TSFS17 - Föreläsning 11

Fuel Cells and Vehicles

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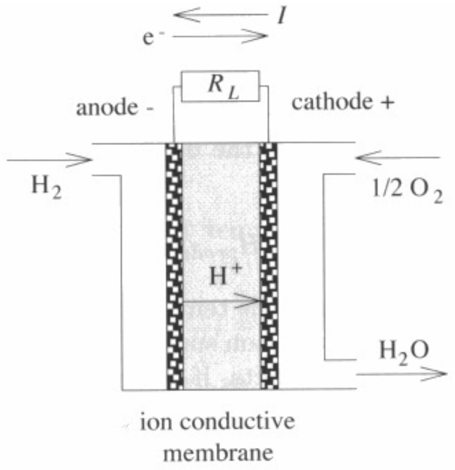
Outline

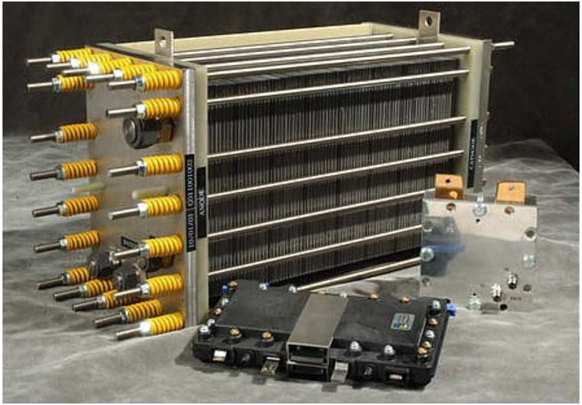
Fuel Cell Basic Principles

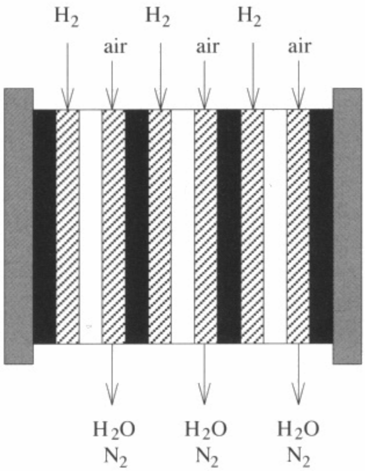
- Convert fuel directly to electrical energy
- Let an ion pass from an anode to a cathode
- Take out electrical work from the electrons



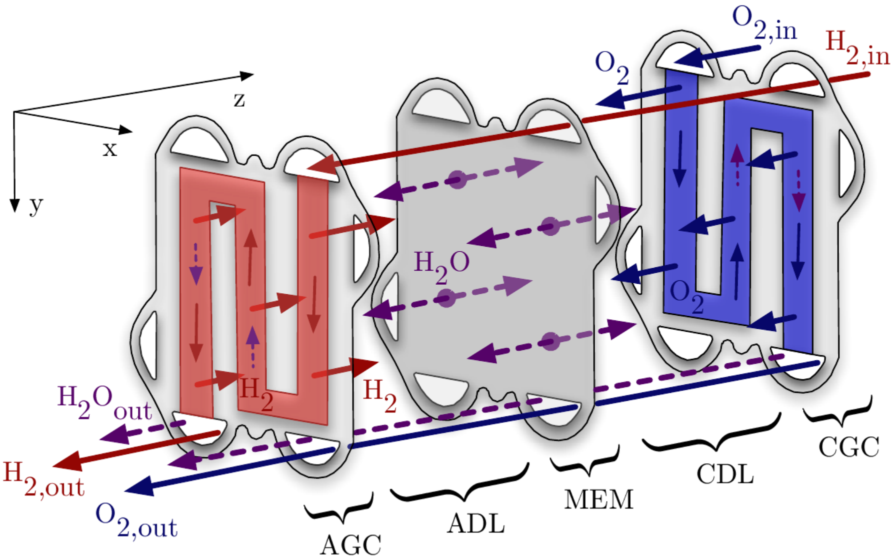
Fuel Cell Stack

- The voltage out from one cell is just below 1 V.
- Fuel cells are stacked, in series.

