47202 I.F.E. Problems, Lecture 9 2023
Solutions

Short questions

1. Which transport processes take place in a fuel cell?

Transport of gasses through the electrode and the gas diffusion layer

Transport of electrons through the electrode and the gas diffusion layer

Transport of heat through the electrode and the gas diffusion layer

Transport of ions through the electrode

Transport of ions through the electrolyte

2. Does the electrolyte always have to be an ion conductor (could it be an electron conductor instead)?

Yes (no). The only useful way to close the electrical circuit is to conduct the formed ions. The circuit can also be closed by an electronic conductor, but then the cell is short circuited and no hydrogen production (electrolyzer) or electricity production (fuel cell) will take place.

3. Why does the polymer in a PEMFC need to be humidified?

The transport of hydrogen ions (protons) can only happen if water is present. The proton cannot jump between the sulfonic acid groups; it has to sit on something all the time, and on a water molecule it becomes mobile – either with the water molecule as shuttle.

4. What is the purpose of the catalysts?

A catalyst eases a chemical or an electrochemical process. It takes part in the process, but is not consumed. Without the catalyst, the overvoltage would be so big that the cell would not work at all.

5. Why is an SOFC very efficient at the high working temperature when the free energy of reaction decreases with temperature?

Due to excellent kinetics resulting from the high operating temperature. Thermodynamics is not favored by high temperature, but kinetics is.

6. What limits the theoretical maximum efficiency of a hydrogen powered fuel cell?

Thermodynamics. The net consumption of gas molecules reduces entropy and therefore part of the energy liberated from the process must be used to give back that entropy. Consequently, the free energy for generating work is less.

7. What limits the practical efficiency of a hydrogen powered fuel cell?

In addition to thermodynamics, overvoltages. Ohmic resistance, mainly in the electrolyte and kinetic resistance in the electrode. Due to these overvoltages, which scale with current, the cell is closest to maximum efficiency at low currents and mass transport limitations do not play a role there.

8. The common types of fuel cells uses electrolytes, which conduct either OH-, H^+ and O^{2-} or CO_3^{2-}. Can you imagine another electrolyte conducting other species?

In principle, other electrolytes can be developed, but the ions conduced have to be part of the electrode reactions. They need to be produced and consumed.

Calculations:

9. A hydrogen/oxygen fuel cell is operated at 0.7 V. What is the electrical efficiency with respect to the thermo-neutral voltage of 1.48 V?

1.48 V corresponds to 100 % electrical efficiency with respect to the HHV. Since voltage is proportional to the energy delivered by the electrons, 0.7 V corresponds to 0.7 V/1.48 V = <u>0.47 or 47 %</u>

10. If the cell above produces 1 kW electric, then how much heat does it produce?

If 47 % is 1 kW, then the total energy is 1 kW/0.47 = 2.13 kW and the fraction that is not converted to work is converted to heat, i.e. 2.13 kW – 1 kW = <u>1.13 kW</u>

Alternative solution:

The voltage proportional to the heat energy released

$$E_{"heat"} = E_{TN} - E_{cell} = 1.48V - 0.7V$$

The heat evolved is $Q = \frac{E_{"heat"}}{E_{TN}} \cdot \text{total energy} = \frac{1.48-0.7}{1.48} \cdot 2.13\ \text{W} =$ 1.12 W

11. The enthalpy of combustion of methane to water is -890.8 kJ mol^{-1} and the free energy of the process is -818.4 kJ mol^{-1}. What is the maximum electrical efficiency and the reversible cell voltage of a fuel cell running on methane and oxygen?

The maximum work (or electrical energy) is the free energy of the reaction. The maximum electrical efficiency is thus the free energy of the reaction divided by the enthalpy of the reaction, $\Delta g/\Delta h$ = -818.4 kJ mol^{-1} / -890.8 kJ mol^{-1} = 0.92, 92 %

The reversible cell voltage is depending on the free energy. It is -Δg divided by the charge transferred. Methane combustion involves 8 electrons (4 for C and 4 for H's for conversion to CO_2 and H_2O, respectively).

$E = -\Delta g/nF$ = 818,400 J mol^{-1} / 8·96485 C mol^{-1} = 1.06 V

12. A fuel cell stack is made from 130 identical single cells each with an electrode area of 64 cm^2 (of each electrode) and performance characteristic like in Figure 10 of the text. The stack is operated at 1.5 A cm^{-2}. Calculate

   a. The total stack voltage

At 1.5 A cm^2 the cell voltage is ca. 0.6 V. Series connection. With 0.6 V per cell, the total voltage becomes 130 · 0.6 V = 78 V

   b. The total stack current

With 1.5 A cm^2 and an electrode area of 64 cm, the total cell current is 1.5 A cm^2 · 64 cm = 96 A. It is the same current that passes through the entire stack. Total stack current: 96 A

   c. The electrical power

The electrical power of the stack, P_{el} is 78 V · 96 A = 7488 W

d. The heat generated assuming water leaves the stack as a liquid at room temperature. The stack is powered by hydrogen.

The total power converted in the stack is the current multiplied by the thermoneutral voltage (times no. of cells) instead of the actual voltage (remember the thermoneutral voltage corresponds to 100 % conversion to electrical energy).

Total power, $P_{tot} = I \cdot E_{TN} = 96\text{ A} \cdot (130 \cdot 1.48\text{ V}) = \underline{18480\text{ W}}$

The heat flow must be $P_{heat} = P_{tot} - P_{el} = 18480\text{ W} - 7488\text{ W} = \underline{\underline{10982\text{ W}}}$

Alternatively:

$$\frac{P_{el}}{P_{tot}} = \frac{E_{\text{cell}}}{E_{\text{TN}}}$$

$$\frac{P_{tot} - P_{heat}}{P_{tot}} = \frac{E_{\text{cell}}}{E_{\text{TN}}}$$

$$P_{heat} = P_{tot}\left(1 - \frac{E_{\text{cell}}}{E_{\text{TN}}}\right) = 18480\left(1 - \frac{0.6\ V}{1.48\ V}\right) = \underline{\underline{10988\text{ W}}}$$

Think and discuss:

What could be showstoppers for the large-scale roll-out of hydrogen as an energy carrier or fuel?

Which alternatives can replace hydrogen in the green transition?

Which sectors are the most obvious for early introduction of fuel cells and hydrogen?