150	8.4
1.7	180	10
1.7	210	11.7

Table 19

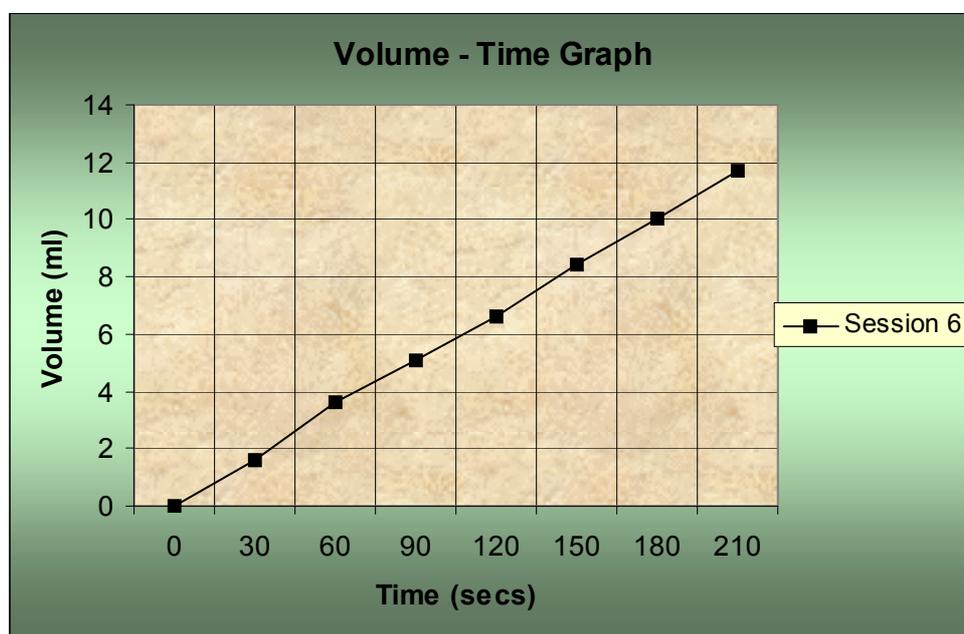


Figure 35: Volume – Time Graph for Session 6

Session 7:

Voltage (Volts)	Time (seconds)	Volume H ₂ (ml)
1.75	0	0
1.75	30	3.6
1.75	60	7.4
1.75	90	11.1
1.75	120	14.5
1.75	150	18
1.75	180	21.9
1.75	210	25.6

Table 20

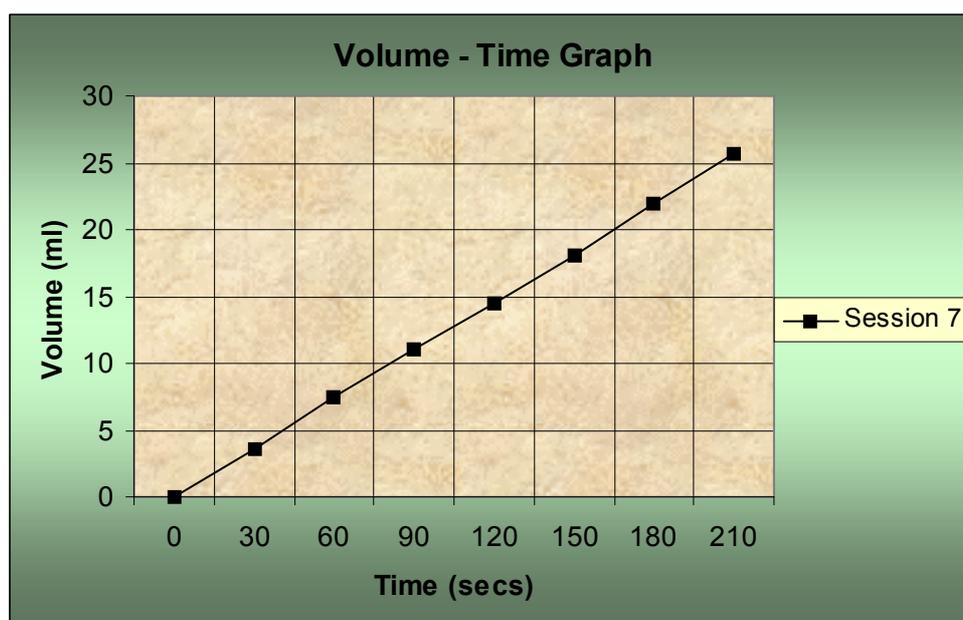


Figure 36: Volume – Time Graph for Session 7

In this experiment again is obvious that as much as the voltage increases, the amount of hydrogen produced is steadier in a specific period of time. At a voltage of 1.5 V both measurements taken are about the same with very slight differences. The same happened when the voltage was increased up to 1.6 V. A common feature of sessions five, six and seven is that the curve is almost a straight line which means that almost the same amount of hydrogen is being produced in every thirty seconds.

Experiment 4:

In this experiment, the measurements of the volume of hydrogen were taken having a constant voltage for thirty seconds.

