Solid Oxide Electrolysis Cells - High pressure operation

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Solid Oxide Electrolysis Cells

- High pressure operation

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SYMPOSIUM
Water electrolysis and hydrogen as part of the future Renewable Energy System
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The Solid Oxide Cell (SOC) — Reversible, SOEC ↔ SOFC

- **Electrolysis Cell (SOEC)**
  \[ H_2O \text{ (cathode)} \rightarrow H_2 \text{ (cathode)} + \frac{1}{2} O_2 \text{ (anode)} \]
  \[ CO_2 \text{ (cathode)} \rightarrow CO \text{ (cathode)} + \frac{1}{2} O_2 \text{ (anode)} \]

- **Fuel Cell (SOFC)**
  \[ H_2 \text{ (anode)} + \frac{1}{2} O_2 \text{ (cathode)} \rightarrow H_2O \text{ (anode)} \]
  \[ CO \text{ (anode)} + \frac{1}{2} O_2 \text{ (cathode)} \rightarrow CO_2 \text{ (anode)} \]
The Solid Oxide Cell (SOC) — Reversible, SOEC ↔ SOFC

- Electrolysis Cell (SOEC)
  \[ \text{H}_2\text{O} \text{(cathode)} \rightarrow \text{H}_2 \text{(cathode)} + \frac{1}{2} \text{O}_2 \text{(anode)} \]
  \[ \text{CO}_2 \text{(cathode)} \rightarrow \text{CO} \text{(cathode)} + \frac{1}{2} \text{O}_2 \text{(anode)} \]

- Fuel Cell (SOFC)
  \[ \text{H}_2 \text{(anode)} + \frac{1}{2} \text{O}_2 \text{(cathode)} \rightarrow \text{H}_2\text{O} \text{(anode)} \]
  \[ \text{CO} \text{(anode)} + \frac{1}{2} \text{O}_2 \text{(cathode)} \rightarrow \text{CO}_2 \text{(anode)} \]

One major advantage of SOECs is the possibility to reduce CO\(_2\) to CO.
Solid Oxide Electrolysis Cells

Oxygen electrode
\[ 2O^{2-} \rightarrow O_2 + 4e^- \]

Fuel electrode
\[ 2H_2O + 4e^- \rightarrow 2H_2 + 2O^{2-} \]
\[ 2CO_2 + 4e^- \rightarrow 2CO + 2O^{2-} \]
Solid Oxide Electrolysis Cells
— Operation at high temperature

\[ \text{H}_2\text{O} \rightarrow \text{H}_2 + \frac{1}{2}\text{O}_2 \]

\[ \text{CO}_2 \rightarrow \text{CO} + \frac{1}{2}\text{O}_2 \]

Energy demand (kJ/mol) vs. Temperature (°C)

- Total energy demand ($\Delta H_f$)
- Electrical energy demand ($\Delta G_f$)
- Heat demand ($T \Delta S_f$)

\[
\frac{1}{n \cdot F} \cdot \text{Energy demand (Volt)}
\]
Renewable electricity

H₂O

Released to the atmosphere

4 e⁻

Electrolysis cell

2H₂O → 2H₂ + O₂
2CO₂ → 2CO + O₂

Vision
Renewable electricity

\[ \text{E} \quad \text{\( \rightarrow \)} \quad \text{H}_2\text{O} \]

Released to the atmosphere

\[ 4 \text{ e}^- \quad \text{\( \rightarrow \)} \quad \text{Electrolysis cell} \]

\[ 2\text{H}_2\text{O} \rightarrow 2\text{H}_2 + \text{O}_2 \]
\[ 2\text{CO}_2 \rightarrow 2\text{CO} + \text{O}_2 \]

Fuel synthesis

\[ 2\text{H}_2 + \text{CO} \rightarrow \text{CH}_2^- + \text{H}_2\text{O} \]

Fuel transport

Vision
Renewable electricity

H₂O

Released to the atmosphere

4 e⁻

Electrolysis cell

2H₂O → 2H₂ + O₂

2CO₂ → 2CO + O₂

CO₂ in the atmosphere

Synthetic petrol/diesel

Fuel synthesis

2H₂ + CO → –CH₂– + H₂O

Fuel transport

H₂O

Consumption

CO₂

Collection

CO₂ + 2 OH⁻ (membrane) → H₂O + CO₃²⁻ (membrane)

