Title
The Effects of Dynamic Dispatch on the Degradation and Lifetime of Solid Oxide Fuel Cell Systems

Permalink
https://escholarship.org/uc/item/2mm6p4gdc

Journal
JOURNAL OF THE ELECTROCHEMICAL SOCIETY, 158(11)

ISSN
0013-4651

Authors
Nakajo, A
Mueller, F
McLarty, D
et al.

Publication Date
2011

DOI
10.1149/2.032111jes

License
https://creativecommons.org/licenses/by/4.0/ 4.0

Peer reviewed
The Effects of Dynamic Dispatch on the Degradation and Lifetime of Solid Oxide Fuel Cell Systems

A. Nakajo¹, F. Mueller², D. McLarty², J. Brouwer², J. Van Herle¹, and D. Favrat¹

¹Laboratoire d’Energétique Industrielle (LENI) Institut de Génie Mécanique
École Polytechnique Fédérâle de Lausanne, Switzerland
²National Fuel Cell Research Center, University of California, Irvine, California, USA

Understanding mechanisms that affect degradation and durability of solid oxide fuel cell (SOFC) stacks and systems is becoming increasingly important as systems are being deployed around the world. A novel simulation approach accounting for state-of-the-art understanding of degradation mechanisms in the context of an operating SOFC system has been developed. Investigative tools simulating lifetime degradation have been applied to a physical SOFC system model designed and controlled to allow dynamic dispatch. The system was operated in two modes (a) constant power output mode, and (b) diurnal dynamic dispatch mode. Results show that on a time basis the SOFC system with dynamic dispatch proved more durable and less degraded than the system operated in constant full-power output. The net energy production was roughly equivalent between the two modes, with the dynamically dispatched fuel cell degrading slightly less and producing a greater portion of power during peak demand.

Introduction

The solid oxide fuel cell (SOFC) is a direct energy conversion technology that provides decisive advantages in terms of efficiency, fuel flexibility, load following capabilities. The current state-of-the-art lacks the durability expected by industry and public utilities, contributing heavily to the lack of market penetration. The lack of understanding of degradation processes that affect performance and mechanical reliability have resulted in conservative operation strategies that hinder the potential effectiveness and benefit of SOFC devices. First generation commercial products are just now being deployed for large field tests by several major manufactures. These manufactures and system operators must consider the possibility of a value added benefit from additional operational strategies including transient dispatch modes.

Several known degradation mechanisms exist that reduce SOFC performance, often depending upon stack design, system implementation and operating conditions. They arise from instabilities of the materials in the harsh reduction and oxidation environment, volatile contaminating species in the feed gases, and uneven distribution of local conditions. Cathodes made of lanthanum strontium manganite and yttria-stabilised zirconia (LSM-YSZ) or lanthanum strontium cobaltite ferrite (LSCF) are subjected to chromium contamination and formation of lanthanum (LZO) or strontium zirconate (SZO) phases with a low electrical conductivity (1-6). Nickel-based (Ni-YSZ) anodes
suffer from sulfur poisoning, nickel particle coarsening and re-oxidation (7, 8). The
ohmic losses increase in a SOFC stack due to the oxidation of the metallic interconnects
(MIC) and decrease of the ionic conductivity of 8YSZ (9, 10).

Analyses and characterization of SOFC material performance and degradation must
be integrated with the analyses of the complete system within which the SOFC operates.
The thermal, mass flow, and electrical integration of the stack with the remaining balance
of plant (BoP) induces several constraints and compounding factors that may lessen or
increase the severity of the degradation mechanisms. A previously developed system
level modeling methodology has been expanded and utilized in conjunction with the
stack degradation analysis to demonstrate the lifetime impact of dispatched operation.
The methodology has previously been used to simulate simple cycle high temperature
fuel cell configurations and advanced concepts such as the fuel cell gas turbine hybrid
(11-18).

The modeling methodology descretized each system component into multiple control
volumes that separate the basic physics and allow for spatial determination of local
conditions such as temperature, pressure, and concentration. Dynamic conservation
expressions for mass, energy, and composition are evaluated simultaneously with
expressions for transport phenomena (e.g. heat transfer and diffusion), chemical reaction
kinetics (e.g. reformation and water-gas shift) and a robust electrochemistry model.
Individual component models can be integrated into complex system models in a variety
of configurations, including combined cooling heat and power applications, upon which
the design of various control strategies can be implemented and tested (19-22).