For All Sessions		Session 1	Session 2	Session 3	Session 4	Session 5
<i>Voltage (Volts)</i>	<i>Time (seconds)</i>	<i>Volume H₂ (ml)</i>				
0	30	0	0	0	0	0
0.5	30	0	0	0	0	0
1.0	30	0	0	0	0	0
1.2	30	0	0	0	0	0
1.3	30	0	0	0	0	0
1.4	30	0	0	0	0	0
1.5	30	0.1	0.1	0.1	0.1	0.2
1.6	30	0.7	1	0.7	0.7	0.9
1.7	30	3.0	2.6	2.5	2.6	2.5
1.8	30	4.2	4.1	4.2	4.3	3.7
1.9	30	-	-	-	-	-

Table 21

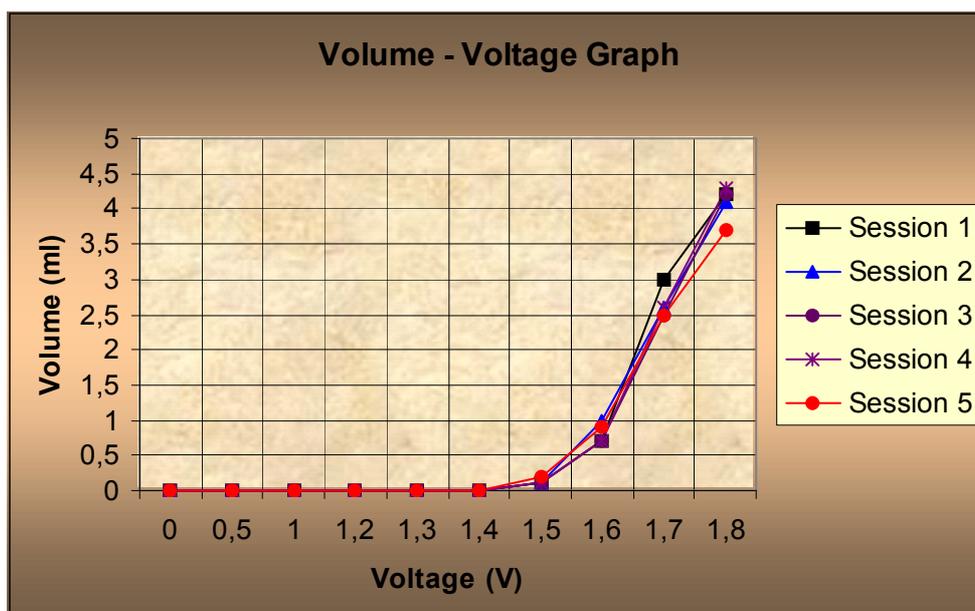


Figure 37: Volume – Voltage Graph for Sessions 1 to 5

Sessions 6 and 7:

In these sessions the increments of voltage have changed, after 1.5 Volts. From 0.1 V to 0.05 V.

For All Sessions		Session 6	Session 7
<i>Voltage (Volts)</i>	<i>Time (seconds)</i>	<i>Volume H₂ (ml)</i>	<i>Volume H₂ (ml)</i>
0	30	0	0
0.5	30	0	0
1.0	30	0	0
1.2	30	0	0
1.3	30	0	0
1.4	30	0	0
1.5	30	0.1	0.1
1.55	30	0.2	0.4
1.6	30	1	1
1.65	30	1.7	1.7
1.7	30	2.5	2.6
1.75	30	3.3	3.6

Table 22

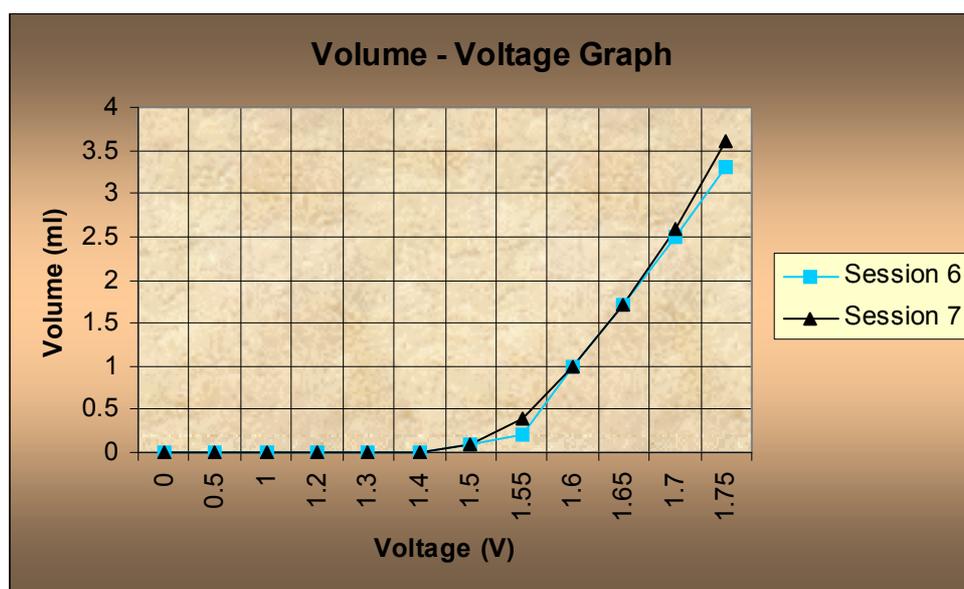


Figure 38: Volume – Voltage Graph for Sessions 6 and 7

In the first five sessions, the amount of hydrogen produced is about the same in every single session. In the graphs is shown that the water begins to split after 1.4 volts and the most hydrogen is produced between 1.6 and 1.7 volts. The values of hydrogen before this are between 0 ml and 1 ml. The slope then rises dramatically and from 1.6 to 1.8 volts it is produced approximately 3 ml of hydrogen.

