Fuel cells, myths and facts

PhD candidate
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Fuel cell history, new or old?

1839 Now
Mond & Langer [coined *Fuel Cell*]
William Grove

1800 1839 1900’s 1930’s 1950’s 1970’s Now

GE’s Membrane FC
AFC
Bacon
PAFC
PEMFC
SOFC
Westinghouse
MCFC
Broes & Ketelaar
DMFC
Fuel cells general principle

- Fuel cells convert chemical energy to electric energy and heat
- Combination of internal combustion engine and battery
- More efficient than combustion, due to higher energy grade
Fuel cells general principle
# Fuel cell types and chemical systems

<table>
<thead>
<tr>
<th>Fuel Cell Type</th>
<th>Common Electrolyte</th>
<th>Operating Temp. °C</th>
<th>Fuel</th>
<th>Applications</th>
<th>Advantages</th>
<th>Power Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alkaline (AFC)</td>
<td>Aqueous solution</td>
<td>65 – 250</td>
<td>Pure H₂</td>
<td>Military Space</td>
<td>Fast electrode reactions, can use several catalysts</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>KOH</td>
<td></td>
<td></td>
<td></td>
<td></td>
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UTC, 12 kW stack
## Fuel cell types and chemical systems

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<td>Phosphoric Acid (PAFC)</td>
<td>Phosphoric acid in a SiC matrix</td>
<td>150 – 200</td>
<td>H₂</td>
<td>Stationary power production</td>
<td>Improved CO tolerance, long lifetime</td>
<td>Low</td>
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**200 kW UTC PureCell 200, installed power stations, PAFC**
### Fuel cell types and chemical systems

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<tr>
<td>Molten Carbonate (MCFC)</td>
<td>Liquid solution of, Li, Na, K carbonates</td>
<td>600 – 700</td>
<td>Reforming of fossil fuel H₂</td>
<td>Large power stations, continuous power</td>
<td>CO tolerant, many fuels, high temperature waste heat, high CHP eff.</td>
<td>Low</td>
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**430 kW hybrid, MCFC**
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<tr>
<td>Solid Oxide (SOFC)</td>
<td>Yttria stabilized zirconia</td>
<td>600 – 1000</td>
<td>Reforming of fossil fuel $\text{H}_2$</td>
<td>Large power stations, continuous power</td>
<td>CO tolerant, many fuels, high temperature waste heat, high CHP eff.</td>
<td>Medium</td>
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220 kW hybrid, SOFC
# Fuel cell types and chemical systems

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<td>Polymer Electrolyte Membrane (PEM)</td>
<td>Solid organic polymer</td>
<td>50 – 100</td>
<td>H₂</td>
<td>Transportation</td>
<td>Low temperature, high power density, quick start-up</td>
<td>Highest</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Power backup systems</td>
<td></td>
<td></td>
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</table>

100 kW (134 hp) Honda FCX Clarity
PEM Fuel cell for transport sector

- Reduce dependence of fossil fuels
- Use PEM fuel cell to open for H₂
Hydrogen economy

Where does $\text{H}_2$ come from?
- $\text{H}_2$ from natural gas
- Shift to electrolysis
- Fossil fuels 85% of current world energy, IEA
- Must invest in renewable energy sources

wind  hydro  geo
PEM Fuel cell for transport sector

- Fuel cell system closest to our everyday life
- Introduced in transport sector to reduce dependence on fossil fuel

- General Motors
- DaimlerChrysler
- Toyota
- Hyundai-Kia Motors
- Volkswagen
- Nissan
- Honda
- Linde
- Air Liquide
 PEM Fuel Cell for transport sector

How conversion of chemicals happen

- Transport in the electrodes
- Transport in the catalyst layer, membrane
- Water management
PEM Fuel Cell for transport sector

Important improvements:

• Membranes with better stability, conductivity, water, temperature
• Catalyst, higher surface area, activity, stability
• Support materials, conductivity, stability, water transport
• Meet targets for lifetime, 40000 stationary, 5000 transport
Status of PEM technology

Polymer membranes, mechanical strength
- Lifetime under cyclic conditions, about 2000 h
- Degrade by swelling and chemical degrading
- Support materials, chemically stabilized

- Micromoulds, Nafion 112
- Swelling/drying cycles
- 3 times less degradation
Status of PEM technology

Polymer membranes, mechanical strength
- Fluorine release used as measure of degradation
- 3 membranes in the same test, Nafion as the reference
- Improvements in stability from different approaches
Status of PEM technology

