LMAPR2231 : Lab report - Fuel cell

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1 Theoretical background

At standard conditions, determine the Gibbs free energy change of the overall electrochemical reaction of a PEM fuel cell and the theoretical maximum voltage a fuel cell can deliver. →Done
Do the same reasoning with a PEM electrolyzer producing oxygen and hydrogen (picture, equation etc...). →Done
What is the theoretical minimum voltage to apply in order to activate the electrolyzer? →TO DO

For a PEM fuel cell, the reactions at the electrodes are:

$$H_{2(g)} \rightarrow 2H^+_{(aq)} + 2e^- \tag{1}$$

$$O_{2(g)} + 4e^- + 4H^+_{(aq)} \rightarrow 2H_2O_{(l)} \tag{2}$$

where eq.(1) is the reaction at the anode and eq.(2) is the reaction at the cathode. Thus, the overall reaction is given by:

$$O_{2(g)} + 2H_{2(g)} \rightarrow 2H_2O_{(l)}$$

At the standard conditions, we can determine the Gibbs free energy change of the overall electrochemical reaction from the cell potential at those conditions thanks to this formula:

$$-\Delta G^\circ = n \cdot F \cdot V^\circ_{eq} \tag{3}$$

where $V^\circ_{cell,eq} = V^\circ_{cathode} - V^\circ_{anode}$, n is the number of electrons involved in the reaction, 4 in this case, and F is the Faraday constant. From the table of standard electrode potential, we have that $V^\circ_{anode} = 0$ and $V^\circ_{cathode} = 1.229$ so, $V^\circ_{cell,eq} = 1.229$ and $G^\circ = -474.32\frac{kJ}{2mol(H_2O)} = -237.16\frac{kJ}{mol} = -56.64\frac{kcal}{mol}$ which correspond approximately (probably some rounding errors) to the value given in the first blue row from table in Figure 1.

Theoretical Cell Potentials of Various Oxidation Reactions at 25°C

Fuel	Reaction	ΔG^0, kcal mole^{-1}	V_e^0, V
Hydrogen	$H_2 + \frac{1}{2}O_2 \rightarrow H_2O$	−56.69	1.229
	$H_2 + Cl_2 \rightarrow 2HCl$	−62.70	1.370
Propane	$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O$	−503.90	1.093
Methane	$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$	−195.50	1.060
Carbon monoxide	$CO + \frac{1}{2}O_2 \rightarrow CO_2$	−61.45	1.333
Ammonia	$NH_3 + \frac{3}{4}O_2 \rightarrow \frac{3}{2}H_2O + \frac{1}{2}N_2$	−80.8	1.170
Methanol	$CH_3OH + \frac{3}{2}O_2 \rightarrow CO_2 + 2H_2O$	−168.95	1.222
Foraldehyde	$CH_2O + O_2 \rightarrow CO_2 + H_2O$	−124.7	1.350
Formic acid	$HCOOH + \frac{1}{2}O_2 \rightarrow CO_2 + H_2O$	−68.2	1.480
Hydrazine	$N_2H_4 + O_2 \rightarrow N_2 + 2H_2O$	−143.9	1.560
Zinc	$Zn + \frac{1}{2}O_2 \rightarrow ZnO$	−76.05	1.650
Sodium	$Na + \frac{1}{2}H_2O + \frac{1}{4}O_2 \rightarrow NaOH$	−71.84	3.120
Carbon	$C + O_2 \rightarrow CO_2$	−94.26	1.020

Figure 1: Theoretical cell potentials and Gibbs free energy change at standard conditions of various oxidation reactions