Renewable electricity

H₂O

Concentrated CO₂

Vision
Vision
— Collection of CO₂ from the atmosphere

CO₂ in the atmosphere

Electrolysis cell
2H₂O → 2H₂ + O₂
2CO₂ → 2CO + O₂

CO₂ collection
CO₂ + 2OH⁻ (membrane) ⇌ H₂O + CO₃²⁻ (membrane)

Fuel synthesis
2H₂ + CO → -CH₂− + H₂O

Synthetic petrol/diesel

Fuel transport

Consumption

Renewable electricity

H₂O

Vision — Collection of CO₂ from the atmosphere

CO₂ in the atmosphere

Electrolysis cell
2H₂O → 2H₂ + O₂
2CO₂ → 2CO + O₂

CO₂ collection
CO₂ + 2OH⁻ (membrane) ⇌ H₂O + CO₃²⁻ (membrane)

Fuel synthesis
2H₂ + CO → -CH₂− + H₂O

Synthetic petrol/diesel

Fuel transport

Consumption

Renewable electricity

H₂O

Vision — Collection of CO₂ from the atmosphere

CO₂ in the atmosphere

Electrolysis cell
2H₂O → 2H₂ + O₂
2CO₂ → 2CO + O₂

CO₂ collection
CO₂ + 2OH⁻ (membrane) ⇌ H₂O + CO₃²⁻ (membrane)

Fuel synthesis
2H₂ + CO → -CH₂− + H₂O

Synthetic petrol/diesel

Fuel transport

Consumption

Renewable electricity

H₂O
Vision
— Collection of CO₂ from industries

**Renewable Electricity**

H₂O Released to the atmosphere

Electrolysis cell

\[ 2 \text{H}_2\text{O} \rightarrow 2\text{H}_2 + \text{O}_2 \]

\[ 2\text{CO}_2 \rightarrow 2\text{CO} + \text{O}_2 \]

**Fuel synthesis**

2H₂ + CO → -CH₂- + H₂O

**Synthetic petrol/diesel**

Fuel transport

Consumption

H₂O Released to the atmosphere

CO₂ Released to the atmosphere

Concentrated CO₂

Vision — Collection of CO₂ from industries
**Vision**
— Collection of $\text{CO}_2$ from power plants

**Diagram**

- **Electrolysis cell**
  
  $2\text{H}_2\text{O} \rightarrow 2\text{H}_2 + \text{O}_2$
  
  $2\text{CO}_2 \rightarrow 2\text{CO} + \text{O}_2$

- **Fuel synthesis**
  
  $2\text{H}_2 + \text{CO} \rightarrow \text{CH}_2 + \text{H}_2\text{O}$

- **Production of Synthetic petrol/diesel**

- **Fuel transport**

- **Consumption**

- **Concentrated CO$_2$**

- **(Renewable) Electricity**

- **$\text{H}_2\text{O}$ Released to the atmosphere**

- **$\text{CO}_2$ Released to the atmosphere**
Vision
— Storing renewable electricity via Natural Gas

Electrolysis cell
2H₂O → 2H₂ + O₂
2CO₂ → 2CO + O₂

Fuel synthesis
H₂ + CO → CH₄

CO₂
Released to the atmosphere

H₂O
Released to the atmosphere

StORAGE
and consumption
Natural gas burners

Fuel transport

Consumption

2O²⁻

4 e⁻

(Renewable)
Electricity

CO₂

H₂O

CO₂
Released to the atmosphere

H₂O
Consumption

CO₂
Released to the atmosphere
Vision
— Biogas upgrading

\[ \begin{align*}
\text{Electrolysis cell} & : 2\text{H}_2\text{O} & \rightarrow & 2\text{H}_2 + \text{O}_2 \\
& & 2\text{CO}_2 & \rightarrow 2\text{CO} + \text{O}_2 \\
& & 2\text{O}^2- & \rightarrow & 4e^- + \text{H}_2 \text{O} \\
\text{Fuel synthesis} & : \text{CH}_4 + \text{H}_2 + \text{CO} & \rightarrow & \text{CH}_4 \\
\text{Storage and consumption} & : \text{Natural gas burners} \\
\text{CO}_2 & \text{Released to the atmosphere} \\
\text{H}_2\text{O} & \text{Released to the atmosphere} \\
\text{H}_2\text{O} & \text{Fuel transport} \\
\text{Consumption} & \text{(Renewable) Electricity} \\
\text{CH}_4 & \text{H}_2\text{O} + \text{CO}_2
\end{align*} \]
Vision

• Production of synthetic fuels from renewable electricity (wind) and:
  – $\text{CO}_2$ from the atmosphere
  – $\text{CO}_2$ from the industry
  – $\text{CO}_2$ from biomass fired power plants