The aim of the present study is to demonstrate that (i) a SOFC system can be
adequately designed and controlled in the view of dispatched electrical power generation,
with (ii) a minimal penalty or even positive impact on the lifetime of the device, with
beneficial economic implications. A set of specific models that have been developed for
(i) SOFC system design and control synthesis (11-22) and (ii) analysis and mitigation of
the electrochemical degradation at the stack scale constitutes the basis for the analysis
(23). The combination of these different aspects is required for the present purpose to
correctly capture the complexity of the issues and understand the underlying physics. To
our knowledge, it is the first time that an approach that retrieves knowledge from the
electrode micro-scale to the system macro-scale is applied on the analysis of the short and
long-term dynamic analysis of a SOFC system. The simulations compare two different
operating modes of the SOFC system: (i) constant power output and (ii) diurnal dynamic
dispatch. The feasibility is first demonstrated at the system level. Then, the impact of the
operating mode on the degradation behavior of the SOFC stack is thoroughly investigated
and characterized.

Model Development

System Level Analysis Model Description

Control design and system analyses were accomplished using detailed first principles
models developed in the MatLab®Simulink® framework. The simulated system employs
a spatially- and temporally-resolved fuel cell model that accounts for internal
manifolding heat transfer using simplified planar flow geometry. Additional bulk and nodal dynamic models account for the remaining balance of plant components to simulate a complete SOFC system (Figure 1) operating with an external reformer (13).

![Figure 1. Externally reformed SOFC system diagram.](image)

**Integrated Stack/Manifold.** The quasi-3D dynamic model simulates a generic planar SOFC design with scalable active area and the option for internal and/or external reforming. Discretization of the cell cross-section into 25 nodes provided a balance of computational efficiency and accuracy. Five distinct control volumes comprise each node; oxidant separator plate (interconnect), cathode gas, electrode/electrolyte (PEN) assembly, anode gas, and fuel separator plate (interconnect). Spatial resolution allows for analyses of internal temperature profiles and thus internal heat transfer must be modeled with precision. This approach provides significant improvement in accuracy over a bulk model, particularly in the tasks of system design, scaling and control, while accurately determining SOFC performance within the system. The primary dynamic expressions for mass flow, temperature, and species conservation assume a perfectly stirred reactor for each gaseous control volume, an equipotential electrode, and ideal gas behavior for mass flow and convective heat transfer. The thermal balance relies upon seven parameter curve fits for the specific heat of each of the seven species considered. The electrochemical model accounts for general overpotential characteristics at the electrode/electrolyte interface including both activation and diffusion polarization losses. The model was tuned to state-of-the-art data.

The current work extends previous methodologies through integration of pre- and post-heating manifolds into the stack configuration. This novel approach captures the physics that couples internal manifolding to cell performance characteristics and temperature distributions within a fuel cell stack. This is achieved through the description of a simplified manifolding geometry wherein the incoming air and fuel streams flow pass the stack edges prior to entering the active cell area and after exiting the active cell area.

**Balance of Plant.** The additional components considered in the system design are an external reformer, air and fuel pre-heaters, oxidizer, blower and bypass valves, which are arranged as shown in Figure 1. Both the nodal heat exchanger models and nodal reformer model utilize the same dynamic expressions for energy and mass conservation. Dynamic species conservation applies only to the reformer model with reformation rates determined using the expressions and constants developed by Xu and Froment (24). The oxidizer assumes complete combustion of any remaining methane, carbon monoxide, and hydrogen in a perfectly stirred reactor volume with the previous control volume analysis for mass conservation and pressure.
Control Design. The SOFC system with external reformation requires control of sufficient system actuators to manipulate electrical power output, fuel utilization, cathode inlet temperature, and cathode exhaust temperature within desired limits. The control scheme applied uses six feedback loops to meet varying power demand while maintaining operating conditions within desired limits. The overall system control strategy is presented in Table I with the proportional and integral (PI) control gains for each of the feedback loops presented. Note that response time of fuel cell outlet conditions is substantially slower due to the gaseous volume and thermal mass of the stack and manifolding. Oxidizer fuel injection and blower bleed valve are triggered feedback loops only active when saturation is reached for the bypass valve and blower power respectively.

