Structural Limitations in the Scale-Up of Solid Oxide Fuel Cells (SOFCs)

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Session #: Solid Oxide 2B
Outline

Performance/structural simulations of SOFCs

- Background
- Objectives
- Modeling Approach
- Results
- Summary
Stresses may limit area scale-up of planar SOFC stacks.

- Stationary & mobile applications (< 10 kW - > 250 kW)
- Current planar stacks < 2 kW
- Scale-up options for planar SOFCs:
  - Multiple stacks or more cells
    - Economy of scale, but manifolding and contact issues
  - Larger area cells
    - Reduced heat loss, but larger probability for stress build-up, difficult to manufacture, and seal
**Background: Motivation**

Purely empirical assessment of limitations to stack scale-up is difficult.

- **Costly and time consuming to construct and test stacks with different active areas**
  - Instrumentation
  - Manufacturing yield
  - Test equipment

- **Complex phenomena**
  - Interpretation of results
  - Reproducibility
Background: Contributions to Stress

Multiple phenomena contribute to stress build-up.

Constrained Deformation

Temperature Gradients
- Heat Loss
  - Conduction
  - Convection
  - Radiation

Stack Geometry Defects
- Stack Weight
- Compressive Load

Stress Distribution
- Heat Generation
  - Chemical and Electrochemical Reactions
  - Joule Heating

Imposed Loads
Background: Objectives

Develop model to assess SOFC thermo-mechanical stresses during operation.

- How much do compressive load and temperature gradients contribute to stress?
- How does stress distribution in the cell depend on design parameters?
  - Cell size (area)
- How does the stress distribution in the cell depend on the operating conditions?
  - Temperature and stoichiometry of the inlet cathode stream
  - Cell voltage
Approach: Overview

Numerical model for cell performance and stress distribution.

Conservation:
- Energy
- Mass
- Charge

Temperature Gradients

Mechanical Stress Distribution

Constraints

Interconnect

Flow passages

Porous electrodes

Anode and cathode reaction zones

Electrolyte
Approach: 1-d Model to Estimate Parameters

Detailed 1-d model was developed for estimating unknown parameters.

Assumed TPB Microstructure*

- 10 µm electrolyte
- Ionic phase in the electrode reaction zone
- Electro catalyst

Approach: Results from 1-d Model

1-d Model was fit to data and then validated.

- Literature values for temperature dependence of ion conductivity
- 800°C data was fit by adjusting 6 parameters
  - Comparisons to data at other temperatures were obtained without further parameter adjustment

Comparison to Literature Data

Results: 3-d Cell Configuration

Cross-flow anode-supported planar SOFC.

- 2 mm x 2 mm channels
- 6.4 cm
- 97% H₂, 3% H₂O
- 650 °C Air
- 650 °C
Results: Current Density Profile at 0.7 V

Maximum local current density is 20% higher than the average.

Current density distribution, average = 1.3 A/cm²
Results: Temperature Profile at 0.7 V

Cathode stoichiometry of ~ 5 ensures moderate temperature gradients.

Temperature distribution
Results: Residual Stress at Room Temperature

Manufacturing steps are needed for estimating residual stresses.

Sinter Ceramics

Cool to RT

Flatten Ceramics

Heat to Operating Temperature

Total Displacement = 120 µm

Cathode: 36 MPa
Electrolyte: -567 MPa
Anode: -11 MPa to 3 MPa

Cathode: 39 MPa
Electrolyte: -556 MPa
Anode: -3 MPa
Results: Contact Pressure

Low contact pressure at the outer edges might lead to high contact resistance.

*Through thickness stress in the metallic interconnect*

Potential for high contact resistance

Pa

- $1.1 \times 10^5$
- $-1.1 \times 10^5$
- $-3.4 \times 10^5$
- $-5.7 \times 10^5$
- $-7.9 \times 10^5$
- $-10 \times 10^5$
- $-12 \times 10^5$
Results: Stress at Operating Temperature at 0.7 V

Stresses are modest under operating conditions.

No slip between the electrodes and the interconnect

Cathode: +9 to +22 MPa
Electrolyte: -201 to -246 MPa
Anode: -6 to +20 MPa
Movie: Heat Up of Cell by Hot-Gases During Startup

Temperature (C)

Fuel Inlet
H$_2$ + H$_2$O
650 C

Air Inlet
Air
650 C

10 cm
Movie: Current Density Evolution During Startup
Movie: Warping of MEA During Cool Down After Sintering
Summary I: Baseline Stress Calculations

- High stress state occurs at room temperature and not during cell operation.
- Significant residual stresses buildup in the ceramic layers of the MEA during cool down from the stress-free sintering temperature.
- At the steady state operating temperatures (650–850°C), residual stresses are relieved to some extent.
- The temperature gradients during steady-state operation do not generate severe stresses.
Summary II: Stress Dependence on Area

- Increasing cell size increases the lateral mismatch strains but not stress state or overall flatness of the MEA.
  - Increased potential for seal failure

- No-slip shear stresses between IC and MEA are not sustainable without bonding.
  - Slip may cause damage

- The average stresses in the MEA layers at room temperature do not depend strongly on the cell area.

- If non-uniform confining pressure is applied, contact resistance at cell edges might increase with area.

These conclusions depend on the assumed values of TEC and elastic moduli and must be better characterized for standard SOFC materials.
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