Solid Oxide Fuel Cell systems and Renewable Energy sources

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(on sabbatical at Imperial College London this academic year)
Future Energy Mix and Biofuels

• Biomass (mainly waste) will/might get increasingly important as an energy source
• Fossil fuels will still be relevant
• Biomass is storable
• Competing uses: biomass for chemicals or energy?
• Electricity and transportation fuel production from biomass – widely studied and already demonstrated
• Efficiency increase will be of importance
• Sanitation systems- potential exists for biofuel production
Biofuels

- Biomass
- Biogas
- Biosyngas
- Hydrogen
- Ammonia
- Ethanol
- Methanol
- Char .........

As biomass will be in limited supply, efficient utilization will be of utmost importance.

Renewable fuel production possible with electrolysis, co-electrolysis and fuel assisted electrolysis - an energy storage option for renewable energy future.
Solid Oxide Fuel Cell

- SOFCs work at high temperatures - 500 °C to 1000 °C
- Electrical efficiencies - 45 to 60%
- Fuel is never completely utilized and the flue gas can be combusted
- Can operate with different biofuels
• If the SOFC is at high pressure, outlet streams can be fed to a gas turbine
• SOFC-GT systems can reach efficiencies as high as 70-80%
• They can still be connected with other bottoming cycles
SOFC-GT system efficiencies with different biofuels

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Energy Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane</td>
<td>78.3</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>69.0</td>
</tr>
<tr>
<td>Ammonia</td>
<td>74.7</td>
</tr>
<tr>
<td>Ethanol</td>
<td>75.5</td>
</tr>
<tr>
<td>Methanol</td>
<td>73.1</td>
</tr>
</tbody>
</table>

Our focus

- Development of high efficiency systems for biofuels
- Waste to energy and resources
- Stationary and mobile applications
- Aircraft and marine propulsion
- A special focus on biomass gasifier-SOFC systems

Our projects include

- Biomass gasifier-SOFC system development
- Waste water treatment- Biogas and Ammonia production for SOFCs together with fertilizer production
- Biofuels and fuel cells for aircrafts
- ..................
What we do- an example: Gasifier-SOFC systems

- Focus on biomass gasifier-SOFC-GT systems
- Studies on electrochemistry of fuel oxidation:
  - Impedance spectroscopy
  - Chem. eq. calculations
  - Electrochemistry integrated CFD
- High temperature gas cleaning for SOFCs
- SOFC cell and stack testing
- Detailed system studies
SOFCs fed with biosyngas

- Sustainable high efficiency electricity production
- Few kW to few MW systems-
- Close to coal gasification and co-gasification based systems (SECA focus)

Knowledge developed/to be developed on

- Type of gasifier
- Choice of SOFC
- Detailed understanding on the influence of contaminants
- Gas cleaning
- System thermodynamics, System dynamics, System integration
Research Approach

- Started with system studies
- Influence of gas composition on anodes (impedance and IV measurements)
- Influence of contaminants on anodes (equilibrium calc., Impedance and IV measurements, surface analysis)
- Gas cleaning
- System integration (system thermodynamics, integrated exps.)
Energy System Thermodynamics at TU Delft

- Modelling Packages used - Cycle Tempo and Aspen

- Cycle Tempo - An in-house product for second law analysis of power plants (~ 100 users worldwide)

**Cycle Tempo Applications**

- fuel cell systems
- gas turbine cycles
- combined cycle plants
- combustion and gasification systems

- heat transfer systems
- steam turbine cycles
- organic Rankine cycles
- refrigeration systems
SOFC- lab facilities

Electrode, Cell, Stack, and Fuel Processing Test stations
Electrochemical Studies

Impedance measurements with Ni/GDC anodes

Several hundred impedance measurements to get clearer concepts on rate limiting steps

Detailed modeling of gas diffusion impedance

Impedance measurements with biosyngas compositions

\[
R_d = \eta_D/I = 2 \left( \frac{RT}{2F} \right) l \left( \frac{1}{D_{H_2O-mix}X_{H_2O,B}} + \frac{1}{D_{H_2-mix}X_{H_2,B}} \right)
\]

Impedance measurements with contaminants

Measurements with different contaminants H$_2$S, HCl, tar, KCl $^{1,2}$

With naphthalene impedance slightly increased

On first look impedance increase is not desirable

With detailed modeling it appears that this increase is due to reforming

Impedance measurements with contaminants

Operating temperature: 800 °C
Operating pressure: Ambient pressure
Anode types: Ni/YSZ
Syngas composition (%): 16 H₂, 1.5 CH₄, 46.5 N₂, 16 CO₂, 20 CO (10 % steam as of dry gas)
Tar concentration: 6.3 g Nm³

1. Higher current density helps to suppress carbon deposition
2. 10% at 150 mA cm⁻² does not ensure a carbon deposition-free scenario

Figure 1. Influence of current density on the impedance spectra of SOFCs

Figure 2. Image of anode microstructure with carbon deposition (arrow direction) after 5 hours tar exposure at 100 mA cm⁻²

SOFCs with contaminants- I-V measurements

SOFC cells and stacks with biosyngas

Electrochemistry integrated Computational Fluid Dynamics for cell performance evaluation

Medium temperature Gas Cleaning Unit- Process Scheme

GCU connected with the gasifier and the fuel cells
- (1 kW stack)
- Lowest temperature 350 °C