The same reasoning can be done for a PEM electrolyzer producing oxygen and hydrogen. The reactions at the electrodes in this case would be:

$$2H_2O_{(l)} \rightarrow O_{2(g)} + 4e^- + 4H^+_{(aq)} \tag{4}$$
$$4H^+_{(aq)} + 4e^- \rightarrow 2H_{2(g)} \tag{5}$$

where eq.(4) is the reaction at the anode and eq.(5) is the reaction at the cathode. Thus, the overall reaction is given by:

$$O_{2(g)} + 2H_{2(g)} \rightarrow 2H_2O_{(l)}$$

The standard electrode potential at the anode and the cathode are respectively $V^\circ_{anode} = 1.229$ and $V^\circ_{cathode} = 0$ which gives a negative standard cell potential $V^\circ_{cell,eq} = -1.229$ and thus a positive Gibbs free energy at the standard condition $G^\circ = 474.32\frac{kJ}{2mol(H_2O)} = 237.16\frac{kJ}{mol} = 56.64\frac{kcal}{mol}$. This global reaction is thus not thermodynamically favored at the standard conditions.

2 Lab 1: Basic study of water electrolyzers and fuel cells

Materials list for the lab:

- an electrolyzer (PEM electrolysis) and a fuel cell
- a power source
- a hydrogen and oxygen storage reservoir
- 2 multimeters
- a measurement board
- electric cables and connecting tubes

TO DO: ADD picture of set up for exp1 & 2

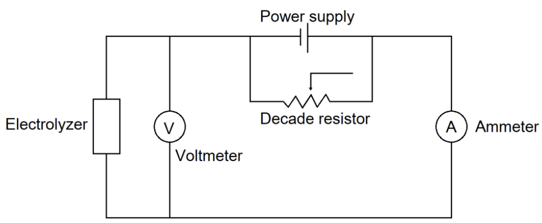

Figure 2: Schematic set up of experiment 1 and 2

On Figure **??**, we can see the experimental set up for experiment 1 & 2. We reproduced the set up that was schematically represented on Figure 2.

At the top left we have the electrolyzer already connected to a hydrogen and an oxygen storage reservoir by tubes at his right and left side respectively. The electrolyzer is also connected to the measurement board at Port 1 by electric cables. The power source supply the circuit with electricity and is connected to it at Port 2. The different resistors are already part of the measurement board and can be modified using a rotary knob. For the measurements, we also have a voltmeter and an ammeter that are connected to the left and right side of the measurement board respectively.

On Figure 3, we can see the experimental set up for experiment 3 & 4. We reproduced the set up that was schematically represented on Figure 4.

At the top left we have the hydrogen reservoir that is connected to the fuel cell (middle left) by a tube at the anode. At the cathode we have a one side connected tube that let the oxygen comes from the air. The tube that let the outlet gases come out from the fuel cell at the anode is closed by a clamp to avoid any loss of hydrogen. The fuel cell itself is connected to the measurement board at Port 1 by electric cables. We still have a voltmeter and an ammeter at the same places as for experiment 1 & 2 for the measurements but no longer a power source at Port 2 since it is directly generated by the fuel cell.