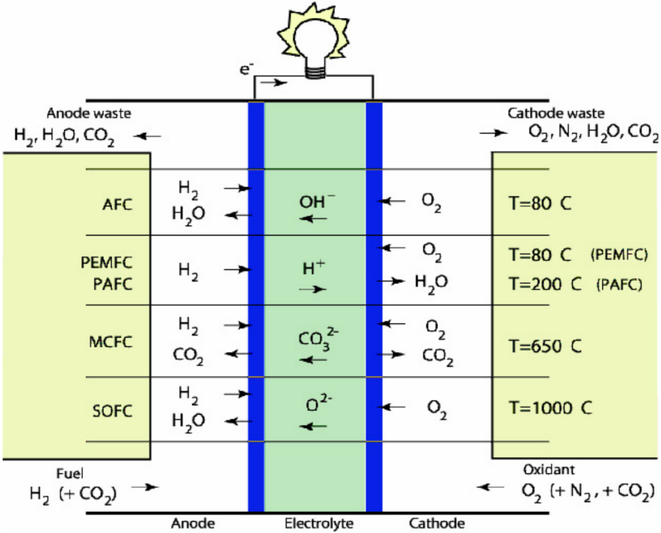




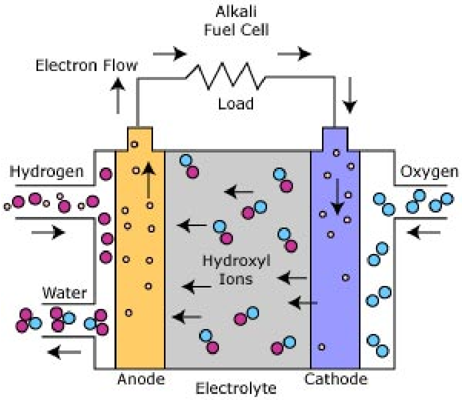
Components in a Fuel Cell Stack



Overview of Different Fuel Cell Technologies



AFC – Alkaline Fuel cell

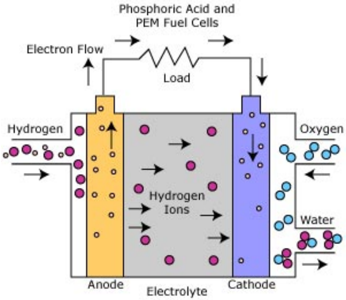


- Among the most efficient fuel cells 70%
- Low temperature 65-220°C
  - Quick start, fast dynamics
  - No co-generation
- Sensitive to poisoning

PEMFC – Proton Exchange Membrane Fuel Cell

Advantages:

- Relatively high power-density characteristic
- Operating temperature, less than 100°C
  –Allows rapid start-up
- Good transient response, i.e. change power
  –Top candidate for automotive applications
- Other advantages relate to the electrolyte being a solid material, compared to a liquid

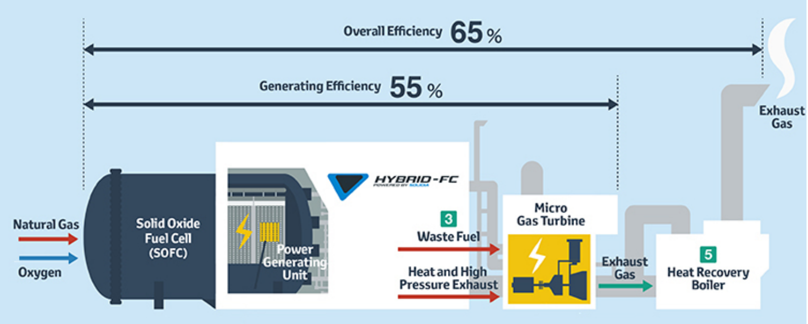


Disadvantages:

- Require expensive catalyst material (Platinum)
- For some applications operating temperature is low
- The electrolyte is required to be saturated with water to operate optimally.
  –Careful control of the moisture of the anode and cathode streams is important

The Other Types of H_2 Fuel Cells

- Other fuel cell types are
  - PAFC – Phosphoric Acid Fuel Cell 175°C
  - MCFC – Molten Carbonate Fuel Cell 650°C
  - SOFC – Solid Oxide Fuel Cells 1000°C
- Hotter cells, slower, more difficult to control
- Power generation through co-generation