Electrodes and catalyst, Pt on Carbon

- Lifetime of the catalyst layer mainly related to the growth of Pt particles and carbon corrosion

- Pt stable under 0.7 V
- Startup/shutdown, above 0.7 V
- Pt dissolves
- Migrates to membrane
- Redeposit on larger Pt particles
Status of PEM technology

Catalysts, Progress

- New alloys increase stability of catalyst, Co, Au, Ni, Cr, Ir

![Improved catalyst stability diagram]
Electrodes and catalyst, Pt on Carbon

- Lifetime of the catalyst layer mainly related to the growth of Pt particles and carbon corrosion

- C stable under 0.7 V
- Startup/shutdown, above 0.7 V
- C corrodes, CO₂
- Reduced conductivity
- Catalyst layer and electrode
Status of PEM technology

Electrode material, Progress

- Support stability increase
- New materials
- Pretreatments

![Bar chart showing improved support stability for different materials: Ketjen, Graphitized, Surface modified. The chart compares carbon and Pt/carbon materials.](image)
Status of PEM technology

Overall issues of PEM fuel cells

• More expensive than competing technologies
• Actual price depends on production numbers
• Lifetime lower than competing technology
• Need research on lifetime issues, performance is good

- P. Mock, Journal of Power Sources, 190, (2009), 133-140
Status of PEM technology

Why keep on trying?
- Research improves technology each year
- Prototypes are closing in on targets
- New technology chosen when it's better
- Also climate crisis and energy crisis urges progress/change
Let’s go mythbusting!!
Myth #1, not enough Platinum?

World Platinum resources
- The lucky few
- 47000 metric tones Pt

- How many fuel cell cars can we make?
Myth #1, not enough Platinum?

World Platinum resources

- The lucky few
- 47000 metric tones Pt

- How many fuel cell cars can we make?

Given, 90 kW with 45 g Pt, 1 billion cars or 1.7 times today's number
Myth #1, not enough Platinum?

World Platinum resources

- The lucky few
- 47000 metric tones Pt

Given, 90 kW with 45 g Pt, 1 billion cars or 1.7 times today's number

Some remarks

- Pt in car catalyzers all ready
- What about Pt production
- Few countries have reserves
- Should research alternatives
Myth #1, not enough Platinum?

World Platinum resources

- The lucky few

Given

- 90 kW with 45 g Pt
- 1.037 billion cars or 1.73 times today’s number

Myth BUSTED
Myth #2, batteries are better!

Batteries or Li-ion, do not H₂

- Easy transport of electrons compared to H₂
- Less energy lost to surroundings
Myth #2, batteries are better!

Yes, but what about…

- Carries oxidizer, heavy
- Low energy density, long charging time
- Low lifetime, 5 years, Tesla Motors
- High cost, 200 – 300 $/kW
- Lithium found in few countries,

5kWh pack in 1 billion cars use 25%

Global Lithium Reserve Base

Metal Production, Reserves and Requirement for 1 Billion 5kWh Batteries
Myth #2, batteries are better!

Yes, but no..
• In price and performance PEMFC is leading
• Both technologies needs further research
• Similar problems regarding Pt and Li reserves
• Combination seems best, Hybrids

So, the myth that Batteries are better!
Myth #3, not limited by the Carnot cycle

Statement found in many text books

- Fuel cells above the law?
- Maximum efficiency of a heat engine

\[ \eta_{H.E.} = \frac{T_H - T_L}{T_H} \]
Myth #3, not limited by the Carnot cycle

Statement found in many text books

- What does it mean?
- Maximum efficiency of a heat engine

1st law
\[ W = Q_H - Q_L \]

2nd law
\[ \frac{Q_H}{T_H} - \frac{Q_L}{T_L} \leq 0 = P_{S.H.E}^{H.E.} \]
Myth #3, not limited by the Carnot cycle

Statement found in many text books

- What does it mean?
- Maximum efficiency of a heat engine

\[
\begin{align*}
1\text{st law} & \quad 2\text{nd law} \\
W_{\text{H.E.}} &= Q_H - Q_L & \frac{Q_H}{T_H} - \frac{Q_L}{T_L} \leq 0 = P_{\text{H.E.}}^{\text{H.E.}} \\
\end{align*}
\]