### Table I. Control System Design Specification.

| System Parameter | Manipulated Variable | Control Type       | Normalized Input | Control Values |
|------------------|----------------------|--------------------|------------------|----------------|
|                  |                      | Control Type       |                  |                |
| Power            | Voltage              | Feed-back          | Specific Power   | 1e-2           |
| Fuel Use         | Fuel Flow            | Feed-forward       | Current          | 0              |
| Inlet Temperature| Bypass Valve         | Feed-forward/back  | Stack Inlet Temp | 0.02           |
| Inlet Temperature| Oxidizer Fuel        | Feed-back          | Stack Inlet Temp | 0              |
| Outlet Temperature| Blower Power        | Feed-forward/back  | Outlet Temp      | 0.02           |
| Outlet Temperature| Bleed Valve         | Feed-back          | Outlet Temp      | 0.01           |

Degradation and Lifetime Analysis Model Description

Stack Design. The degradation and lifetime analyses were conducted using a 2.5 kWe SOFC stack design, based upon anode-supported cells, developed within the FP6 European FlameSOFC project, for combined heat and power (CHP) application. The one-dimensional single-repeated-unit (SRU) model is implemented in gPROMS, an equation-oriented process modeling tool (25). Figure 2 depicts actual geometry of the FlameSOFC SRU, and the simplification to three sub-domains, i.e. electrochemically-active (Ractive), air entry (Rinlet) and exhaust (Routlet) zones. The electrochemical model is based on physical principles, which enables the implementation of degradation phenomena.

Electrochemical Model. Ohmic losses comprise the ionic resistivity of the electrolyte, corrected for constriction effects, the electronic resistivity of the MIC, its oxide layer and contact resistance, and a limited electronic conductivity of the electrolyte.
that induces a small leakage current. The case of LSM-YSZ cathode is considered. The expression for the transfer current holds for the sequence of elementary processes proposed by van Heuveln et al. (26). The dusty-gas model and continuity are solved for the anode supported cell. The approach of Achenbach et al. accounts for reforming and the water-gas shift (27). Only hydrogen is electrochemically converted at the interface, as proposed by Zhu et al. (28).

Five degradation phenomena are modeled; (i) An empirical model reproduces the experimental data on the decrease of the ionic conductivity of 8YSZ during aging in air. (ii) Temperature and gas composition dependence is assumed identical to uncoated MIC (29). The relation by Liu et al. predicts oxide growth and corrosion rates (30). (iii) A percolation model predicts nickel particle growth at the TPB (23). (iv) Chromium contamination for a LSM-YSZ cathode assumes progressive blocking of active sites by electrochemically-deposited Cr$_2$O$_3$ from MIC released CrO$_2$(OH)$_2$\(_{(g)}\). Mass transport limits the gaseous CrO$_2$(OH)$_2$ content (31, 32). Thermodynamic data for Cr$_2$O$_3$ is referenced for all chromium species (33). Modeling of uncoated MIC yields conservative chromium contamination predictions (34, 35). (v) Electrically-insulating LZO/SZO phases cause severe detrimental effects on LSM-YSZ cathode performance (5). Thermodynamic data is interpolated and compared to local oxygen partial pressure (6).

Results

System Analyses

The goal of the current work is to determine: (a) whether or not one can design and control an SOFC system to operate in a peaking mode to increase revenue by producing more power when it is more highly valued, and (b) whether degradation of the SOFC may be adversely affected by dynamic dispatch of the SOFC in such a peaking mode. The simulated SOFC system was cycled between full-load (noon to 8pm) and half-load (8pm to noon). The system turn-down from full- to half-power and ramp-up from half- to full-power were performed in one minute, demonstrating a rapid response to demand changes while maintaining a satisfactory internal SOFC temperature profile. Weak parameter selection led to a resonance phenomenon as thermal energy oscillated between the mass of the FC stack, the external reformer and the air pre-heat heat exchanger masses, Figure 3. The stack inlet and exhaust temperature fluctuate 180° out of phase when the recuperator bypass valve opens on the same time scale as the stack thermal inertia. Similar harmonics subside quicker during a ramp-up because there is an undersupply of thermal energy. Stronger control ensured nominal operating conditions after transient operation, Figure 4. A spatial temperature prediction shows minimal gradient and distribution fluctuation during the transient. Note that the SOFC dynamic simulation suggests that one can moderate the fuel cell inlet perturbations to achieve relatively constant performance during rapid and relatively extreme transient operation associated with dynamic dispatch and changes in ambient conditions.

