Performance Analysis of Reversible Solid Oxide Cells (rSOCs) for Novel Energy Storage Systems

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Introduction

Novel Energy Storage Based on SOCs

In addition to their fuel flexibility, high efficiency, scalability, and long-term cost outlook, reversible high temperature solid oxide cell (rSOC) systems have the potential for round-trip efficiencies competitive with the other available energy storage technologies.

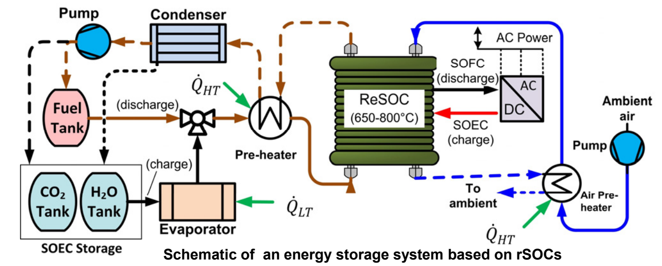
- **Electricity Production**: Operation in fuel cell mode converts the stored fuel (H_2–CO–CH_4 fuel gas mixtures) to dc power
- **Energy Storage:** Operation in high-temperature co-electrolysis mode converts H_2O/CO_2-rich gas mixtures to fuel (H_2-CO-CH_4).

Focus of the Study

The focus of the current study is to investigate modeling methods for rSOCs in order to facilitate future endeavors related to establishing optimal operating conditions and system designs.

The present work seeks to:

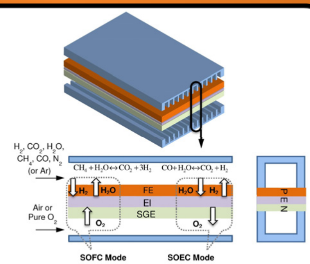
- Develop a high-fidelity, dynamic rSOC stack simulation tool for the purposes outlined above.
- Investigate reversible SOC operation through a combination of modeling and numerical simulation studies.



Schematic of an energy storage system based on rSOCs

Model Description

Geometry & Operation



Reaction in sweep gas electrode:

$$\frac{1}{2}O_2(g) + 2e^- \leftrightarrow O^{2-}$$

Reactions in fuel electrode:

$$H_2(g) + O^{2-} \leftrightarrow H_2O(g) + 2e^-$$

$$CO(g) + O^{2-} \leftrightarrow CO_2(g) + 2e^-$$

Electrochemical Model

Operational voltage: $V_{op} = V_{Nernst} + (\eta_{ohm} + \eta_{act} + \eta_{diff})$

- Only electrochemical reaction of steam is considered.
- Due to slow kinetic of CO_2 electrochemical reaction, CO_2 consumption mostly depends on reverse water gas shift reaction (RWGS).

Ohmic polarisation: $\eta_{ohm} = R_{eq,Ohm}\sum_{k=1}^{n} i$ Ohm Law

Beside the ohmic resistance between the cell components, the model also include the contact resistance available between the cells and stack components.

Activation Polarisation:

$$J = J_{o,FE}\left(\exp\left((1+\alpha_{a,FE})\frac{-n_e F\eta_{act,FE}}{RT}\right) - \exp\left(-\alpha_{c,FE}\frac{n_e F\eta_{act,FE}}{RT}\right)\right)$$

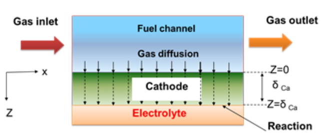
Butler- Volmer Eq. for fuel side

$$J = J_{o,FE}\left(\exp\left(\alpha_{a,SGE}\frac{n_e F\eta_{act,SGE}}{RT}\right) - \exp\left(-\alpha_{c,SGE}\frac{n_e F\eta_{act,SGE}}{RT}\right)\right)$$

Butler- Volmer Eq. for sweep gas side

Concentration Polarisation

Fick's model is considered.
Dusty –gas model is also implemented as an alternative model.