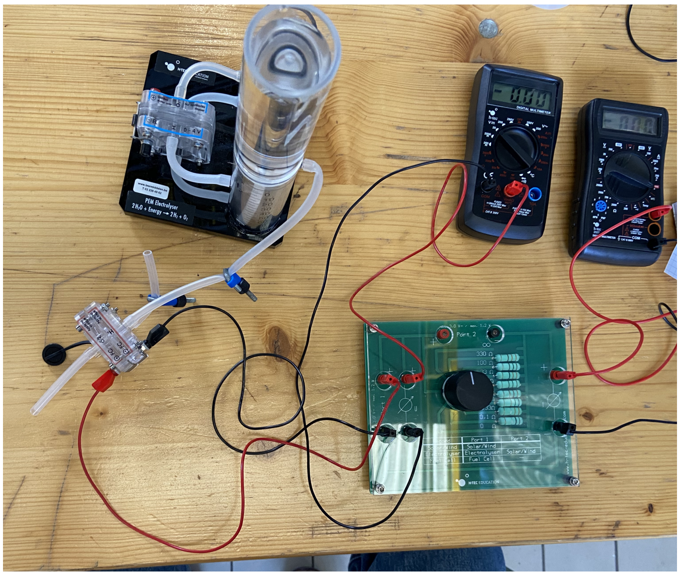

Figure 3: Set up for experiment 3 and 4

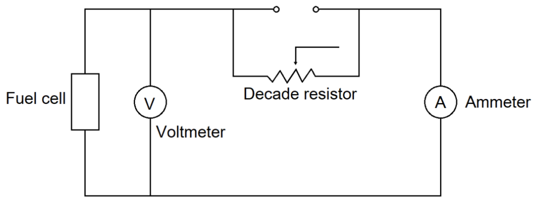

Figure 4: Schematic set up of experiment 3 and 4

2.1 Experiment 1: Current-voltage characteristic of a water electrolyzer

TO DO: What is the experimental water decomposition voltage you obtain? Compare to the theoretical value calculated before and explain the difference.

R	V	I	Observations
0	0	0	-
0.1	0.105	0	-
0.33	0.67	0	-
1	1.43	0	
3.3	3.19	0.24	
10	3.52	0.8	
33	3.64	1.04	
100	3.68	1.1	
330	3.69	1.14	

Table 1: Measured current and voltage when varying resistance

2.2 Experiment 2: Energy efficiency and Faraday efficiency of a water electrolyzer

TO DO: Calculate the energy efficiency of the electrolyzer. The energy efficiency η_{en} is the ratio of the usable energy and input energy. The usable energy is the chemical energy stored in the produced hydrogen, while the input energy is the electrical energy consumed by the electrolyzer. For the usable energy, you can choose between the high heating value and the low heating value for hydrogen, justifying your choice. Compare the energy efficiency with the Faraday efficiency and interpret your results.