System control with calibrated control parameters demonstrates the ability to maintain system operation within design constraints. Figure 4 shows a system response to the same dispatched operation with minimal undesired transient response. The system electrical output can easily ramp from half- to full-load in one minute. However, the
thermal response is much slower due to the large mass of the FC. Calibration of the control strategy eliminates thermal oscillations and peak MEA temperature is held within constraints for both full- to half-load and half- to full-load transients. The sudden drop of cathode inlet temperature is caused by endothermic reformation of additional fuel in the external reformer. Additional fuel, supplied to the oxidizer, provides heat to the reformer and recuperator during the ramp-up transient. The cathode exhaust and MEA peak temperature, both indicators of the internal temperature profile, are minimally affected as the system returns to nominal inlet conditions.

Figure 3. a) 24 hour thermal response to dynamic dispatch with weak controllers; b) associated control perturbation.

Figure 4. a) 24 hour thermal response to dynamic dispatch with strong feedback controllers; b) associated 24 hour control response; c) 30 minute thermal response with strong feedback control; d) associated 30 min control response.
Stack Analyses

The stack performance was investigated under two operating modes; fixed (P) and cyclic (CP). Under fixed load operation the specific power was held constant at either 0.28 W/cm² or 0.14 W/cm². The cyclic operation cycled the specific power between 0.28 W/cm² and 0.14 W/cm². The cyclic operation was constrained in one of four ways; (i) Fixed stack inlet temperature, maximum MEA temperature, and fuel utilization, Or, minimized temperature profile change between full and half load using: (ii) Variable stack inlet temperature, (iii) Variable stack inlet temperature and maximum MEA temperature, (iv)Variable stack inlet temperature and fuel utilization (up to 90%).

The SRU operates in a counter-flow configuration, methane conversion in the external reformer exceeds 99%, and the steam-to-carbon ratio is two. The changes in operating conditions between full and half-load are applied during 1 minute. Table II lists the operating conditions for the different cases studied.

Table II. Operating condition for lifetime durability and degradation tests.

| Case | Specific Power | Inlet T [K] | Max MEA Temp [K] | Fuel Use | Air Ratio¹ | SRU Potential [V]¹ | Current Density [A cm²]¹ |
|------|----------------|-------------|-----------------|----------|------------|----------------------|------------------------|
| a    | 0.14           | 973         | 1150            | 80%      | 5.50, 5.88 | 0.841, 0.808         | 0.180, 0.187           |
| b    | 0.14           | 859         | 1150            | 80%      | 3.38, 3.64 | 0.842, 0.805         | 0.179, 0.187           |
| c    | 0.14           | 913         | 1134            | 80%      | 4.48, 4.83 | 0.842, 0.805         | 0.179, 0.188           |
| d    | 0.14           | 932         | 1150            | 90%      | 5.35, 5.68 | 0.812, 0.781         | 0.186, 0.194           |
| Ref. | 0.269          | 973         | 1150            | 80%      | 6.88       | 0.738                | 0.4                    |

i: (a,b,c,d) Range of values from 0 h to 8000 h. Ref. conditions: range of values at 1440 h (CP28/14).

Determination of Design Limits

The effect of the maximum MEA temperature on the lifetime is investigated from 1100 K to 1220 K, by steps of 10 K, for a constant system specific power of 0.28 W/cm², fuel utilisation of 0.8 and air inlet temperature of 973 K or 950 K. The determination of lifetime can be assessed by one of three methods; (i) The activation of the indicator for the formation of zirconate in the LSM-YSZ cathode, i.e. the time at which the formation of such phases is thermodynamically possible, (ii) A relative decrease in system efficiency of 20%, (iii) An instantaneous degradation rate of the SRU potential of 24 mV/kh, which arbitrarily characterises the start of the regime of accelerated degradation.