Experiment 5:

In this experiment were taken multiple measurements by keeping the current, voltage and time constant. The measurements were taken each session and by finding the average volume of hydrogen that was produced, it was possible to calculate the Faraday's efficiency and the energy efficiency of the electrolyser. Also losses from the internal resistance can be calculated since the Faradaic Efficiency is much less than 100%.

Session 1:

(i)

Current (mA)	Voltage (Volts)	Time (seconds)	V _{H2} (ml)
300	1.62	60	2.1

(ii)

Current (mA)	Voltage (Volts)	Time (seconds)	V _{H2} (ml)
300	1.62	60	2.0

(iii)

Current (mA)	Voltage (Volts)	Time (seconds)	V _{H2} (ml)
300	1.62	60	2.0

Table 23

The average volume of hydrogen produced is:

$$V_{H2ave} = \frac{(V_{H2(i)} + V_{H2(ii)} + V_{H2(iii)})}{3} = \frac{(2.1 + 2.0 + 2.0)}{3} = 2.03ml$$

Therefore, the Faraday's efficiency is:

$$\eta_{Faraday} = \frac{V_{H2experimental}}{V_{H2theoretical}} \quad (\text{Eq. 4.9})$$

The theoretical amount of volume of hydrogen can be calculated using equation 4.10

$$V_{H2theoretical} = \frac{I \cdot t \cdot V_m}{\alpha \cdot F} \quad (\text{Eq. 4.10})$$

The term I is the current used in mA, t is the time each measurement was taken and V_m is the molar volume of hydrogen and is considered to be equal to 24 l/mol at 20 °C and at normal pressure. The constant α is the number of electrons being exchanged in order to release one particle at the electrode and in this case is equal to 2. The Faraday's constant is F and is equal to 96484 C/mol.

So, the theoretical amount of hydrogen is

$$V_{H2theoretical} = \frac{I \cdot t \cdot V_m}{\alpha \cdot F} = \frac{0.3 \cdot 60 \cdot 24}{2 \cdot 96484} = 2.2ml$$

And therefore the Faraday's efficiency for this session is:

$$\eta_{Faraday} = \frac{V_{H2experimental}}{V_{H2theoretical}} = \frac{2.03}{2.2} = 0.92 = 92 \%$$

From the above measurements it is possible to calculate the energy efficiency of the electrolyser using equation 4.11.

$$\eta_{Energy} = \frac{H_{H_2} \cdot V_{H_2\text{experimental}}}{U \cdot I \cdot t} \quad (\text{Eq. 4.11})$$

The term H_{H_2} is the calorific value of hydrogen at a temperature of 20 °C and is equal to 11920 kJ/m³. So, the energy efficiency is:

$$\eta_{Energy} = \frac{H_{H_2} \cdot V_{H_2\text{experimental}}}{U \cdot I \cdot t} = \frac{11920 \cdot 10^3 \cdot 2.03 \cdot 10^{-6}}{1.62 \cdot 0.3 \cdot 60} = 0.829 = 82.9 \%$$

The energy losses in session 1 are:

$$E_{loss} = (U \cdot I \cdot t) - (H_{H_2} \cdot V_{H_2\text{experimental}}) \quad (\text{Eq.8.1})$$

Therefore:

$$E_{loss} = (1.62 \cdot 0.3 \cdot 60) - (11920 \cdot 10^3 \cdot 2.03 \cdot 10^{-6}) = 4.96J$$

The amount of losses due to the internal resistance is calculated using equation 8.2:

$$E_{lossR} = I^2 \cdot R_i \cdot t \quad (\text{Eq. 8.2})$$

In this case it is:

$$E_{lossR} = I^2 \cdot R_i \cdot t = 0.3^2 \cdot 0.316 \cdot 60 = 1.70J$$

The remaining amount of energy is lost due to activation and concentration loss plus losses that occur from the membrane of the electrolyser. The amount of energy loss due to activation can not easily be measured because the value of the exchange current is unknown since it is impossible to measure it with the equipment used. Concentration loss is minimal at these levels of current and therefore the most important loss is due to resistance. In addition it is important to mention, for any

device used, that energy could be lost from possible leaks of hydrogen therefore a well insulated device is preferred for higher efficiencies.

According to the data given on the manual for the electrolyser operating instructions shown on table 4 the energy efficiency of the electrolyser is:

$$\eta_{\text{Energy}}^{\text{electrolyser}} = \frac{H_{H_2} \cdot V_{H_2 \text{ experimental}}}{U \cdot I \cdot t} = \frac{11920 \cdot 10^3 \cdot 7 \cdot 10^{-6}}{1.9 \cdot 1 \cdot 60} = 0.731 = 73.1\%$$

Session 2:

(i)

Current (mA)	Voltage (Volts)	Time (seconds)	V _{H2} (ml)
300	1.625	60	1.7

(ii)

Current (mA)	Voltage (Volts)	Time (seconds)	V _{H2} (ml)
300	1.625	60	1.8

(iii)

