47202 I.F.E.   Problems, Lecture 10   2023
Solutions

Short questions

1. Which types of fuel cell have equivalent electrolyzer sisters and which do not?

AFC, PEMFC and SOFC do.

PAFC, DMFC and MCFC do not

It is possible to make electrolyzers within all the systems, but the advantages are not obvious in all cases. PAFC is one of the early fuel cells, fit for integration with a reformer causing traces of CO. CO tolerance is not relevant to electrolyzers and phosphate poisoning of the Pt, the PAEC is not very attractive. Methanol synthesis in electrolyzer cells is under development, but only in the labs. It is a complicated thing. MCEC is possible, but why not go for SOEC instead. The CO2 component complicated thing and is more obvious in power plants powered by carbonaceous fuels.

2. What are the main advantages and drawbacks of the alkaline electrolyzer?

Advantages: mature, relatively low cost, no limited materials, long lifetime

Disadvantages: Low rate capability, limited pressurability, poor with dynamic operation in some cases.

3. What are the main advantages and drawbacks of the PEM electrolyzer?

Advantages: high current density, small footprint, only pure water in the system, high pressure capability, good with dynamic operation.

Disadvantages: high cost, dependence on iridium, crossover.

4. What are the main advantages and drawbacks of the solid oxide electrolyzer?

Advantages: High voltage efficiency, high electrical efficiency.

Disadvantages: immature, less simple system due to the high temperature, sensitive to dynamic operation in some cases.

5. Which electrolyzer types are fully commercial today?

AEC (with diaphragm) and PEMEC.

6. Which type of electrolyzer has typically the highest voltage efficiency?

SOEC

7. Which type of electrolyzer has typically the highest current density?

PEMEC

8. Why is the alkaline electrolyzer the first commercial and still the most common electrolyzer type while the alkaline fuel cell is not?

The alkaline fuel cell is sensitive to CO_2 in the air. If the fuel cell is operated on air, as usual, the electrolyte carbonates, i.e., forms carbonate. In the electrolyzer, air is not entering the cell.

9. Why is mass transport limitations not seen very often on the polarization curves of low temperature electrolyzers?

Mass transport limitations are indicated by an increasing slope of the polarization curve at high current, because reactants are partly exhausted near the reaction sites. Low temperature electrolyzers are fed with liquid water (not vapour) and as a condensed phase, the water contains a much higher concentration of reactant molecules than a gas phase. From that perspective, exhaustion of water would require a current several orders of magnitude larger. That said, entrapment of bubbles may cause transport problems, but then the polarization curve normally becomes more chaotic/noisy instead.

10. Water management is a classical challenge in PEM fuel cells. Is that also the case for PEM electrolyzers? Why?

No. Because the electrodes are flooded, the wetting is optimal in the electrolyzer. I the fuel cell, the electrode must not be flooded because it hinders access of the reactant gas.

11. The PEM electrolyzer is considered the most compact electrolyzer (smallest footprint). Explain why

I is capable of a high production rate per volume, because the electrolyte resistance is low.

12. The traditional alkaline electrolyzer can be pressurized moderately, but, in contrast to the PEM electrolyzer, only with symmetric pressure. Why is that?

The separator (the diaphragm) is porous. With unbalanced pressure the electrolyte in the pores may be pushed through. Electrolyte will build up at the low pressure side and eventually, the pores may blow out leading to gas mixing.

13. Why is the alkaline system more suited for electrolyzers than for fuel cells?

The classical problem of the alkaline fuel cell is carbonization. CO_2 from the cathodic air reacts with KOH and form K_2CO_3 (potassium carbonate) which is less soluble and may precipitate in the electrode pores. I moreover reduces the ionic conductivity. This problem is not relevant in the alkaline electrolyzer, since no air is entering the cell.

14. Does the Sabatier reaction increase or decrease the energy content of the fuel (the generated methane with respect to consumed hydrogen)?

The ΔH of the process is negative this means that it is exothermal, i.e., that energy is liberated. First law (energy conservation) dictates that the energy of the fuel must be less by the same amount.

Solutions

15. In a future fossil free energy system, how can we cover the need for energy for transport without electrolyzers? Can we have a fossil free energy system without electrolysis?

Probably not.

Calculations:

16. One stack of the electrolyzer plant in Zimbabwe produced 760 Nm^3 h^{-1}. If we assume 75 % efficiency (HHV), then what is the nominal electrical power? (the Nm^3 at 0 °C)

Use Table 2 in text, assume that water enters as a liquid and use HHV numbers.
At 100 % efficiency (HHV), $P_{100\%}$ = 760 Nm^3 h^{-1} · 3.54 kWh Nm^{-3} = 2690 kW
At 75 % efficiency (HHV), $P_{75\%}$ = 2690 kW/0.75 = 3587 kW = 3.6 MW

17. If an electrolyzer needs 4.2 kWh Nm^{-3} of hydrogen (the Nm^3 at 0 °C), what is the higher heating value (HHV) efficiency?