Degradation Patterns

Constant power operation produces faster stack degradation than typical constant current endurance tests. Figure 5a depicts the effect of the degradation on the evolution of the SRU potential. The patterns depicted in Figure 5a have been observed experimentally and are satisfactorily captured by the model (23, 36). Degradation of the electrolyte and anode dominates from approximately 0 h to 2000 h. Degradation mechanisms for the electrolyte and anode reach a plateau after 500-2500 h, and 1000-10000 h, respectively (23). Chromium contamination of the LSM-YSZ and MIC corrosion dominates degradation beyond this time frame, with chromium contamination acting more severely and leading to accelerated loss of potential. The fixed system specific power and maximum MEA temperature necessitates even higher current densities to compensate for
degradation. This effect is compounded by the need for additional power generation to compensate for the increased blower parasitic caused by a higher air requirement as polarization losses increase. The higher current drawn to export the same system power accelerates the degradation (compares dashed/solid grey curves for 0.28 W/cm² and 0.4 A/cm²).

The markers in Figure 5a indicate the end of lifetime computed by the three methods. Criterion (i) yields the shortest lifetime estimations, but does not indicate a strict end of service of the stack. Criterions (ii) and (iii) determine an end of life at potentials lower than 0.65 V, below a practical control threshold value. Cycling between 0.28 and 0.14 W/cm² extends stack lifetime. Experimental results highlight the predominant influence of the overpotential on the chromium contamination of LSM-YSZ cathodes, rather than current density (3, 4, 37). Modeling studies show an increase of operating temperature indirectly extends lifetime, despite additional MIC contaminate release (23). Temperature has two opposing effects on zirconate formation in LSM-YSZ cathodes; reduction of overpotential and additional formation of the undesirable phase zirconate (6, 23). Figure 5b depicts the lifetime determined by criterion (i, ii, iii) as a function of the maximum MEA temperature. High temperatures benefit operation except for the risk of formation of zirconate. Lower air inlet temperature exhibits a similar trend and results comparable to stacks with electrolyte-supported cells and state-of-the art MIC coating, e.g. (38).

Figure 5. a) Evolution SRU potential (left), air ratio (left) and current density (right) at constant power (0.14 W/cm²) and constant current density (0.4 A/cm²); b) Effect of the maximum MEA temperature on the lifetime. Case P28 with 973 K inlet air (black) and 950 K (gray).

Effect of Cycling on Degradation

Figure 6 depicts the effect of the operation strategy at half-load on the system efficiency and lifetime under fixed and cycled system specific power. At half-load, the lifetime is for all criteria the highest for case P14a. The benefit of a reduced air ratio due to the lower air inlet temperature in case P14b and, further lower maximum MEA temperature in case P14b does not compensate the detrimental effect on the electrochemical performance. A high fuel utilization of 90% in case P14d yields a significant increase in system efficiency. Because of the higher air inlet temperature, the time to reach a relative decrease in system efficiency of 20% is delayed, compared with cases P14b and P14c.
During operation, the progressive increase of current density complicates degradation analysis. Figures a) and b) depict the evolution of the SRU potential and ASR of the MIC and of the cathode at the reference conditions. The degradation of the cathode induces higher degradation during constant load operation. In contrast, the evolution of the ASR of the MIC and electrolyte (not depicted) depends solely on the temperature profile and its history. The slight modification of the oxidation of the MIC by the different half-load conditions causes differences in degradation behavior (compare CP28/14a and CP28/14c). In cases P14, the evolutions of the SRU potential and ASR of the cathode and the MIC at the reference condition are identical to those displayed in Figure 6 during the first 15000 h at a constant system specific power (not depicted). In the longer-term, the trends change in accordance with the results shown in Figure 6. This highlights the crucial importance of the history on the degradation behavior of a SOFC stack.

Figure 7. Evolution at the reference conditions of a) the SRU potential and b) the ASR of the cathode (left axis) and MIC (right axis) during operation under dispatched operation (circles: CP28/14a,b,c,d) and constant system specific power (squares: P28).
Figure 8. Energy produced (black markers, left axis) and averaged system efficiency (gray, right axis) over the lifetime determined by the three criteria.