Current (mA)	Voltage (Volts)	Time (seconds)	V _{H2} (ml)
300	1.625	60	1.9

Table 24

$$V_{H_2 \text{ ave}} = \frac{(V_{H_2(i)} + V_{H_2(ii)} + V_{H_2(iii)})}{3} = \frac{(1.7 + 1.8 + 1.9)}{3} = 1.8 \text{ ml}$$

$$V_{H_2 \text{ theoretical}} = \frac{I \cdot t \cdot V_m}{z \cdot F} = \frac{0.3 \cdot 60 \cdot 24}{2 \cdot 96484} = 2.2 \text{ ml}$$

$$\eta_{Faraday} = \frac{V_{H2\text{experimental}}}{V_{H2\text{theoretical}}} = \frac{1.8}{2.2} = 0.81 = 81\%$$

The Energy Efficiency is:

$$\eta_{Energy} = \frac{H_{H2} \cdot V_{H2\text{experimental}}}{U \cdot I \cdot t} = \frac{11920 \cdot 10^3 \cdot 1.8 \cdot 10^{-6}}{1.62 \cdot 0.3 \cdot 60} = 0.73 = 73\%$$

The energy losses in session 2 are:

$$E_{loss} = (1.62 \cdot 0.3 \cdot 60) - (11920 \cdot 10^3 \cdot 1.8 \cdot 10^{-6}) = 7.7J$$

The losses due to internal resistance are:

$$E_{lossR} = I^2 \cdot R_i \cdot t = 0.3^2 \cdot 0.316 \cdot 60 = 1.70J$$

In this session it is obvious that despite the fact of having exactly the same amount of current and voltage as in session 1, the energy losses are much more than in the first session. The losses due to resistance though are the same because of the same values of current and voltage. Therefore the rest amount of losses is mainly activation and membrane losses. The porosity of the membrane is not always the same and may differ infrequently when it is in working condition. In addition, possible wears on the surface and the material of the membrane enable the amount of losses to become much more considerable.

Session 3:

(i)

Current (mA)	Voltage (Volts)	Time (seconds)	V _{H2} (ml)
300	1.625	60	1.9

(ii)

Current (mA)	Voltage (Volts)	Time (seconds)	V _{H2} (ml)
300	1.625	60	1.8

(iii)

Current (mA)	Voltage (Volts)	Time (seconds)	V _{H2} (ml)
300	1.625	60	2.0

Table 25

$$V_{H2ave} = \frac{(V_{H2(i)} + V_{H2(ii)} + V_{H2(iii)})}{3} = \frac{(1.9 + 1.8 + 2.0)}{3} = 1.9ml$$

$$V_{H2theoretical} = \frac{I \cdot t \cdot V_m}{z \cdot F} = \frac{0.3 \cdot 60 \cdot 24}{2 \cdot 96484} = 2.2ml$$

$$\eta_{Faraday} = \frac{V_{H2experimental}}{V_{H2theoretical}} = \frac{1.9}{2.2} = 0.86 = 86\%$$

$$\eta_{Energy} = \frac{H_{H2} \cdot V_{H2experimental}}{U \cdot I \cdot t} = \frac{11920 \cdot 10^3 \cdot 1.9 \cdot 10^{-6}}{1.62 \cdot 0.3 \cdot 60} = 0.77 = 77\%$$

The energy losses in session 3 are:

$$E_{loss} = (1.62 \cdot 0.3 \cdot 60) - (11920 \cdot 10^3 \cdot 1.9 \cdot 10^{-6}) = 6.51J$$

The losses due to resistance for this are:

$$E_{loss R} = I^2 \cdot R_i \cdot t = 0.3^2 \cdot 0.316 \cdot 60 = 1.70J$$

For this session it mostly applies the same as in session 2. The remaining amount of losses is mainly due to the porosity of the nafion membrane as well as due to activation loss.

Session 4:

In this session the current was changed to 400 mA and the voltage to 1.645 Volts.

(i)

Current (mA)	Voltage (Volts)	Time (seconds)	V _{H2} (ml)
400	1.645	60	2.8

(ii)

Current (mA)	Voltage (Volts)	Time (seconds)	V _{H2} (ml)
400	1.645	60	2.8

(iii)

Current (mA)	Voltage (Volts)	Time (seconds)	V _{H2} (ml)
400	1.645	60	2.6

Table 26

$$V_{H2ave} = \frac{(V_{H2(i)} + V_{H2(ii)} + V_{H2(iii)})}{3} = \frac{(2.8 + 2.8 + 2.6)}{3} = 2.73ml$$

$$V_{H2theoretical} = \frac{I \cdot t \cdot V_m}{z \cdot F} = \frac{0.4 \cdot 60 \cdot 24}{2 \cdot 96484} = 2.98ml$$

$$\eta_{Faraday} = \frac{V_{H2experimental}}{V_{H2theoretical}} = \frac{2.73}{2.98} = 0.91 = 91\%$$

$$\eta_{Energy} = \frac{H_{H2} \cdot V_{H2experimental}}{U \cdot I \cdot t} = \frac{11920 \cdot 10^3 \cdot 2.73 \cdot 10^{-6}}{1.645 \cdot 0.4 \cdot 60} = 0.82 = 82\%$$

In session 4, the energy losses calculated are:

$$E_{loss} = (1.645 \cdot 0.4 \cdot 60) - (11920 \cdot 10^3 \cdot 2.73 \cdot 10^{-6}) = 6.93J$$

In addition the resistive losses are:

$$E_{lossR} = I^2 \cdot R_i \cdot t = 0.4^2 \cdot 0.316 \cdot 60 = 3.03J$$

In this session is noticeable that despite the fact of raising the values of voltage and current, the amount of energy losses have not been raised dramatically. A big difference though can be seen in the value of resistive loss which is almost doubled than in the first three sessions. By increasing the value of current seems that it also influences the value of resistive loss significantly. In this case the most important loss is considered to be the resistive loss, however though the same losses discussed in the previous three sessions apply in this session too.