If we consider a Thermal Energy Reservoir

\[
\begin{align*}
1\text{st law} & \quad 2\text{nd law} \\
Q_H &= -\Delta H_{\text{T.E.R.}} & -\Delta S_{\text{TER}} + \frac{Q_H}{T_H} \leq 0 = P_{\text{T.E.R.}}^{\text{T.E.R.}} \\
\end{align*}
\]
Myth #3, not limited by the Carnot cycle

1st law
\[ W^{H.E.} = Q_H - Q_L \]  (1)

2nd law
\[ \frac{Q_H}{T_H} - \frac{Q_L}{T_L} \leq 0 = P_{S}^{H.E.} \]  (2)

If we consider a Thermal Energy Reservoir

1st law
\[ Q_H = -\Delta H^{T.E.R.} \]  (3)

2nd law
\[ -\Delta S^{TER} + \frac{Q_H}{T_H} \leq 0 = P_{S}^{T.E.R.} \]  (4)

Now we can express the efficiency

\[ \eta_{H.E.} = \frac{W}{Q_H} = \frac{Q_H - Q_L}{Q_H} \]  (5)

And from (2) and (4):

\[ Q_L = \left( \frac{Q_H}{T_H} - P_{S}^{H.E.} \right) \cdot T_L \]  (6)

\[ Q_H = \left( P_{S}^{T.E.R.} + \Delta S \right) \cdot T_H \]  (7)
Myth #3, not limited by the Carnot cycle

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\[ Q_H = \left( P_s^{T.E.R.} + \Delta S \right) \cdot T_H \] (7)

Inserting (7) in to (6):

\[ Q_L = \left( P_s^{T.E.R.} + \Delta S - P_s^{H.E.} \right) \cdot T_L \] (8)
Myth #3, not limited by the Carnot cycle

Now we can express the efficiency

\[ \eta_{H,E.} = \frac{W}{Q_H} = \frac{Q_H - Q_L}{Q_H} \]  

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\[ Q_H = \left( P^{T.E.R.}_S + \Delta S \right) \cdot T_H \]  

(7)

Inserting (7) in to (6):

\[ Q_L = \left( P^{T.E.R.}_S + \Delta S - P^{H.E.}_S \right) \cdot T_L \]  

(8)

Inserting (8) in to (5):

\[ \eta_{H,E.} = \frac{Q_H - T_L \left( \Delta S + P^{T.E.R.}_S - P^{H.E.}_S \right)}{Q_H} \]  

(9)

If this is ideal processes:

\[ P^{T.E.R.}_S = P^{H.E.}_S = 0 \]
Myth #3, not limited by the Carnot cycle

Inserting (7) in to (6):

\[ Q_L = \left( P_s^{T.E.R.} + \Delta S - P_s^{H.E.} \right) \cdot T_L \quad (8) \]

Inserting (8) in to (5):

\[ \eta_{H.E.} = \frac{Q_H - T_L \left( \Delta S + P_s^{T.E.R.} - P_s^{H.E.} \right)}{Q_H} \quad (9) \]

If this is ideal processes:

\[ P_s^{T.E.R.} = P_s^{H.E.} = 0 \]

And we get:

\[ \eta_{H.E.} = \frac{Q_H - T_L \Delta S}{Q_H} \]

Since:

\[ Q_H = \Delta H \]

\[ \eta_{H.E.} = \frac{\Delta H - T_L \Delta S}{\Delta H} = \frac{\Delta G}{\Delta H} \]

Which is the same expression we have for PEMFC’s
Myth #3, not limited by the Carnot cycle

Heat engine and PEMFC thermodynamic efficiencies

\[ \eta_{F.C.} = \frac{T_H - T_L}{T_H} = \frac{3802 - 300}{3802} = 0.921 \]

\[ \eta_{F.C.} = \frac{\Delta G}{\Delta H} = \frac{-12.553}{-13.426} = 0.935 \]
Myth #3, not limited by the Carnot cycle

Heat engine and PEMFC thermodynamic efficiencies

\[
\eta_{F.C.} = \frac{T_H - T_L}{T_H} = \frac{3802 - 300}{3802} = 0.921
\]

\[
\eta_{F.C.} = \frac{\Delta G}{\Delta H} = \frac{-12.553 / J / g}{-13.426 / J / g} = 0.921
\]
Fuel cells, summary

- Fuel cells have the possibility to reduce CO$_2$ emissions
- Fuel cells need more research to improve
- Main focus should be on lifetime issues
- There is much to be done.....
Fuel cells, summary

Thank you for your attention!