High Temperature Gas Cleaning Unit - Process Scheme

Contaminants to be removed include

1. Tars
2. Particulates
3. Alkali metal compounds
4. HCl, H$_2$S etc.
Gasifier-SOFC experiments: Delft

Experiments carried out at Delft

Circulating fluidized gasifier employed

SOFCs with Ni/GDC anodes were tested

Tests carried out by TU Delft, NTUA, TU Graz and ECN

Medium temperature gas cleaning employed
Gasifier-SOFC experiments: Results

Few thousand ppm tar had no significant impact on SOFC for several hours

Therm. Eval. : Gasifier-SOFC+GT system with high. temp gas cleaning

<table>
<thead>
<tr>
<th>Apparatus</th>
<th>Energyflow [kW]</th>
<th>Totals [kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorbed power</td>
<td>Sink/Source</td>
<td>164,02</td>
</tr>
<tr>
<td>Delivered gross power</td>
<td>Generator</td>
<td>30,00</td>
</tr>
<tr>
<td></td>
<td>Fuel Cell</td>
<td>62,96</td>
</tr>
<tr>
<td></td>
<td></td>
<td>92,96</td>
</tr>
<tr>
<td>Aux. power</td>
<td></td>
<td>4,49</td>
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<tr>
<td>Delivered net power</td>
<td></td>
<td>88,47</td>
</tr>
<tr>
<td>Delivered heat</td>
<td>Heat Sink</td>
<td>30,12</td>
</tr>
<tr>
<td>Total delivered</td>
<td></td>
<td>118,59</td>
</tr>
<tr>
<td>Efficiencies</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gross</td>
<td>56,67%</td>
<td></td>
</tr>
<tr>
<td>Net</td>
<td>53,94%</td>
<td></td>
</tr>
<tr>
<td>Heat</td>
<td>18,36%</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>72,30%</td>
<td></td>
</tr>
</tbody>
</table>

PV Aravind, T Woudstra, N Woudstra, H Sliethoff, J. Power. Sources, 190(2): 461-475
Therm. Eval. : Gasifier-SOFC+GT system with high. temp gas cleaning-2

With highly integrated systems Electrical Efficiencies achievable are around 70%

Integration of a Siemens 5 kW SOFC stack to a biomass gasifier

- Together with Itajuba University Brazil: Industry/NUFFIC-NESO funded
- SOFC system modification and long term testing
- Combination of low temperature and high temperature cleaning units
- Gas cleaning system components are being developed
- PhD students from Delft and Itajuba

Retrofitting SOFC to an operational ~250 MW IGCC operating on Coal-Biomass mixtures

1. Fully detailed thermodynamic calculations
2. Second law analysis
3. Operational IGCC
4. Base case models validated using experimental data
5. >40% efficiencies achievable
6. SOFCs can be retrofitted
7. CCS integration possible
SCWG-SOFC integration project

1. Dutch national project with industrial participation
2. SCWG's can handle wet biomass and produce cleaner gas mixtures

Preliminary system calculations indicate ~ 50% efficiency for SCWG-SOGFC-GT systems

Reinventing the toilet - the role of SOFCs

1. Multi million dollar project, all for TU Delft
2. Integrated system development
3. Microwave assisted plasma gasification
4. SOFCs for producing electricity for the plasma gasifier
Gasifier-SOFC systems: What is achieved

- Clean syngas compositions are fine with SOFCs
- Tolerance levels for various contaminants are higher than previously thought
- State of the art gas cleaning systems are probably sufficient
- Successful short duration integrated gasifier-SOFC experiments (> 10000 ppm tar fed to SOFC)
- Above 50% electrical efficiency achievable with gasifier-SOFC+GT systems (possibly even around 70% with highly integrated systems)
- With low temp. gas cleaning, electricity production efficiencies are slightly lower for gasifier-SOFC+GT systems
Waste Water to Power

The project involves

• Production of ammonia from waste water and urine (by project partners)

• Evaluation of the influence of contaminants on ammonia fed SOFC

• Demonstration of the concept

• Thermodynamic evaluation and optimization

• Royal Institute of Engineers award for the project for innovativeness

• Joint project together with industrial partners

Modelling SOFC-GT systems for UAVs

- Base case adopted from:

- Present focus: biofuels for such aircrafts

<table>
<thead>
<tr>
<th>High Endurance Long Distance</th>
<th></th>
</tr>
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<tbody>
<tr>
<td>Hurricane science</td>
<td>Communications Relay</td>
</tr>
<tr>
<td>14 day-flight (180 days goal)</td>
<td>12 day-flight (178 days goal)</td>
</tr>
<tr>
<td>Cruise Velocity: 151 km/h</td>
<td>Cruise Vel.: 201 km/h</td>
</tr>
<tr>
<td>Distance: 5000 km</td>
<td>Distance: 3500 km</td>
</tr>
<tr>
<td>Cape verde</td>
<td>Las Cruces, USA</td>
</tr>
<tr>
<td>Altitude: 21km or +</td>
<td>Altitude: 18km (21 km goal)</td>
</tr>
</tbody>
</table>
1. TUD-ECN joint project
2. Detailed system studies and preliminary experiments
Synthetic Methane Project: Fuel Assisted Electrolysis

Conversion electricity to CH₄

Solar
Wind
Hydro

Gas Storage

Solid Oxide Electrolyzer

H₂

SNG plant

CH₄

G-GRID

Combined Heat Power

CO₂ Capture

CO₂ Re-Use

CO₂ from capture plants

Bio-Syngas And/or Biogas

CO₂ from capture plants

Bio-Syngas And/or Biogas

Storage
Summary

1. Biomass need to be converted with highest possible efficiency
2. Solid Oxide Fuel Cell Systems help to achieve high efficiencies in bioenergy conversion
3. Around 70% electrical efficiency achievable with highly integrated gasifier-SOFC-Gas Turbine systems
4. Solid oxide fuel cells can probably tolerate many biomass derived contaminants including tars to certain limits
5. Mobile applications will require production of easy to handle fuels- SOFCs can then be used for electricity production
6. Sanitation systems- potential exists for biofuel production and resource recovery
Thank You!