The benefit of operating at a low constant system specific power or dispatched mode depends on the instantaneous selling price-of-electricity. Figure 8 provides the specific electrical energy, and the efficiency at which it is delivered for the investigated cases, for the different lifetime criteria. Despite the increase in lifetime between operation at constant full-load and under cycling conditions, the latter strategy produces slightly less electrical energy, but at a higher efficiency. The difference between half-load conditions (a,b,c,d) is more pronounced for case P14, than CP28/14. The system efficiency benefits from a higher fuel utilization of 90% at half-load (d). Further economical and control analyses are needed to verify the gain and feasibility of this case.

Conclusions

The outcome of combining complete system level and SRU/stack degradation models to analyze the effects of dynamic dispatch on the lifetime of a SOFC system is presented. Constant system power output and diurnal dynamic dispatch modes have been investigated. The system level analysis showed that an improperly controlled system will exceed thermal limits during transient operation, but properly calibrated control systems can minimize fluctuations to just a few degrees kelvin. A minimum of six independent actuators were needed to fully control the SOFC system behavior during transient operation. However, each actuator represents a physical device thus making the control system applicable to a realistic physical system. The coupled nature of the electrochemical and physical systems leads to complex dynamic interactions that warrant further investigation. The thermal inertia of the system first led to an oscillatory behavior during turn-down which, if left unaccounted for, will damage the system. The thermal oscillations were mitigated with system control development to acceptable amplitude and completely damped within 30 minutes of the system transient. Spatial resolution of the SRU temperature profile reveals gradient fluctuations less severe than anticipated. The mass of the electrochemical system induces transients at a very long scale that are mitigated by a robust control scheme.
These results have been used as operating conditions for degradation simulations with a dedicated SRU model. The predicted degradation behavior is qualitatively in line with experimental results from the literature. The cyclic dispatch mode yielded an extension of the lifetime by a factor up to 1.40, compared with the constant full-load operating mode. The decrease of the cathode overpotential produced by an increase of the maximum MEA temperature alleviates the chromium contamination of the LSM-YSZ cathode, despite the higher release rate of volatile chromium species from the MICs. In the conditions studied here, the risk of formation of zirconate in the LSM-YSZ cathode limits the maximum MEA temperature to 1180 K.

The four strategies for system control at half-load operation yield differing affects upon the lifetime for constant half-power and cyclic dispatch modes. The local accumulation of the degradation induced by MIC oxidation and chromium contamination of the cathode differs between fixed operation and dispatch mode. The difference in lifetime performance for each half-load strategy can be seen in the figures for fixed power at half-load. For the cyclic dispatch mode the strategy of reducing the maximum MEA temperature at half-load yielded the greatest lifetime extension, whereas the strategy of increasing fuel utilization from 0.8 to 0.9 enabled higher system efficiency with minimal detrimental effect on lifetime.

The electrical energy produced during the lifetime of the SOFC device, and the efficiency at which it is delivered is highest in the constant half-power mode, second highest in dynamic dispatch mode, and lowest at full-load operation. The cyclic dispatch mode offers a small advantage in lifetime over constant full-load operation, but the total energy produced over the lifespan is roughly equal. However, the average efficiency of the dispatched system is significantly greater than the fixed operation system. In addition the added value of more power production during peak hours contributes to a net gain in revenue generation over the lifetime of the SOFC system when dynamically dispatched. Thus the dispatched system produces the same electrical energy at a greater average efficiency and higher average value than the base-loaded system.