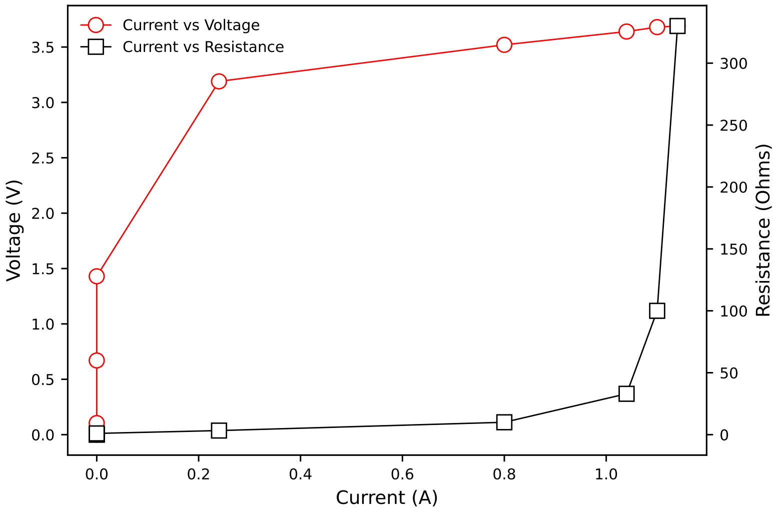

Figure 5: I-V curve of water electrolyzer

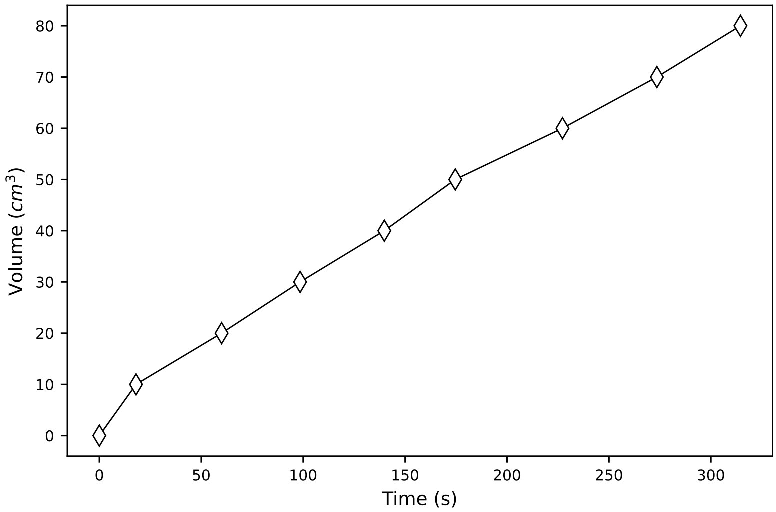

Figure 6: Produced volume of H_2 as a function of time

For this experiment, we chose a resistance of 33Ω. From experiment 1, we saw that the higher the resistance, the higher the power. But to be comfortable to take the measurements, we decided to make a trade off between efficiency and accuracy of the data and 33Ω seemed to be a good choice.

The average production rate is obtain by taking the mean of $\frac{\Delta v}{\Delta t}$ between each successive points. This gives us a average production rate for this experiment of 0.276 cm^3/s.

From the assumption that the produced hydrogen is dry and an ideal gas, we can found the theoretical volume

$$v_{theo} = \frac{nRT}{p}$$

where T is the ambient temperature and p the atmospheric pressure. The number of moles n is related to time t and current i by Faraday's law of electrolysis as $i \cdot t = n \cdot z \cdot F$ where z is the number of electron involved in the reaction which is 4 in our case. This gives:

$$v_{theo} = \frac{i \cdot t \cdot R \cdot T}{z \cdot F \cdot p}$$

The table below gives the v_{exp}, v_{theo} and η_{Farad} associated to the time and current points taken during the experiment as

$$\eta_{Farad} = \frac{v_{exp}}{v_{theo}}$$

v_{exp} $[cm^3]$	i [A]	t [s]	v_{theo} $[cm^3]$	η_{Farad} [%]
0	0	0	0	-
10	1	18	11.22	89.1
20	0.98	60	36.65	54.6
30	0.98	98.5	60.17	49.9
40	0.97	139.8	84.52	47.3
50	0.97	174.6	105.56	47.4
60	0.97	227.2	137.36	43.7
70	0.97	273.5	165.35	42.3
80	0.97	314.5	190.14	42.1

Table 2: Experimental volume, theoretical volume and Faradic efficiencies of experiment 2

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Energy efficiency:

$$\eta_{en} = \frac{\Delta G}{E_{elec,consumed}}$$

2.3 Experiment 3: Voltage-current characteristic and power curve of a PEM fuel cell

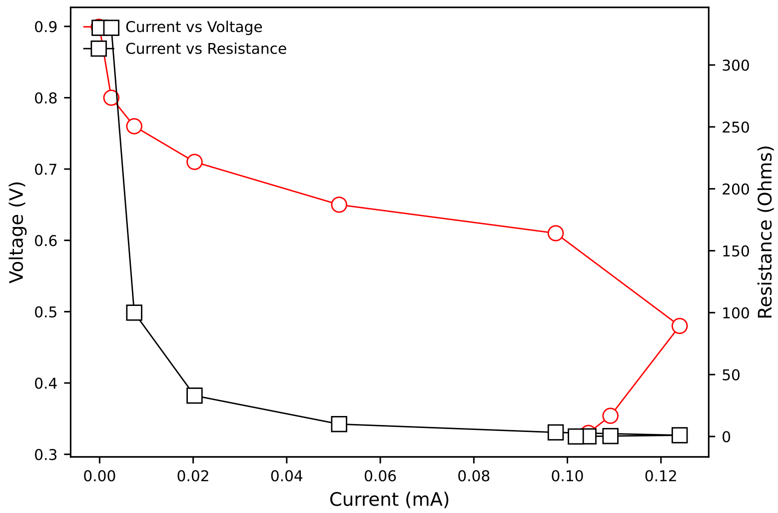

Figure 7: I-V curve of fuel cell (in red)

Power is given by $P = I \cdot V$.