Hydrogen Fuel Storage

- Hydrogen storage is a challenging task.
- Some examples of different options.
  - Compressed Hydrogen storage
  - Liquid phase – Cryogenic storage, -253°C
  - Metal hydride
  - Sodium borohydride $NaBH_4$

Comparison of H_2 Fuel Cells – US DOE

Fuel Cell Type	Common Electrolyte	Operating Temperature	Typical Stack Size	Efficiency	Applications	Advantages	Disadvantages
Polymer Electrolyte Membrane (PEM)	Perfluoro sulfonic acid	50-100°C 122-212° typically 80°C	< 1kW–100kW	60% transportation 35% stationary	• Backup power • Portable power • Distributed generation • Transporation • Specialty vehicles	• Solid electrolyte reduces corrosion & electrolyte management problems • Low temperature • Quick start-up	• Expensive catalysts • Sensitive to fuel impurities • Low temperature waste heat
Alkaline (AFC)	Aqueous solution of potassium hydroxide soaked in a matrix	90-100°C 194-212°F	10–100 kW	60%	• Military • Space	• Cathode reaction faster in alkaline electrolyte, leads to high performance • Low cost components	• Sensitive to CO_2 in fuel and air • Electrolyte management
Phosphoric Acid (PAFC)	Phosphoric acid soaked in a matrix	150-200°C 302-392°F	400 kW 100 kW module	40%	• Distributed generation	• Higher temperature enables CHP • Increased tolerance to fuel impurities	• Pt catalyst • Long start up time • Low current and power
Molten Carbonate (MCFC)	Solution of lithium, sodium, and/or potassium carbonates, soaked in a matrix	600-700°C 1112-1292°F	300 kW-3 MW 300 kW module	45-50%	• Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Can use a variety of catalysts • Suitable for CHP	• High temperature corrosion and breakdown of cell components • Long start up time • Low power density
Solid Oxide (SOFC)	Yttria stabilized zirconia	700-1000°C 1202-1832°F	1 kW–2 MW	60%	• Auxiliary power • Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Can use a variety of catalysts • Solid electrolyte • Suitable for CHP & CHHP • Hybrid/GT cycle	• High temperature corrosion and breakdown of cell components • High temperature operation requires long start up time and limits

Fuel Cell Applications in USA – US DOE

Fuel Cells for Stationary Power, Auxiliary Power, and Specialty Vehicles

The largest markets for fuel cells today are in stationary power, portable power, auxiliary power units, and forklifts.

~75,000 *fuel cells have been shipped worldwide.*

>15,000 *fuel cells shipped in 2009*

Fuel cells can be a cost-competitive option for critical-load facilities, backup power, and forklifts.

Production & Delivery of Hydrogen

In the U.S., there are currently:

- ***~9 million metric tons*** *of H_2 produced annually*
- ***> 1200 miles*** *of H_2 pipelines*

Source: US DOE 09/2010

Fuel Cells for Transportation

In the U.S., there are currently:

- *> 200 fuel cell vehicles*
- *~ 20 active fuel cell buses*
- *~ 60 fueling stations*

Sept. 2009: Auto manufacturers from around the world signed a letter of understanding supporting fuel cell vehicles in anticipation of widespread commercialization, beginning in 2015.

Outline

1. Fuel Cell Basics
   - Fuel Cell Types
   - Applications
2. Fuel Cell Modeling

Quasistatic Modeling of a Fuel Cell

- Standard modeling approach
- Keys for understanding:
  - Cell – The polarization curve
  - Operation – The Surrounding System

Fuel Cell Thermodynamics

- Starting point reaction equation

$$H_2 + \frac{1}{2} O_2 \Rightarrow H_2 0$$

- Open system energy – Enthalpy H

$$H = U + pV$$

- Available (reversible) energy – Gibbs free energy G

$$G = H - TS$$

- Open circuit cell voltages

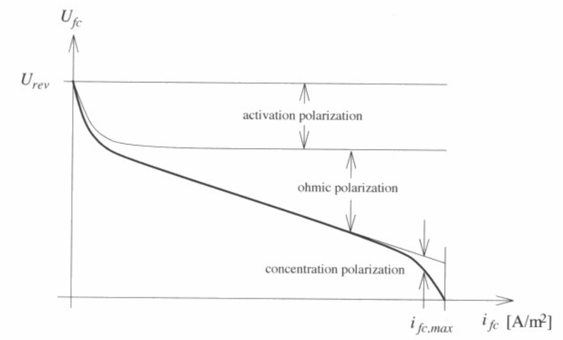
$$U_{rev} = -\frac{\Delta G}{n_e F}, \qquad U_{id} = -\frac{\Delta H}{n_e F}, \qquad U_{rev} = \eta_{id} U_{id}$$