**References**

1. T. Horita, K. Yama ji, H. Yokokawa, A. Toji, T. Uehara, K. Ogasawara, H. Kameda, Y. Matsuzaki, and S. Yamashita. *Int. J. of Hydrogen Energy*, **33** 6308 B (2008).
2. T. Horita, K. Yamaji, Y. Xiong, H. Kishimoto, N. Sakai, and H. Yokokawa. *Solid State Ionics*, **175** 157 (2004).
3. E. Konysheva, J. Mertens, H. Penkalla, L. Singheiser, and K. Hilpert, *J. Electrochem. Soc.*, **154** B1252 (2007).
4. S. Jiang, J. P. Zhang, L. Apatheanu, and K. Foger *J. Electrochem. Soc.*, **147** 4013 (2000)
5. A. Hagen, Y. Liu, R. Barfod, and P. Hendriksen, *J. Electrochem. Soc.*, **155** B1047 (2008).
6. Y. Liu, A. Hagen, R. Barfod, M. Chen, H. Wang, F. Poulsen, and P. Hendriksen, *Solid State Ionics*, **180** 1298 (2009).
7. A. Faes, A. Hessler-Wyser, D. Presvytes, A. Brisse, C. Vayenas, and J. Van. *Quantitative study of anode microstructure related to SOFC stack degradation*, (2008).
8. D. Simwonis, F. Tietz, and D. Stöver, *Solid State Ionics*, 132 241 (2000).
9. C. Haering, A. Roosen, and H. Schichl, *Solid State Ionics*, 176 253 (2005).
10. J. Kondoh, T. Kawashima, S. Kikuchi, Y. Tomii, and Y. Ito, *J. Electrochem. Soc.*, 145 1527 (1998).
11. J. Brouwer et al., *J. Power Sources*, 158 213 (2005)
12. T. Kaneko, J. Brouwer, and G.S. Samuelsen, *J. Power Sources*, 160 316 (2006).
13. D. McLarty, J. Brouwer, and G.S. Samuelsen, *ASME Fuel Cell 2010*, (2010).
14. F. Mueller University of California, Irvine, Master's thesis (2005).
15. R. Roberts, J. Brouwer, F. Jabbari, T. Junker, and H. Ghezel-Ayagh, *J. Power Sources*, 161 484 (2006).
16. R. Roberts and J. Brouwer, *J. Fuel Cell Science and Tech.*, 3 18 (2006).
17. R. Roberts, University of California, Irvine, PhD thesis (2005).
18. F. Mueller et al., *Transactions of the ASME*. 3 144 (2006).
19. Y. Kuniba. University of California, Irvine, PhD thesis (2007).
20. F. Mueller et al., *J. Dynamic Systems, Measurement, and Control*, 1 (2009)
21. F. Mueller University of California, Irvine, PhD thesis 2008.
22. F. Mueller, R. Gaynor, A. Auld, J. Brouwer, F. Jabbari, GS Samuelsen, *J. Power Sources*, 176 229 (2008).
23. N. Arata. Ecole Polytechnique Federal de Lausanne, PhD thesis (2011)
24. J. Xu and G. Froment, *AIChE. Journal*, 35 88 (1989)
25. Process Systems Enterprise Ltd. gPROMS, London.
26. F. H. van Heuveln, H. J. M. Bouwmeester, *J. Electrochem. Soc.*, 144 134 (1997).
27. R. Achenbach, *J. Power Sources*, 52 283 (1994).
28. H. Zhu, R. J. Kee, V. M. Jannardhanan, O. Deutschmann, and D. G. Goodwin, *J. Electrochem. Soc.*, 152 A2427 (2005).
29. J. Froitzheim, G. Meier, L. Niewolak, P. Ennis, H. Hattendorf, L. Singheiser, and W. Quadakkers, *J. Power Sources*, 178 163 (2008).
30. W. Liu, X. Sun, E. Stephens, and M. Khaleel, *J. Power Sources*, 189 1044 (2009).
31. E. Opila, N. Jacobson, D. Myers, and E. Copland. *J. Minerals, Metals and Materials Soc.*, 58 22 (2006).
32. Z. Wuillemin. Ecole Polytechnique Federal de Lausanne, PhD thesis, (2009).
33. B. Ebbinghaus, *Combustion and Flame*, 93 119 (1993).
34. G. Alman, R. Holcomb and D. E. *Scripta Materialia*, 54 1821 (2006).
35. M. Stanislowski, E. Wessel, K. Hilpert, T. Markus, and L. Singheiser. *J. Electrochem. Soc.*, 154 A295 (2007).
36. L. de Haart, J. Mougin, O. Posdziech, J. Kiviaho, and N. Menzler. *Fuel Cells*, 9 794 (2009).
37. J. A. Schuler, P. Tanasini, A. Hessler-Wyser, and J. V. Herle, *Scripta Materialia*, 3 895 (2010).
38. A. Mai, B. Iwanschitz, R. Denzler, D. Haberstock, and A. Schuler, *Proc. 9th European Fuel Cell Forum*, (2010).