• Storage of renewable electricity via synthetic fuels and the natural gas grid

• Biogas upgrading
The Solid Oxide Cell (SOC)
— Reversible, SOEC ↔ SOFC

• Electrolysis Cell (SOEC)
  \[ \text{H}_2\text{O} \text{ (cathode)} \rightarrow \text{H}_2 \text{ (cathode)} + \frac{1}{2} \text{O}_2 \text{ (anode)} \]

• Fuel Cell (SOFC)
  \[ \text{H}_2 \text{ (anode)} + \frac{1}{2} \text{O}_2 \text{ (cathode)} \rightarrow \text{H}_2\text{O} \text{ (anode)} \]

Conditions: 850°C, 50% H\textsubscript{2}O – 50% H\textsubscript{2}
Electrolysis durability at low current density—Cleaned inlet gases and improved setup

Conditions:
Steam electrolysis: 850°C, -0.50 A/cm², 50% H₂O – 50% H₂
CO₂ electrolysis: 850°C, -0.25 A/cm², 70% CO₂ – 30% CO
Co-electrolysis: 850°C, -0.25 A/cm², 45% CO₂ – 45% H₂O – 10% H₂
Electrolysis durability at low current density
—Cleaned inlet gases and improved setup

No degradation or even activation with clean inlet gases and a setup without contaminants

Conditions:
Steam electrolysis: 850ºC, -0,50 A/cm², 50% H₂O – 50% H₂
CO₂ electrolysis: 850ºC, -0,25 A/cm², 70% CO₂ – 30% CO
Co-electrolysis: 850ºC, -0,25 A/cm², 45% CO₂ – 45% H₂O – 10% H₂
Electrolysis durability at high current density
Electrolysis durability at high current density
— Standard Ni-YSZ based cells with LSM $O_2$ electrode

Conditions: $1.0 \, A/cm^2$, 45% CO$_2$ – 45% H$_2$O – 10% H$_2$
Electrolysis durability at high current density
— Today

Conditions: 850ºC, -1.0 A/cm², 45% CO₂ – 45% H₂O – 10% H₂
Electrolysis durability at high current density — Today

Conditions: 850°C, -1.0 A/cm², 45% CO₂ – 45% H₂O – 10% H₂
Electrolysis durability at high current density — Today

Conditions: 850°C, -1.0 A/cm², 45% CO₂ – 45% H₂O – 10% H₂
Electrolysis durability at high current density — Today

Ni/YSZ electrode

Reference

Tested cell

LSM/YSZ electrode

Reference

Tested cell

Conditions: 850°C, -1.0 A/cm², 45% CO₂ - 45% H₂O - 10% H₂
Electrolysis durability at high current density
— Today

LSM/YSZ electrode

Conditions: 850°C, -1.0 A/cm², 45% CO₂ – 45% H₂O – 10% H₂
Vision
— Synthesis at increased pressure

Renewable electricity

H₂O
Released to the atmosphere

Synthetic petrol/diesel

CO₂ in the atmosphere

Fuel synthesis
2H₂ + CO → -CH₂- + H₂O

Fuel transport

CO + H₂

Consumption

Electrolysis cell
2H₂O → 2H₂ + O₂
2CO₂ → 2CO + O₂

Fuel synthesis

CO₂ collection
CO₂ + 2OH⁻ (membrane) → H₂O + CO₃²⁻ (membrane)

Synthetic petrol/diesel

CO₂

H₂O

Renewable electricity

H₂O

Concentrated CO₂
**Vision**

— Synthesis at increased pressure

1) Durable stacks (proven up to -0.75 A/cm²)
2) Stacks operated at pressure up to 50 bar
3) Fuel synthesis (proven technology)
Vision
— Synthesis at increased pressure
Summary

• The Solid Oxide Cells are fully reversible
  
  Fuel cell operation $\leftrightarrow$ Electrolysis operation

• Degradation is more severe in electrolysis mode compared to fuel cell mode

• Degradation at mild conditions is related to impurities
  
  This degradation can be avoided by cleaning for impurities

• At harsh conditions structural changes occur in the cells
  
  Need cells with lower polarisation $\rightarrow$ lower degradation

• Cells can be operated safely at current densities up to -0.75 A/cm$^2$ at 850°C

• Operation at high pressure advantageous for system integration

• Solid Oxide Electrolysis cells may contribute to storage of renewable electricity
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- Danish PSO via the project “Durable solid oxide electrolysis cells and stacks”

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