Session 5:

(i)

Current (mA)	Voltage (Volts)	Time (seconds)	V _{H2} (ml)
500	1.714	60	3.6

(ii)

Current (mA)	Voltage (Volts)	Time (seconds)	V _{H2} (ml)
500	1.714	60	3.5

(iii)

Current (mA)	Voltage (Volts)	Time (seconds)	V _{H2} (ml)
500	1.714	60	3.8

Table 27

$$V_{H2ave} = \frac{(V_{H2(i)} + V_{H2(ii)} + V_{H2(iii)})}{3} = \frac{(3.6 + 3.5 + 3.8)}{3} = 3.63ml$$

$$V_{H2theoretical} = \frac{I \cdot t \cdot V_m}{z \cdot F} = \frac{0.5 \cdot 60 \cdot 24}{2 \cdot 96484} = 3.73ml$$

$$\eta_{Faraday} = \frac{V_{H2experimental}}{V_{H2theoretical}} = \frac{3.63}{3.73} = 0.97 = 97\%$$

$$\eta_{Energy} = \frac{H_{H2} \cdot V_{H2experimental}}{U \cdot I \cdot t} = \frac{11920 \cdot 10^3 \cdot 3.63 \cdot 10^{-6}}{1.714 \cdot 0.5 \cdot 60} = 0.84 = 84\%$$

The energy losses and the resistive losses in session 5 are respectively:

$$E_{loss} = (1.714 \cdot 0.5 \cdot 60) - (11920 \cdot 10^3 \cdot 3.63 \cdot 10^{-6}) = 8.15J$$

$$E_{lossR} = I^2 \cdot R_i \cdot t = 0.5^2 \cdot 0.316 \cdot 60 = 4.74J$$

By raising the value of current to 0.5 A and having a voltage of 1.714 V the resistive losses take up more than 50% of the losses occur at this level which automatically make it the most significant out of all losses. This is of great importance since it does not only depend on the porosity and the resistance of the material of the membrane but also on the resistance of the equipment used such as wires. The rest amount of losses is distributed in activation and concentration loss, where it starts to be significant, plus possible leakage of hydrogen from the electrolyser.

Session 6:

(i)

Current (mA)	Voltage (Volts)	Time (seconds)	V _{H2} (ml)
600	1.723	60	4.0

(ii)

Current (mA)	Voltage (Volts)	Time (seconds)	V _{H2} (ml)
600	1.723	60	4.2

(iii)

Current (mA)	Voltage (Volts)	Time (seconds)	V _{H2} (ml)
600	1.723	60	4.2

Table 28

$$V_{H2ave} = \frac{(V_{H2(i)} + V_{H2(ii)} + V_{H2(iii)})}{3} = \frac{(4.0 + 4.2 + 4.2)}{3} = 4.13ml$$

$$V_{H2theoretical} = \frac{I \cdot t \cdot V_m}{z \cdot F} = \frac{0.6 \cdot 60 \cdot 24}{2 \cdot 96484} = 4.47ml$$

$$\eta_{Faraday} = \frac{V_{H2experimental}}{V_{H2theoretical}} = \frac{4.13}{4.47} = 0.92 = 92\%$$

$$\eta_{Energy} = \frac{H_{H2} \cdot V_{H2experimental}}{U \cdot I \cdot t} = \frac{11920 \cdot 10^3 \cdot 4.13 \cdot 10^{-6}}{1.723 \cdot 0.6 \cdot 60} = 0.79 = 79\%$$

In Session 6, the energy losses and the losses due to resistance are:

$$E_{loss} = (1.723 \cdot 0.6 \cdot 60) - (11920 \cdot 10^3 \cdot 4.13 \cdot 10^{-6}) = 12.8J$$

$$E_{lossR} = I^2 \cdot R_i \cdot t = 0.6^2 \cdot 0.316 \cdot 60 = 6.82J$$

In this case the losses due to resistance occupy 53.2% of all losses. Concentration loss also has become more significant than in the previous case, and holds an essential amount from the rest of the percentage of the losses, while activation loss cannot be considered to be very important at these levels of current.

Session 7:

(i)

Current (mA)	Voltage (Volts)	Time (seconds)	V _{H2} (ml)
700	1.735	60	5.0

(ii)

Current (mA)	Voltage (Volts)	Time (seconds)	V _{H2} (ml)
700	1.735	60	5.1

(iii)