F – Faradays constant ($F = q N_0$)

- Heat losses under load $P_l = I_{fc}(t)\,(U_{id} - U_{fc}(t))$ $\Rightarrow$ Cooling system

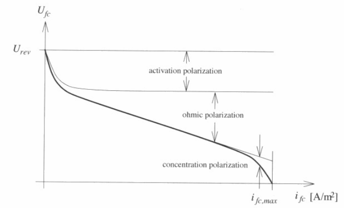
Fuel Cell Performance – Polarization curve

- Polarization curve of a fuel cell
  Relating current density
  $i_{fc}(t) = I_{fc}(t)/A_{fc}$, and cell voltage
  $U_{fc}(t)$ Curve for one operating
  condition
- Fundamentally different compared to
  combustion engine/electrical motor
- Excellent part load behavior
  –When considering only the cell
  –η_{cell} follows the Voltage



Fuel cell voltage

$$U_{fc}(t) = U_{rev}(t) - U_{act}(t) - U_{ohm}(t) - U_{conc}(t)$$



Single Cell Modeling – Describing the Polarization Curve

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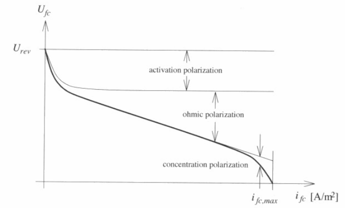

- Activation energy – Get the reactions going
  Semi-empirical Tafel equation

$$U_{act}(t) = c_0 + c_1 \ln(i_{fc}(t)), \text{ or } U_{act}(t) = \ldots$$

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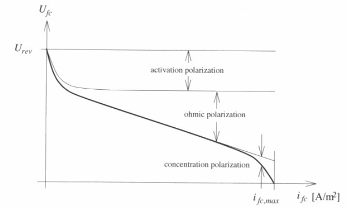

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- Ohmic – Resistance to flow of ions in the cell

$$U_{ohm}(t) = i_{fc}(t)\,\tilde{R}_{fc}$$

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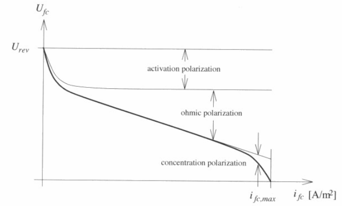

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- Ohmic – Resistance to flow of ions in the cell

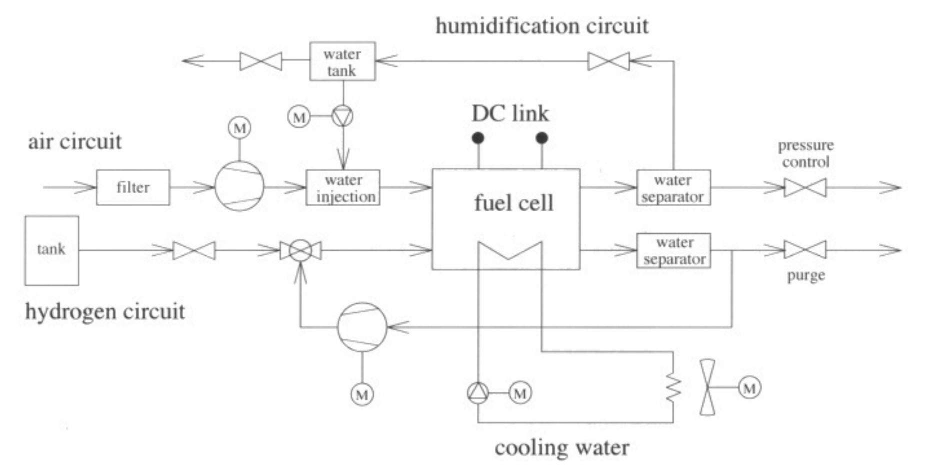
$$U_{ohm}(t) = i_{fc}(t)\,\tilde{R}_{fc}$$

