Solid Oxide Electrolysis Cells - High pressure operation

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-High pressure operation

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

**Electrolysis Cell (SOEC)**

\[
\begin{align*}
H_2O \text{ (cathode)} & \rightarrow H_2 \text{ (cathode)} + \frac{1}{2} O_2 \text{ (anode)} \\
CO_2 \text{ (cathode)} & \rightarrow CO \text{ (cathode)} + \frac{1}{2} O_2 \text{ (anode)}
\end{align*}
\]

**Fuel Cell (SOFC)**

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

- **Electrolysis Cell (SOEC)**
  \[ \begin{align*}
  H_2O_{(cathode)} & \rightarrow H_2{_{(cathode)}} + \frac{1}{2} O_2{_{(anode)}} \\
  CO_2{_{(cathode)}} & \rightarrow CO{_{(cathode)}} + \frac{1}{2} O_2{_{(anode)}}
  \end{align*} \]

- **Fuel Cell (SOFC)**
  \[ \begin{align*}
  H_2{_{(anode)}} & + \frac{1}{2} O_2{_{(cathode)}} \rightarrow H_2O{_{(anode)}} \\
  CO{_{(anode)}} & + \frac{1}{2} O_2{_{(cathode)}} \rightarrow CO_2{_{(anode)}}
  \end{align*} \]

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

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

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

H₂O

Released to the atmosphere

4 e⁻ → Electrolysis cell

2H₂O → 2H₂ + O₂

2CO₂ → 2CO + O₂

Vision

Concentrated CO₂

CO + H₂

2O²⁻

Renewable electricity

H₂O

Fuel transport

2O₂⁻

CO₂ collection

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

H₂O

Released to the atmosphere

4 e⁻ + \(2 \text{H}_2 \text{O} \rightarrow 2\text{H}_2 + \text{O}_2\)

2\(\text{CO}_2 \rightarrow 2\text{CO} + \text{O}_2\)

Fuel synthesis

\(2\text{H} + \text{CO} \rightarrow \text{CH}_2\text{O} + \text{H}_2\text{O}\)

CO + H₂

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 transport

Renewable electricity

Concentrated\(\text{CO}_2\)

\(\text{H}_2\text{O}\)
Renewable electricity

H$_2$O Released to the atmosphere

Electrolysis cell

2H$_2$O $\rightarrow$ 2H$_2$ + O$_2$

2CO$_2$ $\rightarrow$ 2CO + O$_2$

Fuel synthesis

2H$_2$ + CO $\rightarrow$ -CH$_2$- + H$_2$O

Synthetic petrol/diesel

Consumption

Fuel transport

Renewable electricity

Concentrated CO$_2$

H$_2$O

Vision
**Vision**
— Collection of CO₂ from the atmosphere

- **CO₂ in the atmosphere**
- **CO₂ collection**
  \[ \text{CO₂} + 2 \text{OH}^{\text{membrane}} \leftrightarrow \text{H₂O} + \text{CO₃}^{2-}^{\text{(membrane)}} \]

- **Electrolysis cell**
  \[ \text{2H₂O} \rightarrow \text{2H₂} + \text{O₂} \]
  \[ \text{2CO₂} \rightarrow \text{2CO} + \text{O₂} \]

- **Synthetic petrol/diesel**
  \[ \text{2H₂} + \text{CO} \rightarrow \text{CH₂}^- + \text{H₂O} \]

- **Fuel synthesis**
  \[ \text{CO} + \text{H₂} \]

- **Fuel transport**
  \[ \text{H₂O} \]

- **H₂O**
  Released to the atmosphere

- **Consumption**

- **Renewable electricity**
Vision
— Collection of CO₂ from industries

Electrolysis cell

2H₂O → 2H₂ + O₂
2CO₂ → 2CO + O₂

Fuel synthesis

2H₂ + CO → CH₂ + H₂O

Synthetic petrol/diesel

Fuel transport

Consumption

Concentrated CO₂

(Renewable) Electricity

H₂O

H₂O Released to the atmosphere

CO₂ Released to the atmosphere

CO + H₂

H₂O Released to the atmosphere

Vision — Collection of CO₂ from industries
Vision
— Collection of CO$_2$ from power plants

- CO$_2$ Released to the atmosphere
- H$_2$O Released to the atmosphere
- Consumption
- Fuel transport