Current (mA)	Voltage (Volts)	Time (seconds)	V _{H2} (ml)
700	1.735	60	5.0

Table 29

$$V_{H2ave} = \frac{(V_{H2(i)} + V_{H2(ii)} + V_{H2(iii)})}{3} = \frac{(5.0 + 5.1 + 5.0)}{3} = 5.03ml$$

$$V_{H2theoretical} = \frac{I \cdot t \cdot V_m}{z \cdot F} = \frac{0.7 \cdot 60 \cdot 24}{2 \cdot 96484} = 5.22ml$$

$$\eta_{Faraday} = \frac{V_{H2experimental}}{V_{H2theoretical}} = \frac{5.03}{5.22} = 0.96 = 96\%$$

$$\eta_{Energy} = \frac{H_{H2} \cdot V_{H2experimental}}{U \cdot I \cdot t} = \frac{11920 \cdot 10^3 \cdot 5.03 \cdot 10^{-6}}{1.735 \cdot 0.7 \cdot 60} = 0.82 = 82\%$$

$$E_{loss} = (1.735 \cdot 0.7 \cdot 60) - (11920 \cdot 10^3 \cdot 5.03 \cdot 10^{-6}) = 12.9J$$

$$E_{loss R} = I^2 \cdot R_i \cdot t = 0.7^2 \cdot 0.316 \cdot 60 = 9.29J$$

In session 7 resistive losses possess 72% out of all losses. As the amount of current and voltage has been increased to 0.7 A and 1.735 V respectively, the losses due to resistance have been raised dramatically. This is a proof that working in high currents, like most electrolyzers do in industry, the most important problem to overcome is to minimise the losses due to resistance. Concentration loss, which applies mostly to the rest 28% of the losses, is also significant at these levels of voltage and current but as it can be seen from the calculations above resistive losses are the ones that need to be minimised above all.

Current (mA)	Voltage (Volts)	Time (seconds)	V _{H2} (ml)	η _{Faraday} (%)	η _{Energy} (%)	Energy Loss (Joules)	Resistance Loss (Joules)
300	1.62	60	2.03	92	82.9	4.96	1.70
300	1.625	60	1.8	81	73	7.7	1.70
300	1.625	60	1.9	86	77	6.51	1.70
400	1.645	60	2.73	91	82	6.93	3.03
500	1.714	60	3.63	97	84	8.15	4.74
600	1.723	60	4.13	92	79	12.8	6.82
700	1.735	60	5.03	96	82	12.9	9.29

Table 30

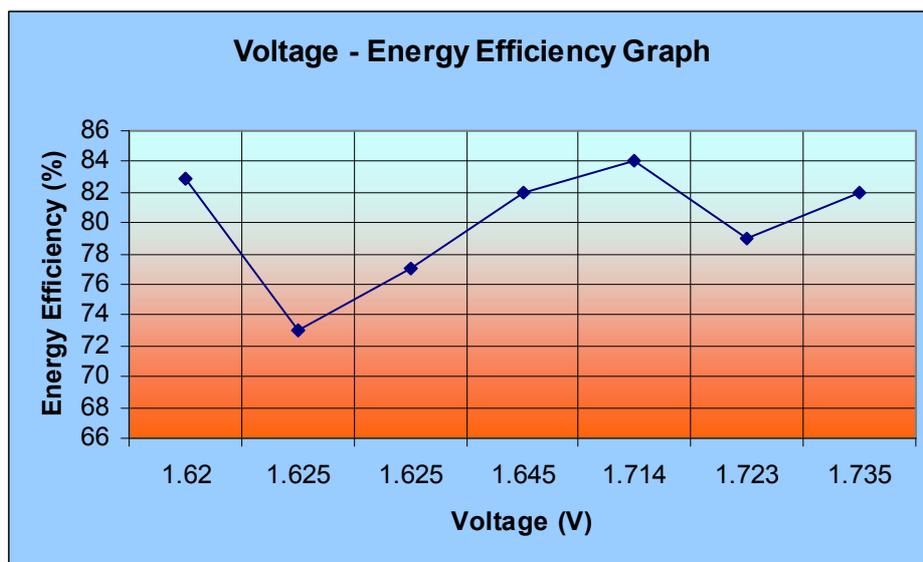


Figure 39: Voltage – Energy Efficiency Graph

The graph above represents the energy efficiency versus the voltage. It is obvious that by applying different values of voltage the energy efficiency varies. This is important for technical applications since it shows in general that as the voltage increases, the amount of hydrogen produced increases but the energy efficiency sometimes declines. This happens because of the amount of each loss that occurs at different values of voltage and current. The energy loss due to the internal resistance is also calculated and shows that as the amount of supplying current rises this loss becomes more significant. The factors that affect the internal resistance are the membrane used in the PEM electrolyser and the wires used to connect the equipment. Therefore the efficiency of the electrolyser is affected since an amount of hydrogen is lost due to the conductive material of the membrane as well as the physical properties of the wires. In addition this is the reason that the Faradaic efficiency is much less than 100%. The experimental volume of hydrogen produced is lower than the theoretical and therefore the efficiency is much below than 100%. Moreover there is difference in the values of energy efficiency obtained from the experimental results and the energy efficiency calculated from the operating data of the electrolyser. The values used are the maximum values of Voltage, Current and Hydrogen produced. Different results are obtained when the electrolyser operates at different voltage and current values due to the factors discussed above.

Also, the overpotential at each different value is a factor that affects the efficiency of the electrolyser. This applies to this experiment in the values of 1.723

and 1.735 Volts. Therefore, in practice an optimum operating point must be found for each electrolyser with the purpose of the energy efficiency to be as high as possible since electrical energy is expensive.

9. Comparison between Experimental and Theoretical Results:

Both experimental and theoretical results of this thesis were interesting about the proton exchange membrane electrolyser. The numbers on the experimental sessions show that there is a difference with theoretical predictions. The Faradic and energy efficiency for different amount of voltage and current are shown below.