The minimum HHV energy consumption is 3.50 kWh/Nm^3 (energy pr. normal cubic meter calculated at 0 °C). This corresponds to 100 % electrical efficiency since only the energy that is contained in the hydrogen is consumed by the system. Efficiency is what you get divided by what you pay:

$\eta = \dfrac{3.54 \text{ kWh/Nm}^3}{4.2 \text{ kWh/Nm}^3} = 0.84 = \underline{84\ \%}$

18. A traditional alkaline electrolyzer operates at 0.5 A cm^{-2}. With large round cells of 1 meter diameter, and with 500 cells in a stack and with a power demand of 4.5 kWh Nm^{-3} Hydrogen (0 °C), how many stacks are needed to match a 3 MW wind turbine?

Strategy: Find the total current, then the charge converted per cell per time. From charge per time, get mole hydrogen per time and then normal cubic meter hydrogen per time. Then calculate the power consumption and compare.

Current: $I = A \cdot i = (50\ cm)^2 \pi \cdot 0.5$ A cm^{-2} = 3927 A . This is 3927 C s^{-1} cell^{-1}.

The total charge converted is $\dot{Q}$ = 3927 C s^{-1} cell^{-1} X 500 cells = 1,963,500 C s^{-1}.

The number of moles hydrogen formed pr. second is $\dot{n} = \dfrac{\dot{Q}}{2F} = \dfrac{1963500 \text{ C s}^{-1}}{2 \cdot 96485 \text{ C mol}^{-1}} = \underline{10.18\ \text{mol}}$ s^{-1}

The volume pr. time is $\dot{V} = \frac{\dot{n}RT}{P} = \frac{10.18 \text{ mol s}^{-1} \cdot 8.314 \text{ J mol}^{-1} 273\text{K}^{-1}}{10^5 \text{ Pa}} = 0.231 \text{ m}^3 \text{ s}^{-1} = \underline{832 \text{ m}^3 \text{ h}^{-1}}$

The electrical power required to run the electrolyzer is $\dot{W}$ = 4.5 kWh/m^3 X 832 m^3 h^{-1} = 3744 kW = 3.7 MW

It is a little more than needed for the 3 MW wind turbine. One electrolyzer will do.

19. The annual production of iridium is less than 10 ton. In 2016 it was 7.1 ton. Assuming 1 mg Ir pr. cm^2 and a rated electrical power of 2 W cm^{-2}, what would the total power be if the total amount of Ir was used for PEM electrolyzers in 2016?

    How big a fraction of the world energy consumption of ca 18 TW would that be?

Total: $7.1 \cdot 10^9$ mg Ir

$P = \frac{7.1 \cdot 10^9 \text{ mg } 2 \text{ W } cm^{-2}}{1 \text{ mg } cm^{-2}} = 14.2 \cdot 10^9 \, W = \underline{14.2 \text{ GW}}$

This is less than 1/1000 of the global energy demand. With lower Ir loading the maximum power can increase correspondingly.

20. An electrolyzer in a hydrogen fuelling station operates in a continuous mode consuming 5 kWh Nm^{-3} hydrogen (use 1 atm and 0 °C for the normal cubic meter).

    a) Which overall efficiency does that correspond to with respect to HHV and LHV?

HHV = 285.8 kJ/mol, LHV = 241.8 kJ mol^{-1}

5 kWh = 5*3600 kJ = 18000 kJ

1 Nm^3: $n = \frac{PV}{RT} = \frac{1.0135 \cdot 10^{-5} \text{ Pa} \cdot 1 \text{ m}^2}{8.314 \text{ J mol}^{-1}\text{K}^{-1} \cdot 273.15\text{K}} = \underline{44.63 \text{ mol}}$

Energy consumption: 18000 kJ/44.63 mol = 403.3 kJ mol^{-1}

η_{HHV} = 285.8 kJ mol^{-1}/ 403.3 kJ mol^{-1} = 0.7087 = 70.9 %

η_{LHV} = 241.8 kJ mol^{-1}/ 403.3 kJ mol^{-1} = 0.5996 = 60.0 %

Alternative:

Use ideal values from slide: HHV (0 °C, 1 atm) 3.54 kWh m^{-3}

                                    LHV (0 °C, 1 atm) 3.00 kWh m^{-3}

η_{HHV} = 3.54 kWh m^{-3}/ 5 kWh m^{-3} = 0.708 = 70.8 %

η_{LHV} = 3.00 kWh m^{-3}/ 5 kWh m^{-3} = 0.600 = 60.0 %

Solutions

b) If balance of plant components consumes 10 % of the total electrical energy, what is the cell voltage (assuming all cell perform identically)?

$\eta_{HHV} = E_{TN} / E_{cell} \Rightarrow E_{cell} = E_{TN} / \eta_{HHV}$

10 % for BOP, then 90 % for the process.
Conversion efficiency (HHV, the cell alone) = 70.9% /0.90 = 78.78 %

$E_{cell} = E_{TN} / \eta_{HHV}$ = 1.48 V / 78.78 % = <u>1.88 V</u>

c) How much water is needed for the production of 4 kg (the need of a typical FC vehicle) of hydrogen under these conditions?

M_{H2} = 2 g mol^{-1}, M_{H20} = 18 g mol^{-1}. Ratio 1:9

4 kg H_2 is made from 4*9 kg of water, i.e. <u>36 kg = 36 L</u>