Electrolysis cell
2H$_2$O $\rightarrow$ 2H$_2$ + O$_2$
2CO$_2$ $\rightarrow$ 2CO + O$_2$

Concentrated CO$_2$

(Fuel synthesis)
2H + CO $\rightarrow$ CH$_2$ + H$_2$O

Synthetic petrol/diesel

Vision — Collection of CO$_2$ from power plants
Vision
— Storing renewable electricity via Natural Gas

\[ 2H_2O \rightarrow 2H_2 + O_2 \]
\[ 2CO_2 \rightarrow 2CO + O_2 \]

\( \text{Electrolysis cell} \)

\( \text{CO}_2 \) Released to the atmosphere

\( \text{H}_2\text{O} \) Released to the atmosphere

\( \text{Stor rage} \)
and consumption
Natural gas burners

\( \text{CO}_2 \)
\( \text{H}_2\text{O} \)

\( \text{Consumption} \)

\( \text{Fuel synthesis} \)
\[ H_2 + CO \rightarrow CH_4 \]

\( \text{Fuel transport} \)

\[ \text{CO} + H_2 \]

\( \text{CO}_2 \) Released to the atmosphere

\( \text{H}_2\text{O} \)

\( \text{CO}_2 \) Released to the atmosphere

\( \text{H}_2\text{O} \)

\( \text{(Renewable) Electricity} \)
Vision
— Biogas upgrading

CO₂ Released to the atmosphere

Fuel synthesis
\( \text{CH}_4 + \text{H}_2 + \text{CO} \rightarrow \text{CH}_4 \)

CH₄ + CO + H₂

Electrolysis cell
\( 2\text{H}_2\text{O} \rightarrow 2\text{H}_2 + \text{O}_2 \)
\( 2\text{CO}_2 \rightarrow 2\text{CO} + \text{O}_2 \)

\( \text{H}_2\text{O} \) Released to the atmosphere

Storage and consumption
Natural gas burners

Consumption

Fuel transport

(Renewable) Electricity

\( \text{H}_2\text{O} \)

CH₄

\( \text{H}_2\text{O} + \text{CO}_2 \)
Vision

- Production of synthetic fuels from renewable electricity (wind) and:
  - CO₂ from the atmosphere
  - CO₂ from the industry
  - CO₂ 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: 850ºC, 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: 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 high current density
Electrolysis durability at high current density
—Standard Ni-YSZ based cells with LSM $O_2$ electrode

Conditions: $-1,0 \text{ A/cm}^2$, 45% $\text{CO}_2$ – 45% $\text{H}_2\text{O}$ – 10% $\text{H}_2$
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: 850ºC, -1.0 A/cm², 45% CO₂ – 45% H₂O – 10% H₂
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

Ni/YSZ electrode

Reference

Tested cell

LSM/YSZ electrode

Reference

Tested cell

Conditions: 850ºC, -1,0 A/cm², 45% CO₂ – 45% H₂O – 10% H₂
Electrolysis durability at high current density — Today

LSM/YSZ electrode

Conditions: 850ºC, -1,0 A/cm², 45% CO₂ – 45% H₂O – 10% H₂
Vision
— Synthesis at increased pressure

Renewable electricity
H₂O
Released to the atmosphere

CO₂ in the atmosphere

Synthetic petrol/diesel

Fuel synthesis
2 H₂ + CO → –CH₂– + H₂O

Fuel transport

CO + H₂

Electrolysis cell

2H₂O → 2H₂ + O₂
2CO₂ → 2CO + O₂

Concentrated CO₂

H₂O

Consumption

H₂O

CO₂ collection

CO₂ + 2 OH– (membrane) → H₂O + CO₃²– (membrane)
Renewable electricity

H₂O Released to the atmosphere

4 e⁻ \rightarrow \text{Electrolysis cell}

2H₂O → 2H₂ + O₂

2CO₂ → 2CO + O₂

CO₂ in the atmosphere

Synthetic petrol/diesel

Fuel synthesis

2H₂ + CO \rightarrow \text{CH}_2- + H₂O

CO + H₂

Fuel transport

Consumption

2O₂- (membrane) \rightarrow H₂O + CO₃²-

Renewable electricity

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 850ºC

• Operation at high pressure advantageous for system integration

• Solid Oxide Electrolysis cells may contribute to storage of renewable electricity
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