Intensification of alkaline electrolysis

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Your partner in essential chemistry for a sustainable future
We are experts in electrochemical production

Nouryon operates 1000 MW of electrolysis capacity

### Chlor-alkali
- Installed capacity: 380 MW
- H₂ production: 38 kta

### Sodium chlorate
- Installed capacity: 620 MW
- H₂ production: 62 kta

### Water electrolysis
- Installed capacity: 8 MW
- H₂ production: 1.2 kta

Nouryon operates 1000 MW of electrolysis capacity

Water electrolysis since 1940
Active in electrochemistry since 1899
46% share of renewable energy
Leading the way for green hydrogen

Projects:
- 20 MW project in Delfzijl with Gasunie and BioMCN
- 100 MW project with Tata Steel and Port of Amsterdam
- 250 MW project with BP and Port of Rotterdam
Plant costs

Material cost + Manufacturing cost

Stack cost
100-600 €/kW

Balance of plant
200-400 €/kW

Other project costs
~1000 €/kW

Installed plant (+/- 20 MW)
1500-2000 €/kW
To make green hydrogen competitive we need to reduce cost.

- **Material cost**
  - Stack cost: $100-600€/kW
  - <100€/kW

- **Manufacturing cost**
  - Balance of plant: $200-400€/kW

- **Other project costs**
  - ~1000€/kW

- **Installed plant (GW scale)**: $1500-2000€/kW
  - -65%
  - 2€/kg Hydrogen
Alkaline and PEM comparison

Energy consumption too high & overheating of electrolyzer

Electrolyzer cools down due to insufficient heat generation

Electrolyzer cools down due to insufficient heat generation

Operation window

E_{\text{ref}} = 1.48 V

Note: current efficiency is 98% for alkaline and PEM (due to leak currents and gas crossover)

* Nouryon stack price analysis based on public information
Developments in alkaline

- We see increased current densities while retaining the same efficiency, made possible by cathodes that have been developed for the chlor-alkali industry and improved membranes

<table>
<thead>
<tr>
<th>Classic Alkaline</th>
<th>Intensified alkaline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Separator</td>
<td>Asbestos (2-4 mm)</td>
</tr>
<tr>
<td>Ohmic resistance separator at 80°C</td>
<td>1.0-1.3 Ωcm$^2$</td>
</tr>
<tr>
<td>Cathode</td>
<td>Nickel (with iron contamination)</td>
</tr>
<tr>
<td>Cathode overpotential electrode at 90°C (V)</td>
<td>0.28 V$^3$</td>
</tr>
</tbody>
</table>

Graph: Recent company presentations and brochures & Vandenborre et al., Int. J. Hydrogen Energy 1984 (for Lurgi data)

1 Vermeiren et al., Int. J. Hydrogen Energy 1998
2 Tilak et al., Comprehensive treatise of electrochemistry 1981
3 O’Brien, Handbook of chlor-alkali 2005, page 263
4 Recent developments in of AKC’ IM technology, 2009
## State-of-the-art and development potential

<table>
<thead>
<tr>
<th></th>
<th>State-of-the-art (in commercial products)</th>
<th>State-of-the-art performance</th>
<th>Further development potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>Separator</td>
<td>polysulfone-ZrO$_2$</td>
<td>0.13 Ω cm$^2$</td>
<td>Better conducting membranes, anion-exchange membranes</td>
</tr>
<tr>
<td>Cathode</td>
<td>Ni with noble metal loading</td>
<td>$\eta_C = 0.08$ V @ 0.6 A cm$^{-2}$, 90°C</td>
<td>Stable cathodes with reduced or no noble metals use</td>
</tr>
<tr>
<td>Anode</td>
<td>Ni (with iron contamination)</td>
<td>$\eta_A = 0.35$V @ 1.0 A cm$^{-2}$, 100°C$^1$</td>
<td>Stable anodes with lower overpotential without noble metals</td>
</tr>
<tr>
<td>Electrode structure</td>
<td>“Zero” gap: meshes/expanded metal pushed against membrane</td>
<td>~0.1 Ω cm$^2$</td>
<td>Membrane-electrode assemblies with lower resistance</td>
</tr>
<tr>
<td>Cell materials</td>
<td>Nickel, Nickel plated steel, EPDM, PPS, Teflon</td>
<td></td>
<td>Reduced use of pure nickel and other materials (eg. thinner bipolar plates, plated steel)</td>
</tr>
<tr>
<td>Operating conditions</td>
<td>90 °C, 30 bara</td>
<td></td>
<td>Operation at higher temperatures to reduce cell potentials</td>
</tr>
<tr>
<td><strong>Total performance</strong></td>
<td></td>
<td>~1.8 V @ 0.6 A cm$^2$, 90°C</td>
<td></td>
</tr>
</tbody>
</table>

$^1$ Baley et al., Int. J. Hydrogen Energy 1985, data for etched nickel plate
Intensified alkaline: importance of costs

- Cell potential / V
- Energy consumption (kWh/Nm³)

- Current density (A/m²)

- Current density (A/€ investment)

Classic alkaline
- 2000 A/m² @ 4.4 kWh/Nm³
- 8000 A/m² @ 4.4 kWh/Nm³

Intensified alkaline

Costs:
- <100 €/kW
- <75 €/kW
- <50 €/kW

4000 €/m²
- Classic: 600 €/m²
- 2000 €/m²
- 1000 €/m²
- 500 €/m²
MW test center in Groningen

- The MW test center aims to support technology development of water electrolysis at higher TRL levels (4-7).
- The technology development at the MW test center should lead to a cost prize for the electrolyzer stack of 50-100 €/kW at an efficiency of >80% (for first 5 years of operation) and a pressure of 30 bara by 2030.

- Partners: Shell, Gasunie, Yara, Frames, GSP, TNO/ECN, Hanze, RUG, ISPT, Yokogawa
- Planned to be operational in summer 2020
Conclusions

• We need to bring down the costs of water electrolysis plants by 65% for a completely installed plant and to <100 €/kW for the stack, while retaining the efficiency of <4.5 kWh/Nm³

• There is ample room for innovation in alkaline electrolysis to achieve these targets
Thank you!

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