Current (mA)	Voltage (Volts)	Time (seconds)	V _{H2} (ml)	η_{Faraday} (%)	η_{Energy} (%)
300	1.62	60	2.03	92	82.9
300	1.625	60	1.8	81	73
300	1.625	60	1.9	86	77
400	1.645	60	2.73	91	82
500	1.714	60	3.63	97	84
600	1.723	60	4.13	92	79
700	1.735	60	5.03	96	82

Table 31

The Faradic efficiency of the electrolyser expresses how much of the current is converted in the desired reaction. In order the electrolyser to be efficient, Faradic efficiency must be close to 100 %. In case it is much smaller than one, it would mean that there were several reason and reactions that were affecting the system such as corrosion. This would be a huge disadvantage, especially for commercial electrolysers, since not only it would shorten the service of the electrolyser but also it would result in high-energy input, which is economically inefficient.

In the experimental session, the current used varies between 300 mA and 700 mA. The reason of picking such values was that below 300 mA, the amount of hydrogen produced was not that high to have reliable results and above 700 mA the rate of production was too high that the scale of the electrolyser would definitely result in false readings. The maximum energy efficiency achieved was 84 % where 3.63ml of hydrogen produced in sixty seconds using a current of 500 mA. The minimum was produced at 300 mA in the second session of experiments and it was 73%. The first session of the experiments was mostly done to verify the correct

operation of the electrolyser and the results should not be considered much reliable. The graph showing the efficiency of the proton exchange membrane electrolyser, as per the experimental results, is shown above the graph involving the theoretical efficiency predicted as it is previously shown in Figure 10.

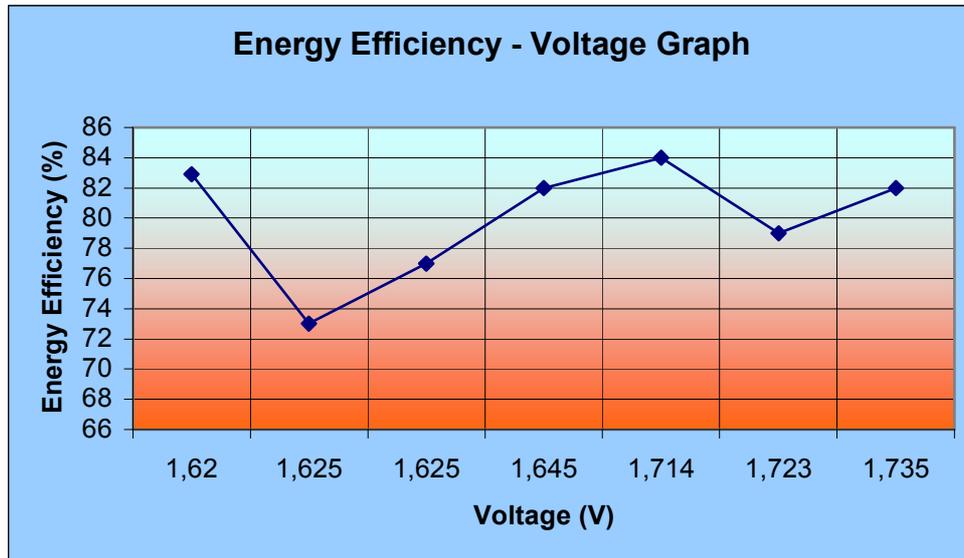


Figure 39: Energy Efficiency – Voltage Graph

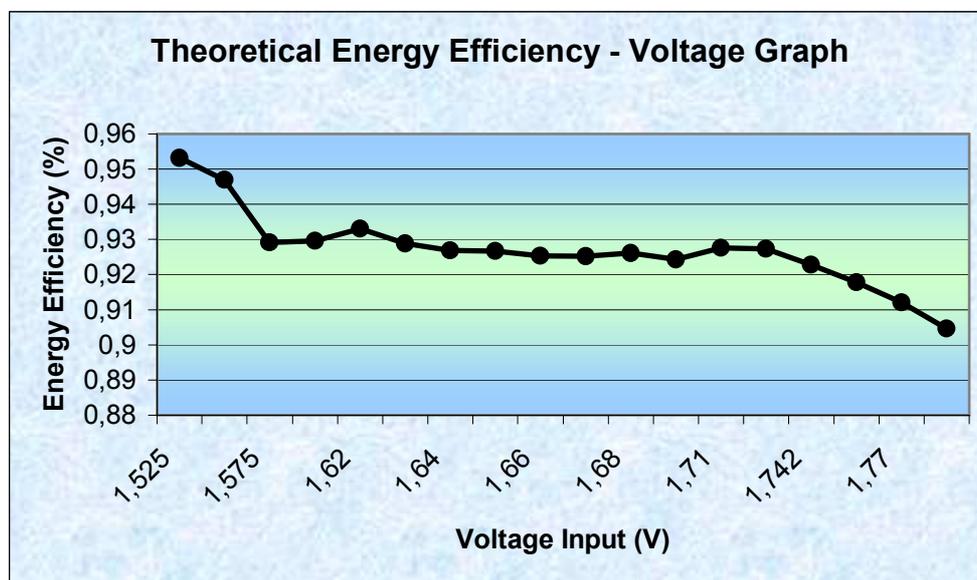


Figure 10: Theoretical Energy Efficiency – Voltage Graph

It can be seen from the efficiency graphs above that there is a big difference between the theoretical and experimental efficiency predicted. Theoretically, the largest efficiency of the proton exchange membrane electrolyser is achieved at

1.525V and it is 95.3% while in the experimental sessions the highest efficiency was achieved at 1.714 V and it is 84%.