- Concentration, change in concentration of the reactants at the electrodes

$$U_{conc}(t) = c_2 \cdot i_{fc}(t)^{c_3}, \text{ or } U_{conc}(t) = \ldots$$

Fuel Cell System Modeling

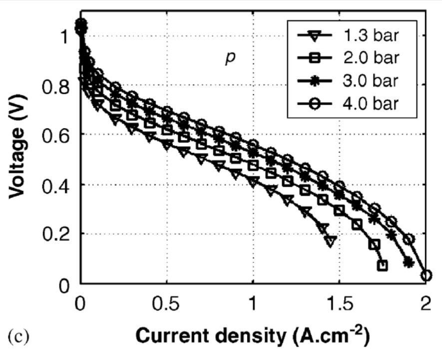
- A complete fuel cell system



- Power at the stack with N cells

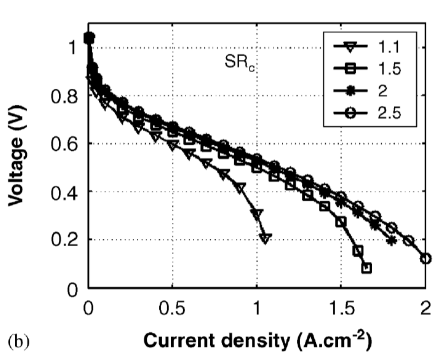
Important effects for the cell and system

Cell Pressure



Boosting the performance

Cell excess air λ



$$2H_2 + \lambda O_2 \rightarrow 2\,H_2O + (\lambda - 1)O_2, \lambda \geq 1$$

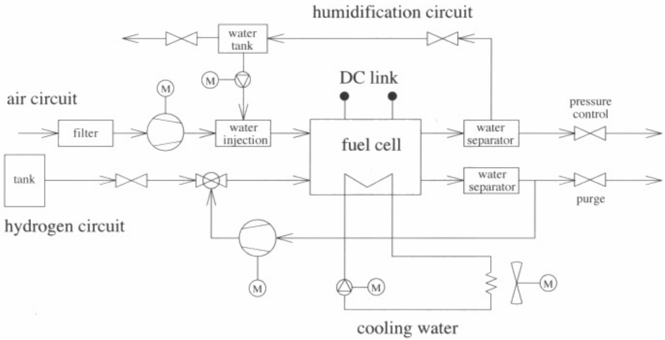
Fuel Cell System Modeling

- Describe all subsystems with models

$$P_2(t) = P_{st}(t) - P_{aux}(t)$$

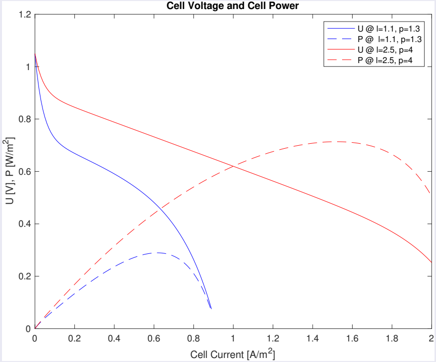
$$P_{aux} = P_0 + P_{em}(t) + P_{ahp}(t) + p_{hp}(t) + P_{cl}(t) + p_{cf}(t)$$

em–electric motor, ahp – humidifier pump, hp – hydrogen recirculation pump, cl – coolant pump, cf – cooling fan.

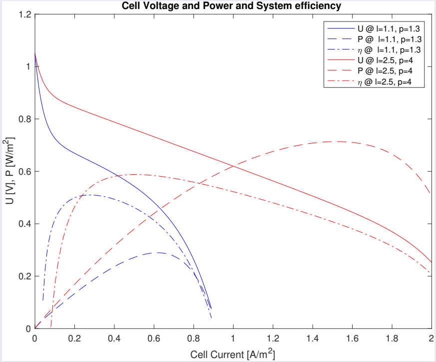


Fuel Cell System Performance at Low and High P_c

Individual Cell



Fuel Cell System



–Efficiency is highest at part loads towards low load.
–The system is stealing current to keep the cell operating.

Outline