Thermo-chemical Model

The continuity equations comprise the anode and cathode molar flow rate variations due to the existing reactions.

$$\frac{\partial(C_i)}{dt} = -u_{Ca}\frac{\partial C_i}{\partial x} + \sum_j \nu_{i,j} r_j \frac{1}{H_{Ca}}$$

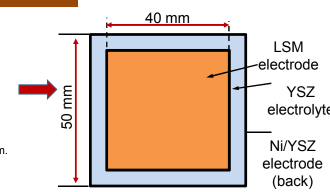
Five modes of energy transport within a cell :
Conduction , Convection, Radiation, Heat release arising from the electrochemical reactions and electrical resistances, Energy accompanying the mass transfer of products and reactants

Results

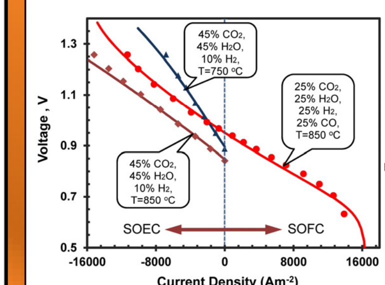
Model Calibration and Validation

Cell consists of 10-15 µm thick Ni/YSZ cermet electrode supported by an ~ 300 µm thick porous Ni/YSZ layer, a 10-15 µm thick YSZ electrolyte, and 15-20 µm thick strontium-doped lanthanum manganite composite LSM/YSZ electrodes.

Ref.: S. D. Ebbesen, R. Knibbe, M. Mogensen, J. Electrochem. Soc., 159 (2012), pp. F482-F489.



Before validation, calibration is needed to establish the BV parameters (exchange current density (J_0), activation energy (E) and symmetry factors (α))



The maximum error observed between the experimental and numerical data is about 5% at current density ~9000 Acm^{-2} for 25% CO_2, 25% H_2O, 25% CO, 25% Ar gas mixture at 850 °C.

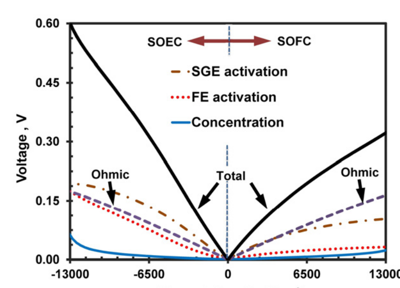
Parametric Study

Effect of temperature on rSOC V-J curve

Reducing the operating temperature

activation polarization in both electrodes is increased significantly due to lower activity of the cell catalyst and surface reactions.

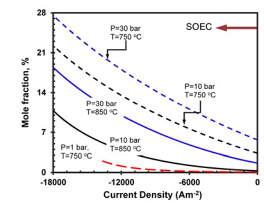
Activation losses in the SOFC mode are less affected by the operating temperature than in SOEC mode.

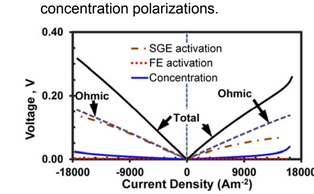


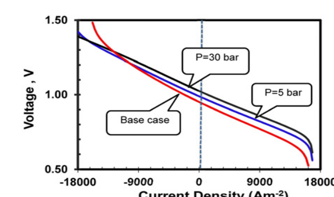
Pressurized Operation

Pressurized operation has two distinct effects on the cell performance.

- pressurized operation promotes the methanation reaction in the SOEC mode.
- it enhances the electrochemical performance of the cell with increasing the Nernst potential and decreasing the losses associated with the activation and concentration polarizations.







The combined effect of the above phenomena increases the overall performance of the cell in both pressurized operating modes.

Conclusions and Future Work

- **The SGE activation polarization and the ohmic resistances are generally the main contributors to the cell losses.**
- **The total electrochemical losses can be significantly different in each operating mode depending on the operating conditions of the cell.**
- **It is observed that the practical way to decrease thermoneutral voltage is to increase the pressure.**
- **The model can readily predict the rSOC performance in various operating conditions and will be a useful tool for rSOC energy storage system studies.**

Next steps: Integrating the rSOC model into the system model

Acknowledgments
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