The differences of theoretical and experimental efficiencies are due to three main types of losses that take place and affect the hydrogen production. Activation loss that occurs at low currents, ohmic loss that takes place throughout the process and concentration loss that is significant at high currents. Combining the sensitivity analysis with the experimental results the most important parameter that affects the efficiency of the electrolyser is the ohmic loss. The sensitivity analysis of internal resistance shown in figure 16 presents the influence of the resistance in the hydrogen production. Several values from 0.1 Ω to 0.316 Ω were plotted and the difference is obvious for every selected value. By reducing the value of resistance from 0.316 Ω to 0.2 Ω there is almost an improvement of 33% in the hydrogen production rate. Resistive losses occur because of the equipment used and the physical properties of the membrane. Better quality of wires and insulation would result in decrease of ohmic loss and will increase the hydrogen production dramatically since it is the most important factor of losses. Also changes to the nafion membrane will result in the increase of the efficiency. A bigger area of the membrane used will affect the hydrogen production positively since nafion is a low resistive membrane and it is the most preferred out of all types of membranes. In addition by minimizing the thickness of this membrane to the minimum and keeping it constantly humidified would result in reducing the amount of losses due to resistance. Thin film composite membranes could also be used for the same purpose but they consist of two or three layers and the conductivity is low due to high resistive values and therefore this result in even lower efficiency.

As for activation and concentration loss that occur at low and high amounts of current respectively the most important factor to minimize these losses is temperature. Both are depended upon temperature and the only way to improve the efficiency of the electrolyser based on these losses is to achieve low temperature operating conditions using appropriate insulating material for the equipment. Also a nafion membrane would be better to be used than other membranes since nafion can remain intact at both high and low temperatures without affecting its conductivity.

It is of great importance to mention that in the experimental graph, as the voltage increases, the efficiency curve is increasing with the exemption in the value of 1.723 Volts. On the other hand, the efficiency curve representing the theoretical

calculations is decreasing as the voltage increases. This difference means that in reality, the losses taking place in the electrolysis process are greater than they can be measured in theory because there are also external factors that affect efficiency such as corrosion, overuse of the equipment and replacement of faulty parts. In order to achieve high efficiencies in practice, the overpotential must be minimised along with any other factor, except losses, that would directly affect the electrolyser.

10. Conclusions:

The aim of this project was to investigate the efficiency of electrolysis and examine the factors that directly affect it. A proton exchange membrane electrolyser was used to carry out several experiments in order to study the volume production of hydrogen and to be able to calculate the efficiency based on practical results. According to the theoretical efficiency, for this specific electrolyser, the experimental results were impressive since the experimental efficiency was reaching around 80 % in average. Commercial electrolysers have the potential to reach an efficiency of up to 90 % but when large quantities of hydrogen are involved, even the smallest increment would make a large difference.

Also, the scale mounted on the electrolyser's tubes was not very accurate and therefore some of the results could slightly be different. The scale was in ml units without any decimal values in some readings there could be a slight error of ± 0.1 ml. This of course would not effect that much the final calculation, as the units that were chosen to work are quite low but that could be considered a difficulty in collecting 100 % accurate readings.

An important part of this thesis is the theory used to predict each loss. There are three types of losses in electrolysis and are taking place in a specific order. Activation loss is important when the process of electrolysis starts and occurs at low currents. Ohmic loss is the only one that can be considered the most significant and occurs throughout the electrolysis process for as long as a current flows. Finally, concentration loss exists only at high values of current. All losses were calculated for all values of current between 0.1 A to 0.9 A in increments of 0.1 A. After a certain value, activation loss becomes insignificant and the same occurs with concentration loss at low levels of current. The factor that is the most important for these losses is temperature. Both concentration and activation loss are proportional to the temperature. The sensitivity analysis shows that as temperature increases, activation and concentration loss increases too. For high amounts of current both losses become significant and if temperature is high these losses deduct an important amount of hydrogen produced. The only way to minimise these losses is to operate the electrolyser at low temperatures where the both losses, no matter the amount of current used, are at their minimum values.

Ohmic loss applies as soon as the current starts to flow, it is the most important out of all losses and it cannot be avoided. Several ways to minimise it such as the use of a low resistance membrane, the permeability of the membrane, the choice of a suitable value of current and voltage where resistive losses could hold a low amount and the use of different type of wires of low resistance to allow more current passing through at low voltage are suggested.

Also, the overpotential is a major source of loss in the electrolyser. Overpotential is small in the case of electrode reactions that lead to the deposit of metals; however it can be particularly large when gases (H_2 , O_2 , Cl_2) are released. In order to keep the overpotential to a minimum the electrodes used must be suitable for water or any other medium that will be used in the electrolyser, i.e. KOH, and also the electrolyte materials specifications, such as temperature, must be appropriate for the specific medium used.

According to the literature review, there are other types of losses too but depending on the equipment used, these were difficult and some impossible to verify considered to the results. In different electrolysers and different types of equipment, especially commercial electrolysers, these losses would definitely be included in the calculations concerning the theoretical predictions.

Some future work that could be done would be to create an economic model for proton exchange membrane electrolysers. A comparison of the efficiency and what would be economically feasible for the companies according to the demand of hydrogen in the market would be a topic worth of investigation.

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