Evaluation studies of solid oxide-based fuel cells for light-weight electrical power in aviation: Concepts and opportunities for the application of additive manufacturing

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NASA is investigating the feasibility of a hybrid-electric, solid oxide fuel cell power (SOFC) system for generation of electrical power for airborne propulsion and secondary/auxiliary power.
The electrochemical reactions:

**cathode:** \( \frac{1}{2} O_2 + 2e^- = O \)

**anode:** \( H_2 + \frac{1}{2}O_2 = H_2O + 2e^- \)

**overall cell reaction:** \( \frac{1}{2}O_2 + H_2 = H_2O \)
Solid Oxide Fuel Cell Stack Technology Challenges

- High temperature operation
- Thermal cycling
- Performance degradation
- Structural integrity
- Sealing
- Packaging
Current Solid Oxide Fuel Cell Technology
Gas flow manifold configurations

Cross-Flow XF1

Co-Flow CF1

Bipolar Plate
Anode
Electrolyte
Cathode

Fuel

Oxidizer
# Stack Information

<table>
<thead>
<tr>
<th>SOFC Stack Designation</th>
<th>Architecture</th>
<th>Number of Cells</th>
<th>Manifold Type</th>
<th>Power Rating</th>
<th>Operational Temperature</th>
<th>Normal Open circuit Potential per Cell</th>
<th>Active Area cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stack-XF1</td>
<td>Electrolyte Supported</td>
<td>10</td>
<td>Cross-flow</td>
<td>400</td>
<td>800</td>
<td>1.1</td>
<td>105</td>
</tr>
<tr>
<td>Stack-CF1</td>
<td>Electrolyte Supported</td>
<td>30</td>
<td>Co-flow</td>
<td>850</td>
<td>860</td>
<td>0.9</td>
<td>127.8</td>
</tr>
</tbody>
</table>

## Start-Up Sequence

<table>
<thead>
<tr>
<th>Stack</th>
<th>Heating Rate °C/min</th>
<th>Gas Temperature, °C</th>
<th>Gas Flow, LPM</th>
<th>Applied Electric Current Rate, Amp/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stack-XF1</td>
<td>2</td>
<td>800</td>
<td>800</td>
<td>8</td>
</tr>
<tr>
<td>Stack-CF1</td>
<td>4</td>
<td>800</td>
<td>800</td>
<td>8</td>
</tr>
</tbody>
</table>
FuelCon Model: Evaluator –S 70630

Furnace (electric hoist)

Applied external clamping

SOFC Stack

Electronic Load
Commercial 30 – cell 700 Watt stack
Stack XF1 Performance

Dry H2 setpoint = 10.03 Nlpm ; N2 setpoint = 10.03
Air Flow setpoint: 47.88 Nlpm to 178.33

~802 °C

ASR (0.1 - 0.5 A/cm²) = 0.64 ohm-cm²
Average cell performance within the stack

Stack-XF1

Stack-CF1
Thermal Cycling Schedule

- **Cold Standby**
  - Average Stack Temperature
  - Temperature Ramp 2 °C/min
  - 1 hour hold
  - 150 °C
  - 1 Hour Hold

- **Graph**
  - Temperature vs. Time
  - Temperature, °C vs. Time, minutes
  - Temperature Range: 0 to 800 °C
  - Time Range: 14,000 to 24,000 minutes
  - Oscillating pattern indicating thermal cycling
Open Circuit Potential as a Measure of Seal Integrity

Stack Open Circuit Electric Potential, V

Thermal Cycle

Thermal ramp 2 °C/min
Thermal ramp 6 °C/min

Open Circuit Potential as a Measure of Seal Integrity
Can we improve things?
The Bipolar Plate
Let’s apply finite element analysis: COMSOL
Thermal response when heating the fuel cell stack
The model cell set up
Unit cell power as a function of porosity of the bipolar plate
Time to reach average temperature of 795°C as a function of the porosity of the bipolar plate

Graph showing the cell heat-up time to 795°C minutes as a function of interconnect porosity.
One possible way: Electrode-less Plating Nickel Foam from a Polymer Template
Another possible way: Combine Additive Manufacturing to Solid Oxide Fuel Cell Technology

- Novel Flow-field designs for bipolar plates
- Unique surface chemistries which promote in-situ catalytic reformation
- Balance of Plant components
- Implement SOFC design that will promote high heat and mass transfer.
- Pattern designed
- Transfer to file
- Machined manufactured
- Using standard screen printable inks

A simple example: 20 mm fuel cell anode applied to metal foam
LASER cut nickel foam with applied anode ink
Summary

• Conventional solid oxide fuel cell stacks perform relatively well under static and dynamic conditions.

• Increasing the specific power through architectural design offers the possibility of meeting aviation requirements.

• Applications of methods such as additive manufacture may be a viable path to realizing novel SOFC stacks designs.
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