Solid Oxide Electrolysis Cells - High pressure operation

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Publication date:
2013

Citation (APA):
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- High pressure operation

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SYMPOSIUM
Water electrolysis and hydrogen as part of the future Renewable Energy System
Copenhagen, May 10-11 2012
The Solid Oxide Cell (SOC) — Reversible, SOEC ↔ SOFC

• Electrolysis Cell (SOEC)

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

• Fuel Cell (SOFC)

\[ \text{H}_2 (\text{anode}) + \frac{1}{2} \text{O}_2 (\text{cathode}) \rightarrow \text{H}_2\text{O} (\text{anode}) \]
\[ \text{CO} (\text{anode}) + \frac{1}{2} \text{O}_2 (\text{cathode}) \rightarrow \text{CO}_2 (\text{anode}) \]
The Solid Oxide Cell (SOC) — Reversible, SOEC ↔ SOFC

• Electrolysis Cell (SOEC)

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\[ \text{CO} \text{(anode)} + \frac{1}{2} \text{O}_2 \text{(cathode)} \rightarrow \text{CO}_2 \text{(anode)} \]

One major advantage of SOECs is the possibility to reduce \text{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

CO + H₂

CO₂ collection

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

Concentrated CO₂

Renewable electricity

H₂O

Vision
Renewable electricity

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

$4e^- \rightarrow \text{Electrolysis cell}$

$2\text{H}_2\text{O} \rightarrow 2\text{H}_2 + \text{O}_2$

$2\text{CO}_2 \rightarrow 2\text{CO} + \text{O}_2$

**Fuel synthesis**

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

**Fuel transport**

**Concentrated CO$_2$**

**H$_2$O**

**Renewable electricity**
Renewable electricity

\[ H_2O \text{ Released to the atmosphere} \]

Electrolysis cell

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

Fuel synthesis

\[ 2H_2 + CO \rightarrow -\text{CH}_2- + H_2O \]

Synthetic petrol/diesel

Fuel transport

Consumption

CO\(_2\) in the atmosphere

H\(_2\)O

CO\(_2\) collection

\[ CO_2 + 2OH^- (\text{membrane}) \rightarrow H_2O + CO_3^{2-} (\text{membrane}) \]

Renewable electricity

H\(_2\)O

Concentrated CO\(_2\)
Vision
— Collection of CO₂ from the atmosphere

Renewable electricity
H₂O
Released to the atmosphere

H₂O
Fuel transport

Synthetic petrol/diesel

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

CO + H₂

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

Concentrated CO₂

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

CO₂ in the atmosphere

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

CO₂ Released to the atmosphere

Electrolysis cell

2H₂O → 2H₂ + O₂
2CO₂ → 2CO + O₂

(renewable) Electricity

Synthetic petrol/diesel

Fuel synthesis

2H₂ + CO → –CH₂– + H₂O

CO + H₂

Fuel transport

Consumption

H₂O Released to the atmosphere

H₂O

Concentrated CO₂

Vision—Collection of CO₂ from industries

Electrolysis cell

2H₂O → 2H₂ + O₂
2CO₂ → 2CO + O₂

(renewable) Electricity

Synthetic petrol/diesel

Fuel synthesis

2H₂ + CO → –CH₂– + H₂O

CO + H₂

Fuel transport

Consumption

H₂O Released to the atmosphere

H₂O

Concentrated CO₂

Vision—Collection of CO₂ from industries

Electrolysis cell

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2H₂ + CO → –CH₂– + H₂O

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Fuel transport

Consumption

H₂O Released to the atmosphere

H₂O

Concentrated CO₂

Vision—Collection of CO₂ from industries

Electrolysis cell

2H₂O → 2H₂ + O₂
2CO₂ → 2CO + O₂

(renewable) Electricity

Synthetic petrol/diesel

Fuel synthesis

2H₂ + CO → –CH₂– + H₂O

CO + H₂

Fuel transport

Consumption

H₂O Released to the atmosphere

H₂O

Concentrated CO₂
Vision
— Collection of CO₂ from power plants

CO₂ Released to the atmosphere

H₂O Released to the atmosphere

Synthetic petrol/diesel

Fuel synthesis
2 H₂ + CO → CH₂ + H₂O

Fuel transport

Concentration of CO₂

CO₂ Released to the atmosphere

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

Concentrated CO₂

(Renewable) Electricity

H₂O

Consumption
Vision
— Storing renewable electricity via Natural Gas

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

Fuel synthesis
H₂ + CO → CH₄

Storage and consumption
Natural gas burners

CO₂ Released to the atmosphere
H₂O Released to the atmosphere

Consumption
Fuel transport

(Renewable) Electricity

CO₂

H₂O

Natural gas burners

Consumption
Fuel transport

(Renewable) Electricity

Vision
— Storing renewable electricity via Natural Gas

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

Fuel synthesis
H₂ + CO → CH₄

Storage and consumption
Natural gas burners

CO₂ Released to the atmosphere
H₂O Released to the atmosphere

Consumption
Fuel transport

(Renewable) Electricity

CO₂

H₂O
Vision
— Biogas upgrading

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

Fuel synthesis
CH₄ + H₂ + CO → CH₄
CH₄ + CO + H₂

Storage
and consumption
Natural gas burners

CO₂
Released to the atmosphere

H₂O
Fuel transport
(Renewable) 
Electricity

H₂O
Released to the atmosphere

CH₄
H₂O + CO₂

Consumption

Natural gas burners

Fuel synthesis

Vision
— Biogas upgrading
Vision

• Production of synthetic fuels from renewable electricity (wind) and:
  
  – CO$_2$ from the atmosphere
  
  – CO$_2$ from the industry
  
  – 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% H₂O – 50% H₂
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 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: 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

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

CO₂ in the atmosphere

H₂O Released to the atmosphere

Synthetic petrol/diesel

Fuel synthesis
2 H₂ + CO → CH₄ + H₂O

Fuel transport

Consumption

CO + H₂

Fuel transport

Renewable electricity

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

2O²⁻

4 e⁻

Concentrated CO₂

H₂O
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 $-0.75 \text{ A/cm}^2$ at $850^\circ\text{C}$

- Operation at high pressure advantageous for system integration

- Solid Oxide Electrolysis cells may contribute to storage of renewable electricity
Acknowledgement

• The Danish National Advanced Technology Foundation’s advanced technology platform “Development of 2nd generation bioethanol process and technology”

• Danish Council for Strategic Research, via the Strategic Electrochemistry Research Center

• European Commission via the project “Hi2H2”

• European Commission via the project “RelHy”

• EUDP via the project “Green Natural Gas”

• Danish PSO via the project “PlanSOEC”

• Danish PSO via the project “Durable solid oxide electrolysis cells and stacks”

• DTU Energy Conversion (Former Risø DTU) via the project SOECcell

• Topsoe Fuel Cell A/S (TOFC)