From Figure 8, we find that we have a maximum power for a resistance of 1Ω. The Maximum Power Point (MPP) is reached at a current of 0.124 A and the power at this point is of 59.52 mW.

2.4 Experiment 4: Energy efficiency and Faraday efficiency of a fuel cell

TO DO: Calculate the energy efficiency and the Faraday efficiency of the fuel cell. Compare the energy efficiency with the Faraday efficiency and interpret your results.

To calculate the efficiencies, we do the same methodology as in experiment 2. The results for the Faradic efficiency lies in Table ??.

3 Bibliography

- *Standard electrode potential (data page)*. Wikipedia. `https://en.wikipedia.org/wiki/Standard_electrode_potential_(data_page)`

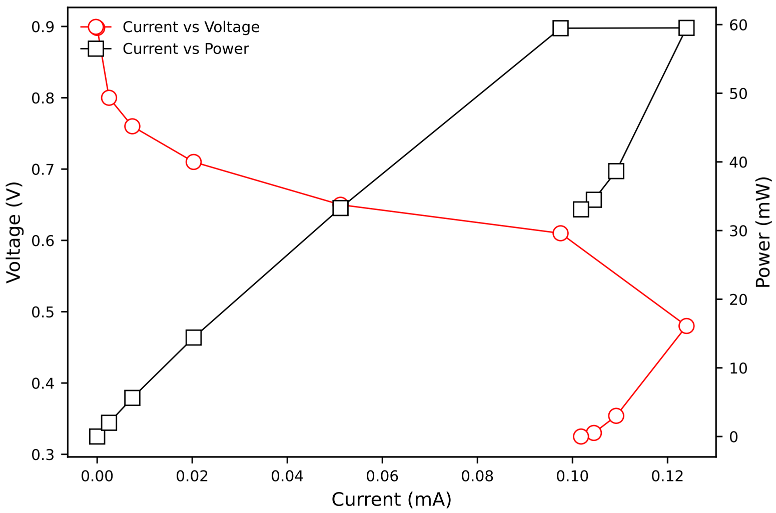

Figure 8: Power output vs current (in black)

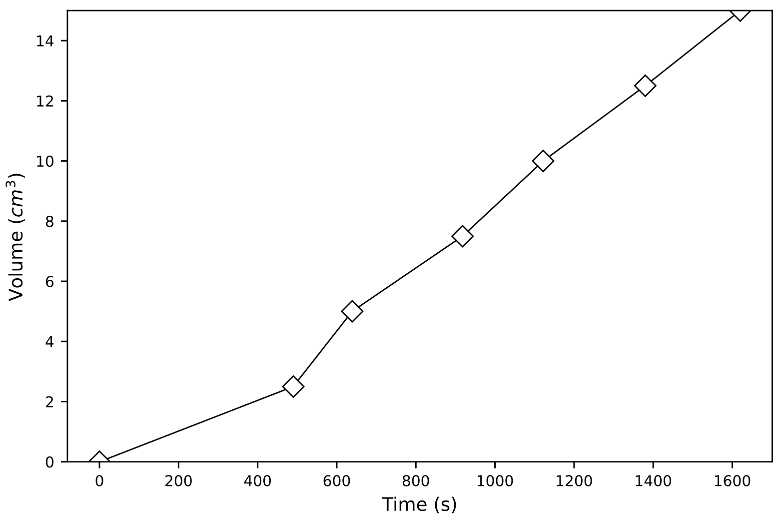

Figure 9: Consumed volume of H_2 as a function of time

v_{exp} $[cm^3]$	i [A]	t [s]	v_{theo} $[cm^3]$	η_{Farad} [%]
0	0.055	0	0	-
2.5	0.0762	490	23.27	10.7
5	0.078	639	31.07	16.1
7.5	0.0791	918	45.26	16.6
10	0.0786	1122	54.97	18.2
12.5	0.0786	1380	67.61	18.5
15	0.0786	1620	79.36	18.9

Table 3: Caption