H₂ Compression and Purification

- Energy efficient
- No moving parts
- Silent operation
- Single-stage
- Scalable

Pressure up to 100MPa
Purification > 99.5% H₂

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Mechanical Compression

- Minimum feed pressure
- Multi-stage configuration
- Interstage cooling
- Regular maintenance
- Noisy
Mission & Competence

• **Mission:** Develop innovative *silent* technologies and make available products for **Purification** and **Compression** of hydrogen gas

• **Core competence:** deliver high pressure Membrane-Electrode-Assembly (MEA) in stack with BOP system.
Working Principle of EHC

Anode: $\text{H}_2 = 2\, \text{H}^+ + 2\, \text{e}^-$

Cathode: $2\, \text{H}^+ + 2\, \text{e}^- = \text{H}_2$

Special membranes block hydrogen gas, but allow fast proton conductivity. Catalysed interfaces enable the indicated redox reaction equilibrium. An external power source drives the electric current and the internal hydrogen mass transport direction, controlling hydrogen gas flow.

Electrons move Protons

pump rate: $2\, \text{e}^- \sim \text{H}_2$
HyET successfully demonstrated a pressure record of 100 MPa pressure, single stage, on a laboratory cell to prove the concept of Electrochemical Hydrogen Compression (EHC).
Like with air-conditioning, isothermal compression effectively dried hydrogen supply.
Product-Market relationship

HyET provides a critical “Puzzlepiece” in the hydrogen infrastructure daisy chain

Source side  Demand side
Project PHAEDRUS developed and validated a scalable HRS design using the latest technologies including Electrochemical Hydrogen Compression (EHC) and hydrogen production on-site.
Hydrogen Refueling Station

HyET engages field testing using MoHyTO systems to assess customer applications and increase Technology Readiness Level above 5.

Successful integration of ITM electrolyser and HyET EHC validated in field test in summer 2015.
Project Don Quichote realises 60 kg/day hydrogen production, compression and storage at the Colruijt distribution centre in Belgium for refuelling forklift trucks and fuelcell power generation.
The basic stack and subsystem form the basic element, enabling modular upscaling on demand.

Scaled to demand

Base Oriented Compressor Iso-Thermal Organisation (BOCITO) in design phase

3x MoHyTO systems currently operational
Ultimately, our silent EHC device could enable home refuelling: storing hydrogen in a tank, integrating renewable energy sources together with the security of gas and grid connections by combining electrolysis and/or reformer and/or heating systems under SMART GRID control.
Membranes that block high pressure hydrogen also block other gas species from permeating.

Selective Hydrogen extraction is achieved from different gas mixtures containing in various ratios CH₄, CO₂, CO, N₂, H₂S.
Purification is Included

<table>
<thead>
<tr>
<th>Gasses</th>
<th>H2</th>
<th>CO2</th>
<th>CO</th>
<th>CH4</th>
<th>H2O</th>
</tr>
</thead>
<tbody>
<tr>
<td>supplied</td>
<td>70.05</td>
<td>19.97</td>
<td>7.477</td>
<td>2.507</td>
<td>bubbler</td>
</tr>
<tr>
<td>as-received</td>
<td>99.551</td>
<td>0.024</td>
<td>0.002</td>
<td>0.423</td>
<td></td>
</tr>
<tr>
<td>purified</td>
<td>Permeating gas</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

concentration of CO is reduced >5000 fold, CO₂ is reduced >1000 fold
No CH₄ observed in the permeate gas
Membrane properties

Optimum balance between the key membrane properties depends on the application.

- **Ideal membrane properties**
  - Good Mechanical Integrity
  - High Proton Conductivity
  - Low H₂ Back Diffusion
Assuming:

35 cm Ø
70 MPa

The EHC classifies as pressure vessel

- Spherical form factor with wall thickness:

<table>
<thead>
<tr>
<th>Material</th>
<th>Yield Strength [Mpa]</th>
<th>Wall Thickness [mm]</th>
<th>including Safety factor x2.35 [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>HDPE</td>
<td>26</td>
<td>236</td>
<td>554</td>
</tr>
<tr>
<td>Steel (average)</td>
<td>250</td>
<td>25</td>
<td>58</td>
</tr>
<tr>
<td>Steel (high strength)</td>
<td>690</td>
<td>9</td>
<td>21</td>
</tr>
<tr>
<td>Aluminium</td>
<td>15</td>
<td>408</td>
<td>960</td>
</tr>
<tr>
<td>Aluminium alloy</td>
<td>400</td>
<td>15</td>
<td>36</td>
</tr>
<tr>
<td>Titanium alloy</td>
<td>830</td>
<td>7</td>
<td>17</td>
</tr>
<tr>
<td>Lead</td>
<td>10</td>
<td>613</td>
<td>1439</td>
</tr>
</tbody>
</table>

Example to show how much material is required to keep such pressure in a sphere, depending on the materials used for its construction.
Internal $\text{H}_2$ Pressure

Hydrogen gas pressure also pushes against the membrane within EHC

- 70MPa Compressive force in $z$-direction
- Tension forces created in $xy$-plane
- Impact on water management
- Cell closing pressure subjected on MEA
- Tenting into gas flow-field channels
- Puncturing / pinhole propagation

*Technical solutions are called for when dealing with extreme pressures on soft matter*
Forces during compression and decompression could cause cell-to-cell variations, if too much room is available for displacement and deformations between cells.
Pressure increase (bara) and current density have minor influence on resistance
Membrane properties

Optimum balance between the key membrane properties depends on the application.
Impact of H₂ cross-over

Cross over of hydrogen measured with 430mV polarisation and nitrogen on anode
Impact of H$_2$ cross-over

Membrane types are normalised for thickness, temperature indicated.
Temperature influences the hydrogen cross over through membrane significantly.
Membrane properties

Optimum balance between the key membrane properties depends on the application.
Schematic diagram

Equivalent circuit model of the process in the EHC to pump hydrogen using DC current

Mapping all EHC resistances
Schematic diagram

Hydrogen loss
\[ \text{d}P, \text{sealing} \]

Back Diffusion
\[ \text{d}P, T, \text{RH}\% \]

Power source
\[ I_{\text{back}}, V_n \]

External Energy
driving DC current

Anode
\[ P_{\text{in}}, T, \text{RH}\% \]

Nernst Voltage
\[ \text{d}P, T \]

Cell-to-Cell Resistance
Ohm

Cathode
\[ P_{\text{in}}, T, \text{RH}\% \]

Equivalent circuit model of the process in the EHC to pump hydrogen using DC current
Nernst energy equals compression energy, applying to over-pressure as well as vacuum.
Incredible compression was achieved with little energy from only one battery
Equivalent circuit model of the process in the EHC to pump hydrogen using DC current

- **Forward**
  - Power source
  - \( I_{\text{back}} \) to \( V_n \)
  - \( R_{\text{tot}} \)

- **Backward**
  - \( I_{\text{back}} \) from \( V_n \)
  - \( R_{\text{tot}} \)

**Components**

- **2x** Ohmic resistance
  - wires, cellplate, flowfield, including interfaces

- **2x** \( \text{H}_2 \) gas transport
  - supply flow anode, diffusion to/from catalyst, exit cathode

- **2x** Reaction \( \text{H}_2 = \text{H}^+ + e^- \)
  - oxidation on anode, reduction on cathode

- **1x** Proton resistivity
  - movement of \( \text{H}^+ \) through polymer electrolyte phase

**Equation**

\[
V_n = I_{\text{back}} \cdot R_{\text{tot}}
\]
Schematic diagram

Equivalent circuit model of the process in the EHC to pump hydrogen using DC current

- <5% Ohmic resistance
- <5% H₂ gas transport (... up to 100%) IF low currents, no obstruction, P_in > 1 bar
- <1% Reaction H₂ = H⁺ + e⁻ IF pure H₂, no catalyst poisoning
- >90% Proton resistivity IF Temp, RH%, all OK
Potentiostatic hydrogen compression from 10 → 400 bar and back from 400 ← 10 bar
Electrochemical pump need **one** single stage and have more isothermal compression
Pump rate flexibility

Variable hydrogen pumping rates feasible with one stack module
Pump energy \([\text{kWh/kg}]\)

Hydrogen pump efficiency calculated for different current densities

- Low Current
- Medium Current
- High Current

\[ P_{in} = 10\text{bar} \]

Typical example

EHC energy requirement is a function of current density and pressure difference
Hydrogen pump curves plotted as a function of the current density (i.e. pump rate). Slow pumping is more energy efficient, and has little influence on pressure capability.
Energy efficiency with HyET membrane during compression from 10 → 45 MPa, plotted as a function of the Mass Flow rate (Current Density) and Cell Temperature.
Total Energy Efficiency

Energy efficiency with HyET membrane during compression from 1 → 45 MPa, plotted as a function of the Mass Flow rate (Current Density) under best conditions.
HyET offers technology capable of simultaneous silent compression and selective purification of hydrogen gas

- **Purification** guarantees high quality hydrogen
- **Compression** up to 1000 bar output pressure feasible
- **Multiple sources** of hydrogen gas (mixtures) useable
- **Scalable units** enable growth with HRS market demand
- **Compatible with “decentralised” Power and Smart Grid**

Stand-alone 2 kg/day Electro-chemical Hydrogen Test unit **available now** for preliminary customer test trials (MoHyTO)
we thank everybody that contributed personally to building our foundation
Existing gas distribution networks serve as transportation pipelines as well as energy storage buffer. Hydrogen could play a role here...

“Gas roundabout” infrastructure initiated to secure energy supply security.

Source: http://www.rijksbegroting.nl/algemeen/gerefereerd/1/7/1/kst171191.html